The impact of sustainable Agroforestry on Carbon stock and Biodiversity conservation around Cyamudongo isolated rain forest in Rusizi and Huye Districts, Rwanda

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DEDICATION

This work is chiefly dedicated to my beloved wife Marie Chantal ZANINKA and my beloved sons Zidane HIRWA and Lucky HIRWA for their endless love, good smiles, and who make me feel like a strong daddy and gentleman. This work is also dedicated to my father Charles KARONKANO and mother Anysie MUNDEKAYO; my brothers Charles Lwanga TWAGIRAMUNGU and Jacques NDAYISENGA; my sisters Charlotte NYIRAHABAKWIHA, Mediatrice NYIRAHABIMANA, and Epiphanie UWAMBAZA for their encouragement to my life in achieving this high aspiration.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS AND ACRONYMS

ABGB: Above and belowground biomass

AF: Agroforestry

AGB: Above ground biomass

AGB: Above ground biomass

BD: Biodiversity

BGB: Below ground biomass

BRs: Biosphere Reserves

BZA: Buffer Zone AF

CAI: Current Annual Increment

CDM: Clean Development Mechanism

CEC: Cation Exchange Capacity

CL: Cropland

CO_2e: C stock equivalent

DBH: Diameter at breast height

DD: Data deficiency

DRC: Democratic Republic of Congo

ECEC: Effective Cation Exchange Capacity

EDPRS: Economic Development and Poverty Reduction Strategy

FAO: Food Agriculture Organization

G: Basal area/Ha

GPS: Global Positioning System

ha: Hector

IPPC: International Plant Protection Convention

LC: Least concern

LDSF: Land Degradation Survey Framework

LULUCF: Land Use, Land Use Change, and Forestry

MAB: Man and Biosphere

NF: Natural forest

NISR: National Institute of Statistics of Rwanda

NT: Near threatened

OC: Organic Carbon

OM: Organic matter

PAs: Protected areas

pH: potential of Hydrogen

RDB: Rwanda Development Board

RS: Random Samples

SS: Systematic Samples

t: Tonne

UNEP: United Nations Environmental Program

UNESCO: United Nations Educational, Scientific and Cultural Organization

UNFCCC: UNFCCC

VU: Vulnerable

WSD: Wood specific density

ABSTRACT

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 climate change, soil degradation, and loss of biodiversity. Therefore, this study aims to broaden current knowledge on the impact of sustainable Agroforestry (AF) on the Carbon (C) stock and Biodiversity conservation on the surroundings of Cyamudongo isolated rain forest and Ruhande Arboretum.

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 while 3 PSPs were established in the Ruhande AF plot. The Arc Map GIS 10.4 was used to design and map the sampling areas while GPS was used for localization of collected items. Statistical significance was analyzed through the R-software especially for wood and soil variables while for biodiversity indicator species, MVSP Software 3.0 was used to determine the Shannon Diversity indices and similarities among species.

In this study, I have obtained comprehensive results demonstrating that in all study areas, the various AF tree species contribute differently to C stock and C sequestration and the amount of C stored and removed from the atmosphere depends on different factors such as tree species, plantation density, growth stage, or the age of establishment, applied management practices, wood specific density (WSD), wood C concentration, and climatic conditions. The estimated quantity of sequestrated C for 2 years and 34 years AF species were 13.11 t C ha^{-1} yr^{-1} (equivalent to 48 t CO_2 ha^{-1} yr^{-1}) and 6.85 t ha^{-1} yr^{-1} (equivalent to 25.1 t CO_2 ha^{-1} yr^{-1}) in Cyamudongo and Ruhande respectively. The estimated quantity of C stored by the Ruhande AF plot is 232.94 t ha^{-1}. In Cyamudongo, the overall C stored by the AF systems was 823 t ha^{-1} by both young tree species established by the Cyamudongo Project (35.84 t ha^{-1}) and C stored by existed AF species before the existence of the Project (787.12 t ha^{-1}). In all study areas, the *Grevillea robusta* was found to contribute more to overall stored C compared to other species under this study.

The tests revealed differences in terms of nutrient contents (C, N, C: N ratio, K, Na, Ca, and Mg) for various AF tree species of Cyamudongo and Ruhande study areas. The differences in

terms of correlation for various variables of AF tree species in different study areas varied with tree species, age, stage of growth, and tree shape. By comparing the correlation coefficients for various tree variables for young and mature AF tree species, the results showed a high correlation variability for young species than mature or old species recorded in different environmental conditions of Cyamudongo and Ruhande study areas.

The recorded soil pH mean value across in Cyamudongo study area is 4.2, which is very strongly acidic. The tests revealed that the soil pH, C, C: N ratio, OM, NH_4^+, $NO_3^-+NO_2^-$, PO_4^{3-}, and CEC were significantly ($P < 0.05$) different in various soil depths whereas the N was not statistically significant. 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 $NO_3^-+NO_2^-$ 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. The bulk density of soil was statistically different across land uses and altitude ranges. 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, 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. The overall estimated soil C stock of the study area was 16848 t ha^{-1}.

The sustainable AF practices changed significantly the frequency of reptiles, amphibians, and flowering plants while there was no statistical change observed on ferns with time. In terms of species richness, 16 flowering plants, 14 ferns, 5 amphibians, and 3 reptiles were recorded and monitored. These findings add to a growing body of literature on the impact of AF on the C stock, soil improvement, and Biodiversity. It is recommended that further researches should be undertaken for the contribution of other AF tree species to the C stock found in the agricultural landscape around all protected areas of Rwanda and the impact on them on the soil and biodiversity.

CHAPTER ONE

GENERAL INTRODUCTION AND LITERATURE REVIEW

1.1 Background

The presence of trees in farming systems, although an ancient practice, began to gain institutional attention during the 1970s and 1980s, with the beginning of studies on Agroforestry (AF) systems (Pinho et al., 2012). Several authors have attempted to define AF. For example, according to Lundgren and Raintree (1982), the term AF is generally understood to mean "*a collective name for land-use systems and technologies where woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately used on the same land-management units as crops and/or animals, in some form of spatial arrangement or temporal sequence. In AF systems, there are both ecological and economical interactions between the different components*".

What is known about AF is largely based on its contribution to the products and services it provides to the environment. The AF is preliminarily implemented in the agricultural landscape to provide various products for farmers such as stakes, fuelwood, fodders for livestock, timbers, and medicines among others. Gabiso & Abebe, (2017) highlighted that the AF provides a wide range of products that contribute to income generation and most of the farmers of the third countries especially those of remote areas get the fuelwood from their farms, and the fuelwood is considered as the main source of the energy. On the other hand, the leaves of some AF tree species can be used to feed the livestock (Rose et al., 2018). The farmers can establish the AF fodder trees in different locations of their lands (on contour lines, fences, bench terraces, haphazardly scattered on cropland (CL) and in fodder banks, etc.) with the main purpose of production of fodders for livestock and soil conservation which in turn affects the crop productivity (Holmström, 2013). Apart from the consideration of AF as the source of the energy (fuelwood and charcoal), it provides also the stakes for climbing beans (Rose et al., 2018). The mulch resulted from trees can contribute to the soil productivity enhancement which can reduce the cost of the external input to fertilize the soil.

Generally, the farmers integrate the trees in their farms by selecting the fast-growing tree species to satisfy their needs in terms of timbers at household and market levels (Noordwijk et al., 2003). The production of timbers through AF can help to reduce the pressure of the people who rely on collecting wood from the natural forest (NF). The incorporation of timber production in the agricultural landscape also contributes to the enhancement of proper management of land and the improvement of people's wellbeing by securing their food security (Robin et al., 2014).

An increased number of studies have found that apart from the productive role of AF, it provides also various environmental services such as land protection, soil productivity improvement and can serve as a climate change mitigation and adaptation tool through the C stock and C sequestration. AF has been gaining much attention due to its contribution to C sequestration and C stock. Roshetko et al., (2002) draw attention to the role of AF in C sequestration and storage as a good investment to the farmers who apply AF in their land through the Clean Development Mechanism (CDM). The AF trees and soil can contribute to the regulation of the overall climate through the removal of the CO_2 from the atmosphere and this requires the application of the best practices which rise the C stock and C sequestration (Besar et al., 2020). The AF contributes more to the reduction of the CO_2 from the atmosphere and the importance of AF is enhanced by its ecosystem services that minimize the emissions from the farming activities and the increased amount of the stored C. The ecosystem service of the AF is estimated by the stored amount of C available in the standing tree biomass (Hergoualc'h, 2012).

The Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC) widespread the interest in AF as a tool to overcome many problems while providing considerable importance related to various aspects of the environment especially in the third countries (Dhyani, 2014). Recently, AF has received much attention via Kyoto Protocol as an approach to control environmental pollution through Carbon (C) capturing from the atmosphere (Nair et al., 2009). More recent evidence (Luedeling et al., 2011), suggests the change in the management of land where AF should be promoted all over the world to save our environment because of its ability to store more C through various aspects of the land. Moreover, tree planting on unused soils will improve the properties of the soils and enhance the C stock while preventing climate change-related issues (Nsabimana, 2009).

However, capturing C from the atmosphere and storing it in biomass is known as C sequestration. The C stock tends to be used to refer to the amount of C stored in the reservoir (e.g. t C ha $^{-1}$) while C sequestration often refers to process degree of C elimination from the atmosphere considering the aspect of time (e.g. t C ha^{-1} year^{-1}). Mostly, similar AF practices tend to capture the same amount of C (Luedeling et al., 2011). Several factors such as rotation of crops and soil available nutrients contribute to the C capturing from AF and its contribution to soil improvement depends on the types of trees associated with crops (Nair et al., 2009). Under favorable environmental conditions, both AF trees and soils help to capture the C from the atmosphere (Jose, 2009). The nutrients soil composition and C results from the association between trees and soil (Nsabimana, 2009).

Primarily, changes in land use can significantly affect soil properties, and improper land management results in soil and water loss (Haghighi et al, 2010). Globally, the poor soil conditions affect its long-term productivity especially in the African countries of sub-Sahara (Zingore et al., 2010). Furthermore, land degradation has long been recognized as a major problem in Rwanda, especially impacting the Southwest of the country, but important everywhere (Olson and Berry, 2003).

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.

Henceforward, 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). 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. These last take a considerable part of agricultural land out of production and have often proved to be inappropriate and may even increase erosion risks on steep slope sites susceptible to mass movements. The biological control cannot only reduce runoff and soil loss to tolerable limits but are also able to improve soil fertility and thus increase crop production.

The contribution of AF to safeguarding the various aspects of the environment not only in climate and land management but also the biological resources. Biological resources have received much attention for their conservation by most people (Jose, 2009). For the sustainable use of biodiversity, immediate actions have to be taken (Arroyo et al., 2014). If well managed, the AF systems can sustain the biodiversity resources (Kaushal1 et al., 2017). Further, Udawatta et al. (2019) concluded that the AF positively contributes to the management of biodiversity resources.

As far as nature conservation is concerned, some conservation approaches have been adopted. One of the relatively new and integrated conservation approaches is the buffer zone. Wild and Mutebi (1996) described "a Buffer zone as any area, often peripheral to a protected area, inside or outside, in which activities are implemented or the area managed to enhance the positive and reducing the negative impacts of conservation on neighboring communities and vice versa". Specifically, buffer zone AF (BZA) is one of many strategies currently being promoted because it can provide alternative sources of forest products commonly harvested from protected forests for the livelihood of dependent local communities. For this strategy to succeed, tree species selection for BZA must be handled carefully, to respond to the felt needs of beneficiary communities. This requires their participation in the species selection process (Kasolo and Temu, 2008).

AF can be highly appropriate in buffer zones, as it is a multi-purpose system with various economic opportunities and a relatively high intrinsic biodiversity level (Ebregt and de Greve, 2000). Thereafter, different initiatives around the world have used BZA in the conservation of protected areas including national parks. BZA case studies from Burundi, Uganda, Cameroon, Mexico, China, and Sri Lanka are typical examples (Orsdol, 1987).

Rwanda is generating considerable interest in terms of the use of BZA in the management of its protected areas. Since 2017, there has been a rapid rise in the use of BZA where the Cyamudongo Project of the University of Koblenz-Landau in cooperation with the Government of Rwanda established the BZA around Cyamudongo isolated rain forest.

1.2 AF for C and climate change mitigation and adaptation

1.2.1 C sink, C stock, and C sequestration

According to Assefa et al., (2013) C sink is a C pool from which more C flows in than out. Forests can act as a sink through the process of tree growth and resultant biological C sequestration. The C pool is a system that can accumulate or release C. C stock is understood to mean the mass of C contained in a C pool. C stock assessment is one of the important steps to start with sustainable land use planning about low C emissions. The change in C stock with the dynamics of land-use changes may result in either C emission or sequestration. According to the International Plant Protection Convention IPPC (2006), C pools in forest ecosystems are comprised of C stored in the living trees aboveground and belowground, in dead matter including standing dead trees, down woody debris, and litter among others.

Various approaches have been proposed under the international conventions and programs to demonstrate the role of combining trees with crops in the regulation of climate-related issues and suggested how its support should be achieved. For example, the UNFCCC and more specifically in the Kyoto Protocol, tree plantation programs are considered to contribute to the removal of the atmospheric C and storing it in the C pool such as soil and forests (Nair & Kumar, 2011).

The above-ground biomass (AGB) and belowground biomass (BGB) are made by different components of vegetation and soil (Hairiah et al., 2010). More C can be removed from the atmosphere and stored through the use of trees of high rotation periods in the management of land (Nair & Kumar, 2011). The AF systems capture and store a considerable amount of C both below and above the soil surface (Nair et al., 2010). The amount of C stored by the AF system is more than the amount which can be fixed by a land use management system without a tree component (Nair & Kumar, 2011). The C stored by any AF system is found in various components of the system such as woody components, crops, and soil either below ground or above ground. Besides, the C stored by trees is in different proportion in various tree parts such as stems, branches, leaves, roots, flowers, fruits among others and total C estimation should consider all parts and components within the system (Nair & Kumar, 2011).

Scientists have always seen the measurement and estimation of C stored by forests and AF systems as an appropriate approach to mitigate climate change-related issues. Various researchers have developed several approaches and models wherever the word. These models are being applied in the environmental conditions through which they have been developed. Until now, the forest has been considered as the major C sink of terrestrial ecosystems. The amount of C stored depends on the type of contributing C sink and how was managed. Among developed best models which can fit both climate and forest types in tropics with tree size between 5-60 cm diameter were developed by Chave et al., (2014) and was used in this study. Similarly, a few models for AF tree species and multi-stem trees or shrubs especially for the small trees with < 5 cm diameter at ground level (D_{30}) were developed and the one of Mokria et al., (2018) was followed and applied on young AF species.

In the literature, C sequestration usually refers to the process of eliminating C from the atmosphere and loading it in one or more C pools (Jose, 2009; Assefa et al., 2013; UNEP, 2017). In AF, the term C sequestration has been applied to refer to the removal of CO_2 from the atmosphere via the system composition and deposit it into the reservoir for a long period (Nair et al., 2010). The amount of C removed from the atmosphere by an AF system varies according to the status and the nature of the system, ecological factors, and how the system is maintained (Jose, 2009). The C sequestration is an asset to the third-world farmers who apply AF practices as the captured C amount may be sold to industrialized countries (Nair et al., 2010). Wherever the world, AF has been receiving much attention due to its ability to capture CO_2 from the atmosphere (Nair & Kumar, 2011). Ultimately, AF contributes to C sequestration, increases the range of regulating ecosystem services, and enhances biodiversity (Kay, 2019).

1.2.2. The climate change and mitigation measures

In the environment, several definitions of climate can be found. The term climate has been used by Assefa et al., (2013) to refer to " the weather at a location over a long time; a minimum recording period of 30 years is deemed necessary to account for normal variation". Climate change is described as "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over large time" (UNFCCC, 2015).

The most current accepted serious environmental issue affecting human lives on a global scale is global climate change commonly called global warming (Nair et al., 2009). In recent years, there have been considerable environmental-related problems due to global warming (Nair and Kumar, 2011). It has been demonstrated that changing the forested areas to other land uses and their poor management resulted in the ozone layer exhaustion (Sobola & Amadi, 2015b).

Various approaches have been hypothesized to solve this issue. The establishment of forest and AF practices under various international conventions especially those attached to the UNFCCC such as Land Use, Land Use Change, and Forestry (LULUCF), Kyoto Protocol, and Clean

Development Mechanism (CDM) has been receiving much attention due to the capacity of trees to sequester more C from the atmosphere (Nair et al., 2009).

The vegetation is a large C pool than the atmosphere and its change affects the global environment (Schaaf, 2009). The forest has been identified to control global C and plays an important role to the people. Pan et al., (2011) identified that change with time of the forest resources must be well mastered to know how they contribute to climate regulation. It has now been suggested that environmental-related issues can be addressed by AF (Agevi et al., 2017). AF has been demonstrated to play several advantages including environmental, economic, and social at different scales (Sobola & Amadi, 2015b). Conversely, the AF has to be well managed to maximize the intended target (Mbow et al., 2014).

1.3 AF for soil erosion control, soil properties improvement, and nutrients availability

1.3.1 AF for soil erosion control

The high human population growth in Sub-Saharan Africa has led to the intensification of agriculture, deforestation, and the use of less suitable land for agriculture. Poor agriculture practices interrupt soil productivity (Lagerlöf et al., 2014).
Olson & Berry, (2015) affirm that inadequate soil fertility affects crop production, and soil quality is reduced by underprivileged agriculture-related practices. Restoring degraded forests and agricultural lands have become a global conservation priority (Christin et al, 2016). Various approaches have been put forward to solve the aforementioned issue. 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, which take a considerable part of agricultural land out of production and have often proved to be inappropriate and may even increase erosion risks on steep slope sites susceptible to mass movements.

Land degradation can be controlled by tree plantation by taking into account the shape and structure of the land (Lundgren & Nair, 1985). Moreover, Sobola & Amadi (2015b) show that AF helps not only to enhance the properties of the soil but also contributes to the long-term management of the atmosphere.

Countries need to restore the land in order to produce commodities like food, fuel, or fiber that can improve local livelihoods and reduce poverty or be sold to finance restoration activities; however, they also need to restore landscapes to produce public goods like watershed protection, disaster risk reduction, and biodiversity conservation (Christin et al., 2016).

In Rwanda, 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 (Ministry of Land and Forestry, 2018).

1.3.2 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 & 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 & 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 nutrients 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).

The biota is considered critical to soil health and ecosystem sustainability because of their role in the decomposition of soil OM, nutrient cycling, and thereby influencing soil chemical and physical properties, which will ultimately determine soil fertility and long-term sustainability (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).

1.4 Preservation of biodiversity with AF

The 2nd Ministerial Conference on the Protection of Forests held in Helsinki in June 1993, broadly emphasized the definition of biodiversity as defined by the Convention on Biological Diversity. Biodiversity is defined as "the variability among living organisms from all sources including, inter alia, terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems" (Bachman et al, 1998). Biodiversity indicators at the stand level are increasingly being used to help identify conservation areas and to develop forest management strategies. Indicators must be chosen carefully to "capture" as large a proportion of biodiversity as possible. Indicators also need to be continually re-assessed to check whether they are supplying valid information (Bachman et al., 1998). In recent years there has been growing interest in biodiversity conservation and immediate action to design effective strategies is needed worldwide (Jose, 2009). The status of the environment must be evaluated to provide the alarm of change using the biological indicator species (Dale and Beyeler, 2001).

Amphibians are considered "indicator" species due to their delicate nature; they are easily disrupted by even minor changes in the environment. Amphibians and reptiles are two classes of animals that are grouped because they are considered “cold-blooded”. In biological terms, ectothermic, meaning they derive heat from outside sources, most commonly the sun. The lifecycle of amphibians is very important and is a great way to link amphibians to ecological destruction and wetland conservation (Kinsey, n.d.). The complex life cycle of many amphibian species potentially exposes them to both aquatic and terrestrial environmental changes. These attributes, and the fact that amphibians are ectotherms, make them especially sensitive to changes in temperature and precipitation, and other environmental changes such as greater ultraviolet (UV) radiation (Blaustein and Bancroft, 2007). Rapid amphibian declines exhibit important taxonomic as well as regional patterns. Biodiversity loss, including habitat loss either as a result of direct human activity or climate change and overexploitation, is serious for amphibians (Stuart et al., 2004). Moreover, he further reported that the Amphibians are more threatened and are declining more rapidly than either birds or mammals (Stuart et al., 2004). Amphibians are generally considered suitable as indicator species in a variety of systems. Their biphasic life cycle and semi-permeable skin are two justifications often given for this use of amphibians (Waddle, 2006).

The anthropogenic activities disturb the biological resources particularly reptiles and amphibians and various organizations are working with people to address the biodiversity-related issues especially in the Albertine Rift Region (Kanyamibwa, 2013). AF creates a conducive environment for biological resources because of its complexity in nature (Rahim et al., 2010). AF is recognized as a possible partial solution for biodiversity conservation and improvement (Udawatta et al., 2019).

Jose (2009) highlighted the main roles of AF in the conservation of biological resources and its contribution is due to the various ecological services offered by the system. Through AF systems, the communities have their basic needs for food, medicine, fuels, raw materials for construction and handicrafts, and their free cultural development. The biodiversity of these traditional agroecosystems and the additional resources of their neighboring area secure the livelihoods and well-being of many (Vandreé & Wolfgang, 2017).

1.5 Buffer zone AF in forest protection

In many regions of developing countries, there is a significant loss of natural resources caused by deforestation and unsustainable agriculture (Orsdol, 1987). Human activities such as land conversion and urban sprawl pose pressures and threats to the ecologically valuable areas which play an important role in providing ecosystem services (Galvão et al., 2018). The environmental degradation and inefficient agriculture affect the rural population who are intimately tied to the use of natural resources and drive them to do illegal activities such as encroachment and deforestation which result in the rapid decline of biological diversity within the protected areas (Orsdol, 1987).

There is a vast amount of literature on the buffer zone. The term buffer zone is generally understood to mean " a common land management strategy that is established around National Parks (NP) to protect the biodiversity against human activities (Heinen and Mehta, 2000).

The buffer zone separates the protected area from direct human pressures and provides an area of controlled land use and it can be most effective when designed to maximize the flexibility of management plans of both the buffer zone and the protected area. From the perspective of development agencies, buffer zones present the opportunity to develop sustainable agriculture and forestry practices in areas either where the natural resource base remains largely intact or where it can be improved to support managed utilization. From the conservation viewpoint, buffer zones represent a crucial methodology for preserving biological and species diversity in reserves under threat from the surrounding human population (Orsdol, 1987).

AF can be highly appropriate in buffer zones, as it is a multi-purpose system with various economic opportunities and a relatively high intrinsic biodiversity level (Ebregt and de Greve, 2000). In other words, the use of multipurpose trees and shrubs is of great importance to providing diversified products from AF land use while sustaining the role of ecological function from the same system. Multipurpose trees and shrubs are defined as all woody perennials that are purposefully grown to provide more than one significant contribution to the production and/or service functions of a land-use system that they occupy. AF can be promoted around protected areas because of the multiple functions it provides to the environment (Rahim et al., 2010).

In many of the conservation programs and projects, the zoning principle is applied to allow protection to be combined with human use, whereby important areas are surrounded by the so-called buffer zones which are seen as important tools in both conserving areas of ecological importance and addressing development objectives (Ebregt and de Greve, 2000).

It has now been suggested that AF helps to manage the negative interaction between people and protected areas (Wild and Mutebi, 1996). Buffer zone AF (BZA) is one of several strategies currently being promoted because it can provide alternative sources of forest products commonly harvested from protected forests (Kasolo and Temu, 2008).

AF practices have been gaining much attention due to their ability to promote people's well-being while attracting and maintaining biological resources (Orsdol, 1987). AF practices, when integrated into buffer zones around protected forest areas, offer considerable potential for alleviating pressures on forest resources while promoting the living standards of the surrounding rural population. Furthermore, the introduction of AF practices can help replace many of the resources which the local population traditionally derived from the protected area (Orsdol, 1987).

In the BZA, AF practices integrate trees with crop production to enhance the long-term productivity of the agricultural plots and provide forest-related products such as fuelwood, stakes, fruit, timber, fodder, biomass to the local farmers. Several AF technologies showing particular promise include improved fallow cultivation, taungya, alley cropping, shade trees, and shelterbelts (Orsdol, 1987). This simply means that BZA supports more effective agricultural and forestry production outside the reserves to satisfy the subsistence resource requirements of the local population and simultaneously protect forest ecosystems.

BZAs present the opportunity to maintain the biological diversity in protected forest areas as well as promote the standards of living of the surrounding human population to significantly reduce the pressures being faced by many forest reserves and national parks. To maximize the benefits of BZA, the following criteria are suggested to identify particular areas where Buffer zone AF could be most effective: poor resource availability outside the protected area, the recent opening of forested areas, levels of biological diversity in a protected area, forest fragmentation around the protected area and tourist potential (Orsdol, 1987).

The Government of Rwanda through its Vision 2020 program (which is a government developing program launched in 2000) has targeted biodiversity and ecosystems to be well conserved. In this regard, the Government identified environment protection as one of the important cross-cutting areas and the suggested strategies recommend a 3 km development buffer for the biodiversity protection areas and habitat corridors (Kigali City, 2013). The immediate action to design effective strategies to conserve biodiversity in Rwanda started with the Cyamudongo Project of the University of Koblenz-Landau/ Germany in partnership with the government of Rwanda through Rwanda Development Board (RDB) to protect the biodiversity and geo-ecological function of Cyamudongo isolated rain forest and prevent further degradation of this important C sink by reducing the land use pressure on the forest through supporting local farmers in the establishment of sustainable AF systems.

1.6 Description of the problem, aims, and assumptions of the research

A growing body of literature has examined the negative influence of human activities on the conservation of the natural environment of our planet. This instability has heavily caused several environmental problems such as soil erosion, depletion of soil fertility, natural disaster as well as seasonal changes in world climate (Sobola and Amadi, 2015).
In light of the recent events in the Cyamudongo study area, some problems resulted from the effect of anthropogenic activities on the Cyamudongo isolated rain forest. These problems are mainly the harvesting of wood and non-wood components from the forest, land degradation resulting from the poor agriculture practices on the high slopes especially on mountains characterizing the study area, and loss of an important part of existing biodiversity resources. This particular area of Cyamudongo has been overlooked to address the impacts of unsustainable land use on the soil, biodiversity, and climate change.

Specific area of Arboretum of Ruhande and more specifically the AF plot established by the University of Koblenz-Landau in the years 1986 remains unclear in terms of its contribution to the climate change mitigation through C sequestration and C stock. Previous work has only focused on the role of AF in soil improvement and conservation.

The aim of this study is to evaluate the impact of sustainable AF on C stock and Biodiversity conservation of the Cyamudongo isolated rain forest in the Rusizi and Huye districts. Specifically, it first estimated the C stock and C fixation rate of AF trees established by Cyamudongo Project and existing AF tree species around Cyamudongo isolated rain forest and AF plot located in the Arboretum of Ruhande. Secondary, determine the nutrients content of AF trees established by the Cyamudongo Project and existing AF tree species of study areas. Thirdly, evaluate the change of selected soil chemical and physical properties of ongoing land-use of sustainable AF in the study area of Cyamudongo Project intervention. Finally, find out available individual species for each of four taxonomic groups of flowering plants, ferns, reptiles, and amphibians that are found both in Cyamudongo isolated rain forest and in the community farms around the forest and their change with time (before and after the Cyamudongo Project implementation).

This study followed the following research hypotheses:

H_a 1: There is a significant difference between the amount of the fixed C in the biomass of AF trees species established by the project and the existing AF trees species of the study areas.

H_a 2: There is a significant difference between the amount of nutrients content of AF trees established by the Cyamudongo Project and the existing AF trees species of the study areas

H_a 3: There is a significant difference of selected soil physical and chemical properties in different soil depths, altitude ranges, land uses, and throughout the time in the study area

H_a 4: There is a significant difference in biodiversity indicator species, which includes 4 taxonomic groups of flowering plants, ferns, reptiles, and amphibians in the study area before and after the implementation of the Cyamudongo Project.

CHAPTER TWO

CARBON SEQUESTRATION, CARBON STOCK, AND NUTRIENTS CONTENT OF AGROFORESTRY TREE SPECIES AROUND CYAMUDONGO ISOLATED RAIN FOREST AND ARBORETUM OF RUHANDE

2.1 Introduction

In Africa, C sequestration is generally be considered as a co-benefit of strategies to support sustainable livelihoods and adapt to climate change (Mbow et al., 2014). The people's views on tree species to be used for the interventions related to the C sequestration are taken into consideration for better achievement of the project goal especially in the countries of sub-Saharan Africa (Dimobe et al., 2018). The significance of AF with regards to C sequestration and other CO_2 mitigating effects is being widely recognized, but there is still a scarcity of quantitative data on specific systems (Albrecht and Kandji, 2003).

AF contributes to the improvement of people's well-being, biological resources, and environmental conditions (Lasco et al., 2014). The C stock of the land depends on the land use management practices applied and the amount of C stored differ from one land use to the other. There should be a consideration of all fixed quantities of C for better estimation at a large scale (Palm et al., 2005).

Hairiah et al. (2010) reported that the amount of C fixed or C removed from the atmosphere depends on the forest maturity. Mature forest stores more C while sequestering a small amount of C compared to the newly established plantation. Further, they asserted that more C is in above-ground biomass (AGB) in the subsoil. The C storage depends on several factors including climatic, edaphic, and socio-economic conditions. Perennial systems like home gardens and agroforests can store and conserve considerable amounts of C in living biomass and also in wood products (Albrecht and Kandji, 2003). Tree biomass varies from one region to the other and is dependent on species density, age, climatic factors, and soil factors. In Sub-Saharan Africa, it ranges from 0.29-15.2 Mg C ha^{-1} (Agevi et al., 2017). The allometric equations can be used to evaluate the AGB. In the estimation of tree biomass, the use of allometric equations is the most appropriate since it is non-destructive (Hairiah et al., 2010).

The Government of Rwanda recognizes the importance of forestry resources for providing various ecosystem services including C sequestration. Rwanda adopted the implementation of various international agreements (eg. UNFCCC and Paris Agreement) related to climate change mitigation issues and has put in place specific programs and policies (Green Growth and Climate Resilience (GGCRS), Forestry Sector Strategic Plan (FSSP, 2018-2024), National forestry policy of 2018) contributing to the mitigation and adaptation to climate change (REMA, 2018). Long-term management of natural resources contributing to the mitigation of climate change issues is among of Rwandan core interventions (MINILAF, 2018).

Not much is known about C stock and sequestration in the forest and AF land uses in Rwanda especially in Rusizi and Huye Districts. In the literature, there are few examples of studies. Nsabimana, (2009) assessed the C stock and fluxes in Nyungwe forest and Ruhande Arboretum in Rwanda. The AGB dominated the C stocks (70% in the Ruhande Arboretum and 57% in the Nyungwe forest). The study recommended that other studies should be done in other forests and other land cover types in Rwanda to help calculate a C balance for Rwanda.

Nyirambangutse et al. (2017) assessed the C and nutrient cycling in Afromontane tropical forests at different successional stages in the Nyungwe forest. The results showed that the late-successional stands of Nyungwe tropical mountain forest had higher AGB than the average old-growth lowland tropical forests in 10 Central/East Amazonia forests (+11%) and a bit lower than lowland forests in Central Africa (-11%) and Borneo (-15%).

Ndayambaje et al. (2014) estimated the woody biomass on farms and in the landscapes of Rwanda. The study found that the woody biomass dry weight of scattered trees on the agricultural landscape was different in different altitudinal ranges of Rwanda.

This study firstly estimated the C stock and C fixation rate of AF tree species throughout the time in two ecological conditions of Cyamudongo and Ruhande on the following seven AF tree species: *Cedrela serrata, Croton megalocarpus, Grevillea robusta, Markhamia lutea, Maesopsis eminii, Podocarpus latifolius,* and *Polyscias fulva.* The used alternative hypothesis was verified: There is a significant difference between the amount of the fixed C in the biomass of AF trees species established by the project and the existing AF trees species of the study areas.

Further, this study determined the nutrient contents of AF trees established by the Cyamudongo Project and existing AF tree species of study areas, and the following hypothesis was followed: There is a significant difference between the number of nutrient contents of AF trees established by the Cyamudongo Project and the existing AF trees species of the study areas. The research questions were expressed in line with the objectives of the study as follow:

- What is the amount of AGB, BGB, and ABGB for each of the AF tree species under study?
- What is the amount of C for each of the AF tree species under study?
- What are the AF tree species, which sequester and store more C?
- What are the factors that contribute to more C sequestration and C stock?
- What is the amount of K, Ca, Mg, Na, and P for each of the AF tree species under study?
- What is the amount of K, Ca, Mg, Na, and P of different parts/components for the AF tree species under study?
- What are tree parameters or variables with high correlation coefficients of determination?

2.2 Methodology

2.2.1 Study area description

The Rusizi and Huye Districts have been selected to estimate the C stock, C fixation rate, and nutrient contents of AF tree species and their comparison with time. Rusizi District is located in the South-East of Rwanda and is one of seven districts of the Western Province. The two study areas are characterized by different environmental conditions. The area of the Rusizi district is 959 km^2. 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-}. Most of the people (>89%) own < 2 ha which compromises the development of agriculture productivity. Several crops are mixed and grown on one ha (GOR-KD, 2019).

The Rusizi district has both public and private forests which occupy a total area of 357 km^2. The private forest occupies the largest percentage with 64 % corresponding to 35% of the total district area and it is followed by state forest with 35% and the least is 1% of total district area. High demographic pressure combined with a large number of people who rely on agriculture and intensive precipitation, resulted in land degradation, especially on high slopes. Therefore, land protection measures are needed for sustainable district land management (District, 2013). 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).

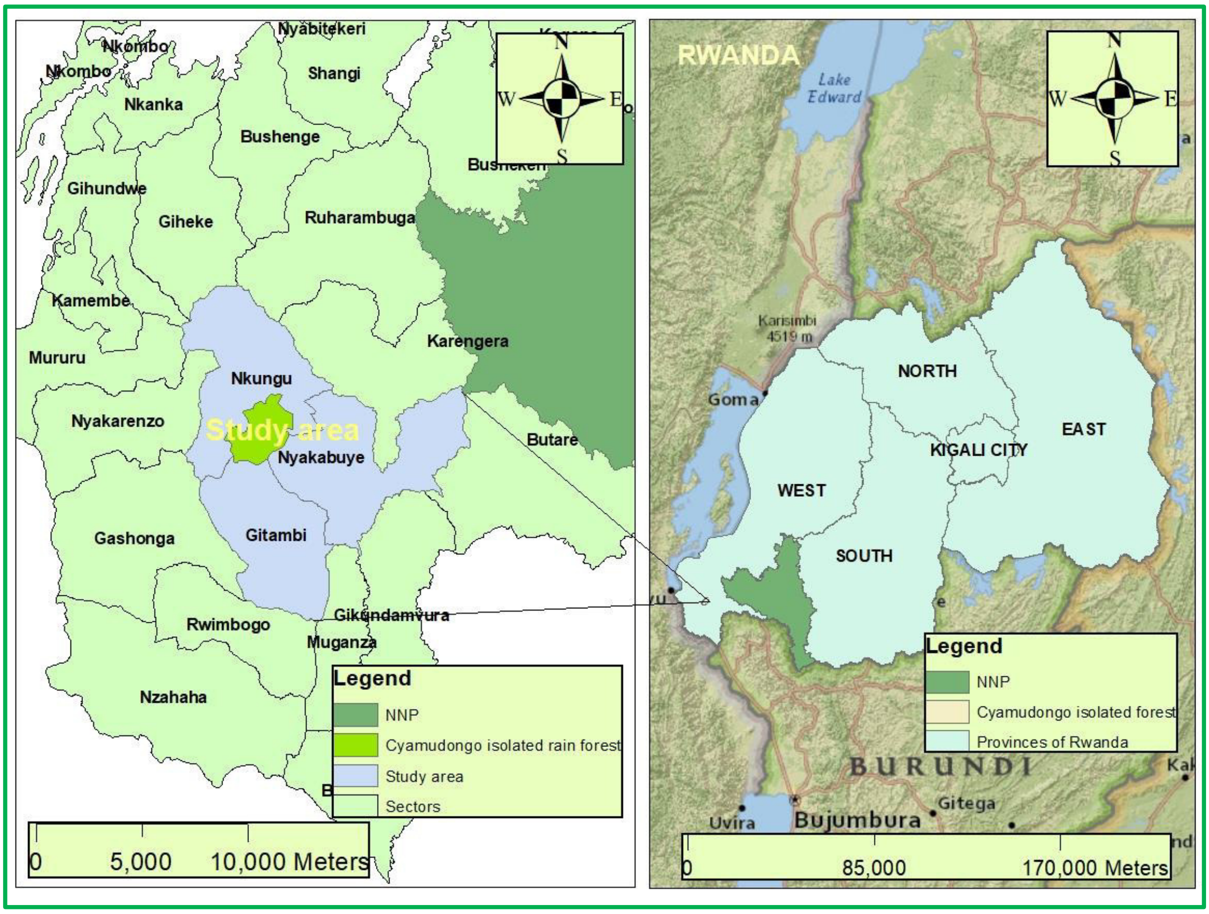


Figure 1: Study area location at Cyamudongo isolated rain forest and its surroundings

Huye district is one of eight districts of the Southern province of Rwanda. It has a total surface area of 581.5 km^2. Huye district is bordered by Nyanza district in its North, Gisagara district in the East and South, Nyaruguru district in the South West, and Nyamagabe district in the North West. Its estimated population density is 540 inhabitants km^{2-}. The Arboretum of Ruhande is located in the Ngoma sector and was established in 1934 on a total area of 200 ha with the main purpose of research, seed production, and promoting AF in Rwanda. It contains several species of conifers (56) and broadleaved (148). The climate of Ruhande is characterized by two rainy seasons and two dry seasons. The first rain season starts in March and ends in May whereas the second starts in September and ends in December. The first dry season starts in January and ends in February while the second starts in June and ends in August (Nsabimana, 2009).

The study was conducted in the AF plot that was established by the University of Koblenz-Landau of Germany in October 1986 (König, 1992) as an extended area attached to the Arboretum of Ruhande with the main purpose of research in AF and soil conservation. The altitude range across the study area in that particular AF plot is 1669 to 1683 m asl.

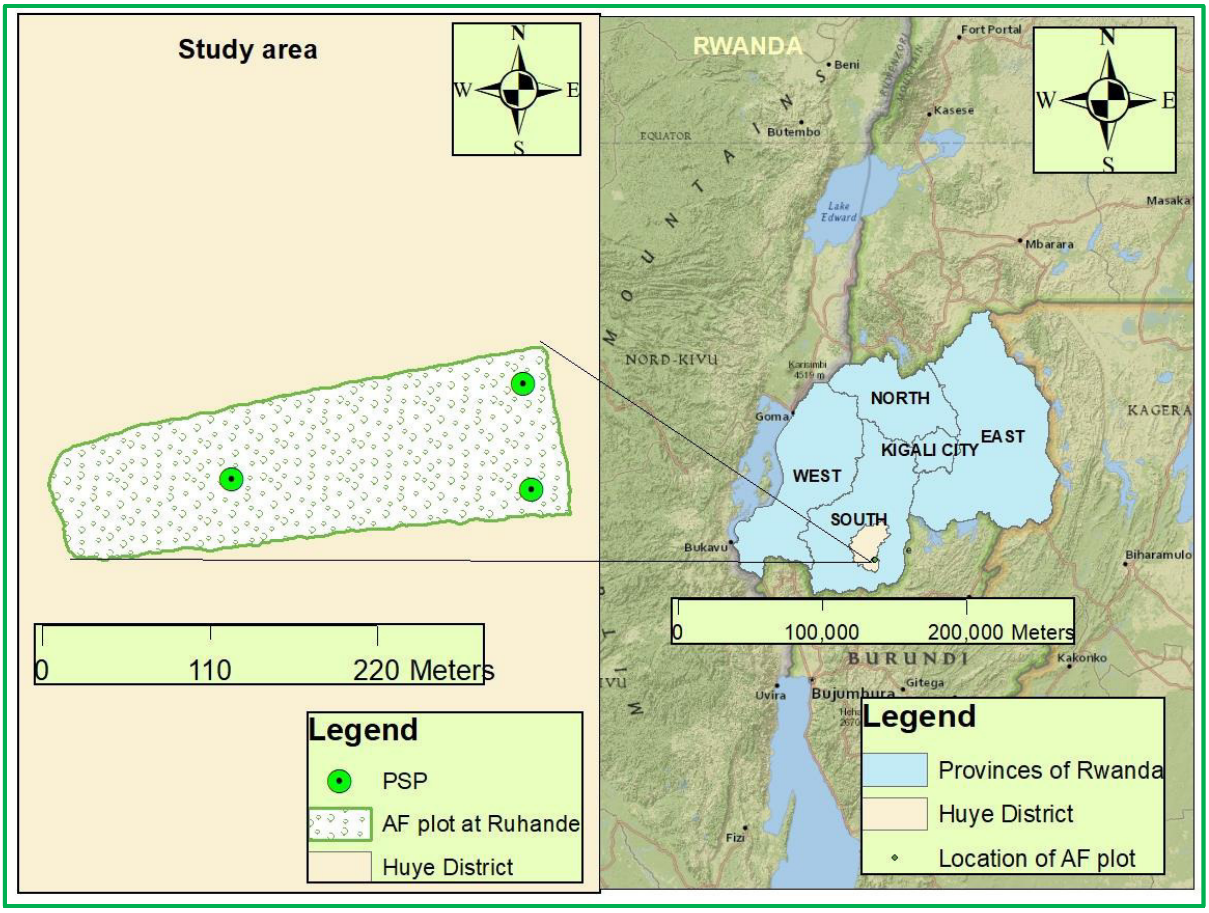


Figure 2: Location of AF plot and PSPs for data collection at Ruhande Arboretum in Huye District

2.2.2 Species description and purpose for intervention

Seven AF tree species from different families were used to estimate AGB, BGB, C stock, C sequestration rate, and nutrients availability including C, N, C: N ratio, K, Ca, Na, and Mg. Table 1 describes the species by scientific names, common names, family, and natural habitat. The study was conducted in two agro-ecological areas including the surroundings of Cyamudongo isolated rain forest of Ruzizi District and Arboretum of Ruhande in Huye District.

The targeted AF tree species in Cyamudongo were either young established AF tree species by Project or existed (mature) AF tree species in the agricultural landscape in the surroundings of Cyamudongo isolated rain forest. These AF tree species include *Cedrela serrata, Croton megalocarpus, Grevillea robusta, Maesopsis eminii, Markhamia lutea, Podocarpus latifolius,* and *Polyscias fulva*. Cyamudongo Project started the plantation of AF tree species in 2017, which are considered young in this study whereas the farmers used to mix AF tree species in their lands even before the Cyamudongo Project intervention, and those species were considered mature. The farmers used to grow AF tree species using the traditional techniques such as poor management practices of trees, poor spacing management, poor plantation techniques, and poor AF tree species selection among others, which compromised the productivity of both crops and AF products for example stakes, firewood, the folder for livestock, firewood and timber.

On the other hand, there were only four targeted ancient AF tree species in the AF small plot (3 ha) managed by the University of Koblenz-Landau of Germany that was established in 1986 in partnership with the Government of Rwanda through the University of Rwanda former "Université Nationale du Rwanda". These AF tree species were *Cedrela serrata*, *Grevillea robusta, Maesopsis eminii,* and *Polyscias fulva*. Initially, the purpose of this plot was the research where its contribution to soil erosion control and the role of AF tree species to the improvement of soil productivity was investigated and published by previous researchers (for example Prof. Dr. Dieter König) of the University of Koblenz-Landau. As the AF has received too much attention in these recent years for its contribution to the removal of C from the atmosphere as a strategy for mitigation of climate change-related issues and its role in the rehabilitation of degraded lands through soil improvement in terms of availability of micro and macronutrients, there was a need to monitor the C stored and sequestered by that AF plot and to estimate the nutrients contained in different AF tree species and their compartments.

Table 1. Species description

#	Scientific name	Common name	Family	Natural habitat
1	*Cedrela serrata*	Hill toon	Meliaceae	Secondary forests. Natural distribution in Tropical Asia from Pakistan to Borneo.
2	*Croton megalocarpus*	Croton tree	Euphorbiaceae	It occurs in evergreen and semi-deciduous forests at (700–) 900–2100(–2400) m altitude, sometimes also in riverine woodland and wooded grassland.
3	*Grevillea robusta*	Silky Oak	Proteaceae	It grows in riverine, subtropical, and dry rainforest environments in Australia
4	*Markhamia lutea*	Markhamia	Bignoniaceae	Occurs naturally in evergreen forest, riverine forest, forest edges, and wooded savanna at 600–2400 m altitude
5	*Maesopsis eminii*	Umbrella tree	Rhamnaceae	Moist forests, particularly forest edges. It occurs from lowland tropical rain forest to savanna, extending into the sub-montane forest up to 1500 m altitude.
6	*Podocarpus latifolius*	Broad-leaved Yellowwood	Podocarpaceae	A canopy tree in coastal to montane primary forests at elevations up to 2,000 m
7	*Polyscias fulva*	Ekwo	Araliaceae	It is found in different types of forest up to 2450 m altitude, often in secondary forest, also in mountain grassland, and in vegetation dominated by bamboo

2.2.3 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 (Figure 3). The four km corresponds to the radius 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. The plots fallen in AF land use were counted while those fallen in forest land use were removed from the scope of our study. Expectedly, there would be 68 plots if the study area were uniform i.e. {4000 m (length of transect) /250 m (distance between 2 consecutive plots) +1} x 4 (number of transects)}. Consequently, 19 plots were found in forestry land use type which resulted in 49 plots in AF land-use type which equals 4.9 ha since the plot size is 1000 m^2.

According to Nizami (2010), the sampling intensity may be reduced from the standard of 2.5 percent of the total forest area to 1.0, 0.5, and 0.25 percent. This reduction of sampling intensity does not increase the coefficient of variation or uncertainty associated with the mean estimated Forest Carbon. One of the important recommendations of Nizami's study is that 1.0% sampling intensity is adequate. Contrary to the previous statement, the size of 4.9 ha was not representative of the entire project intervention area in AF land use as it was below 1% of the total study area (6125 ha). Therefore, 12 additional plots were subjectively established out of transects to cover 1% of the total study area to determine C fixation and C stock in AF land use around Cyamudongo fragmented rain forest.

It has now been suggested various sizes of AF plots vary from small to big ones (FAO, 2018) and depend on tree density (Heiskanen et al., 2013). In this study, the large circular plots with large radius were established as the trees were established with a small density by either scattering trees on CL, or planting trees on the boundary and contour lines. The circular plots were selected because they were easy to be designed and easily established on the steep slopes found in the study areas, especially in Cyamudongo. A recent review of the literature on circular plots, Karki et al., (2016) and FAO, (1992) found that the circular plots minimize the edge and borderline trees effect which usually occurs on rectangular shapes. The number of established plots was dependent on the size of the plots and the targeted area of the study.

A circular sample plot of 0.1 ha (1000 m^2) in size is used for measuring the woody biomass (Heiskanen et al., 2013). The plot radius of 17.84 m (0.1 ha plots) is used on very sparse woody vegetation (Macdicken, 1997). The Land Degradation Survey Framework (LDSF), sample plot design with a sample plot of 0.1 ha (1000 m^2) corresponds to the tenth of the area of the established permanent sample plots (PSP) was used in this study.

The 6.125 ha corresponds also to 61 Permanent Sample Plots (PSPs) since the plot size is 1000 m^2 with a circular plot radius of 17.84 m (equivalent to 1000 m^2) was taken to measure above-ground tree biomass (diameter at breast height (DBH) ≥ 5 cm for large trees and D_{30} cm for small trees < 5 cm) to maximize the chance of having more individual trees within the plot for data collection since the project established AF systems with a density of about 200 trees per ha. The plot size was consistent for Ruhande Arboretum where 3 plots corresponding to 0.3 ha representing a tenth of the study area (3 ha). Besides, the Global Positioning System (GPS) was used to take geographic coordinates of the centers of established plots and ArcMap GIS was used to design and display data on the map.

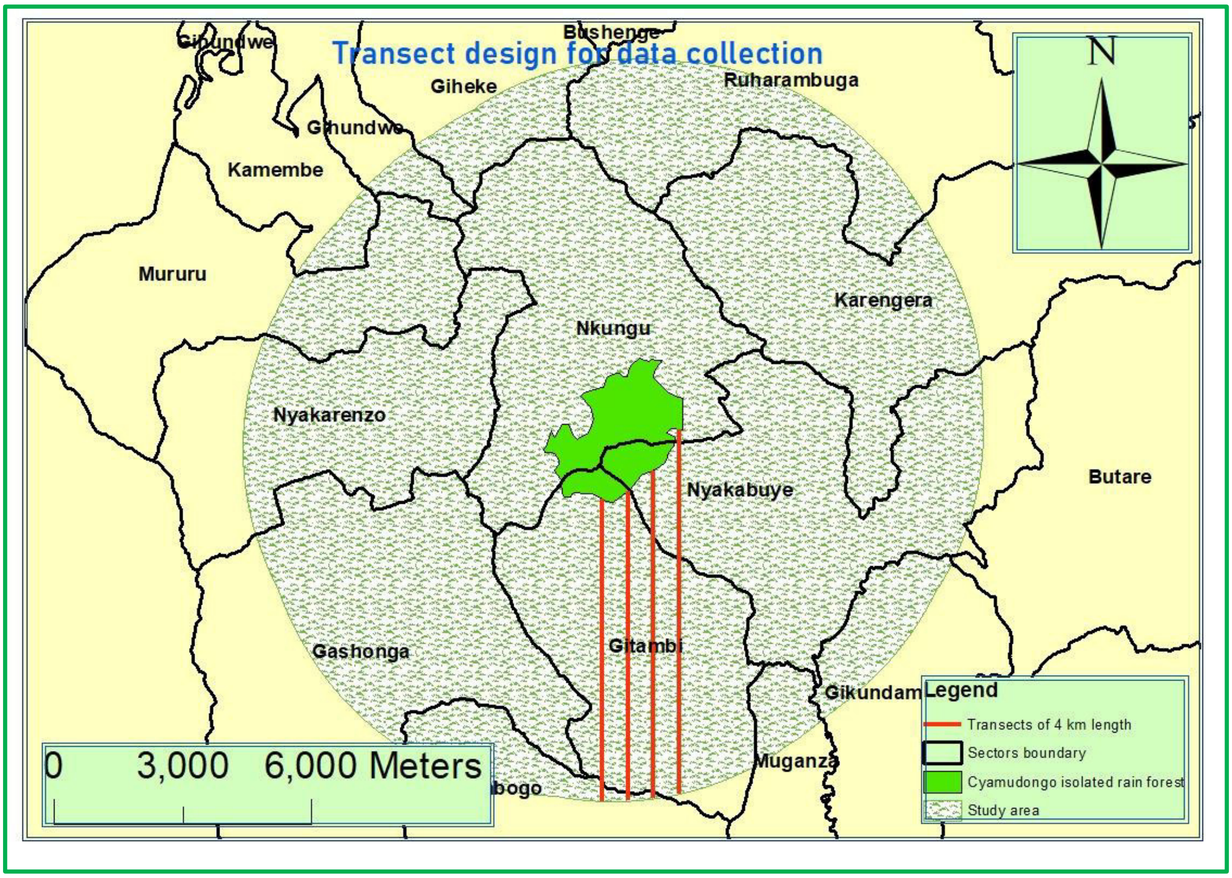


Figure 3. Transect design with 4 km buffer around Cyamudongo isolated rain forest

2.2.4 The correction of the slope

The study area was characterized by the high slopes and the establishment of the PSPs was not done easily as it should be done on the flat area. In this regard, the slopes were corrected to make sure that all established plots for different slopes of the study area are of the same size and are established on the plane area. By projecting the distances measured on the sloped area, the resulted horizontal distances became smaller. The slope correction was applied to enlarge the plot radius by a factor of $\sqrt{1/\cos(\theta)}$ where θ is the slope of the ground in the direction of the average maximum slope (UNFCCC, 2015). As the study was conducted on the sloping terrain, the radius was adjusted according to the slope. After determining, the center of a plot, its boundary was delineated. The slope measurement was performed following the LDSF field guide and the plot radius was corrected to keep the plot area constant (0.1 ha). Therefore, the slope angles were measured using a Suunto PM-5/360 PC clinometer. First, the slope was measured in degrees to the plot boundary in the upslope direction from the center point. Measurement was repeated for the downslope direction. The average slope was recorded in the field recording sheet. Husch et al. (2003) provided a formula for the corrected radius (r_c) of the one-tenth hector. The corrected radius of the 0.1 ha (1000 m^2) sample plot for different slopes is provided in appendix 1.

$$r_c = \sqrt{\frac{1000}{\pi \cos(slope)}}$$

(Equation 1)

2.2.5 Meteorological data

The meteo data were obtained in two ways. Primarily, the meteo stations from the automated National Meteo Agency were used. Secondary, there were established field buckets in the area of Cyamudongo and as the study was conducted in three sectors, there was one bucket for each. The targeted data were precipitation and temperature which were collected daily. Nyakabuye and Nyakibanda automatic meteo stations were used for Cyamudongo and Ruhande respectively. Besides, the 3 buckets in Cyamudongo for various altitude ranges were installed in the field for rain data collection to maximize the quality of the estimate of the rainfall of the Cyamudongo region and were found within a 4 km radius of buffer (Figure 3) as the delimitation of the study area confirmed the project intervention. In addition, the Kamembe aero station was also used for temperature estimation of the Cyamudongo study area.

The daily rainfall for both automated meteo station and bucket were averaged for two years. As the daily rainfall recorded in buckets was in ml per area of 63.5 cm^2 for the used bucket of 9 cm diameter, it was converted into comprehensively daily rainfall in mm per m^2. Furthermore, the yearly rainfall was obtained by summing up all the daily rainfall of the total days of the year.

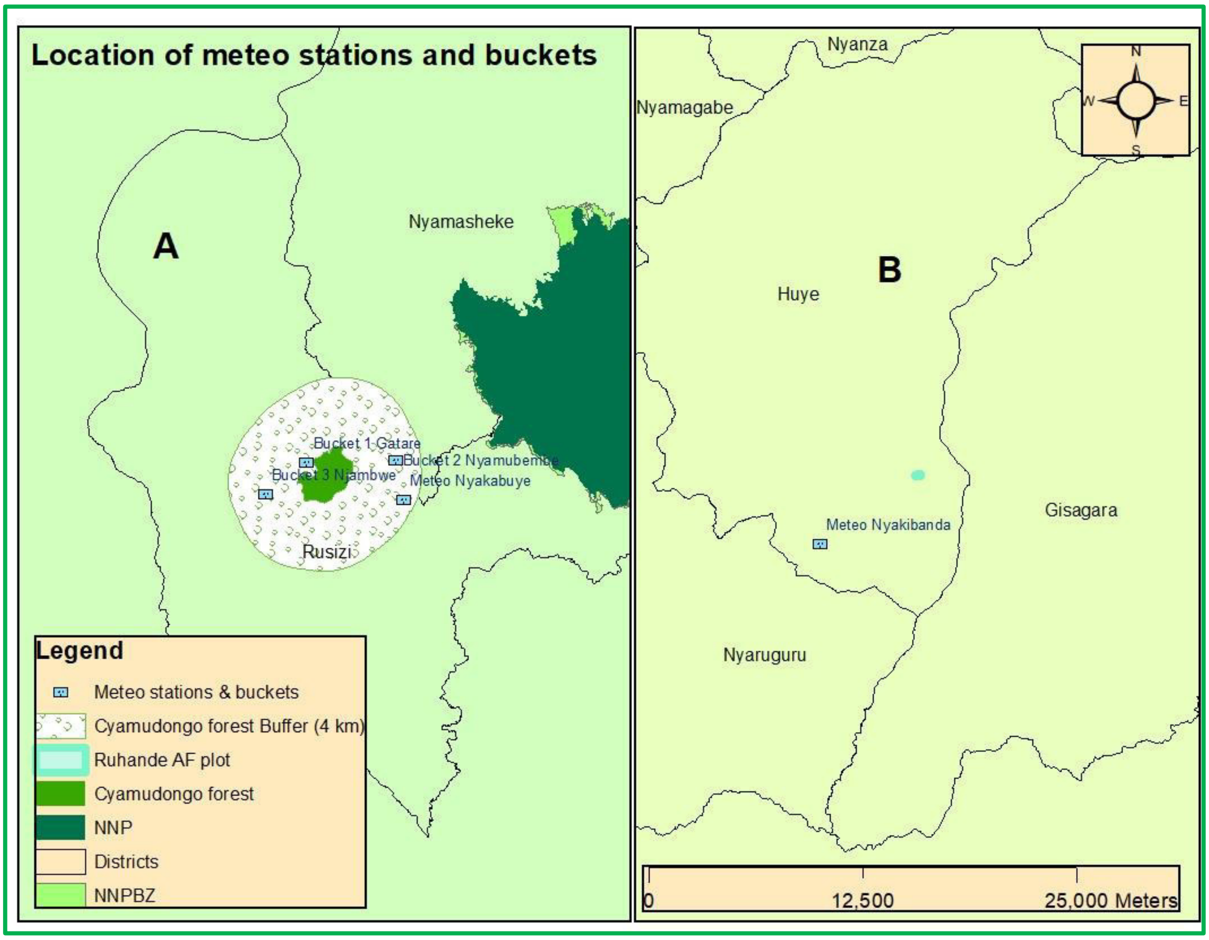


Figure 4. Location of Nyakabuye meteo station and field buckets (A) in Rusizi District and Nyakibanda meteo station (B) in Huye District

A: Nyakabuye meteo station is one of the local meteo stations of Rwanda located in the Nyakabuye sector of Rusizi district and field buckets were established at different altitude levels in the agricultural landscape around Cyamudongo isolated rain forest, in Nkungu and Nyakabuye sectors of Rusizi districts.

B: Nyakibanda meteo station is also one of the local meteo stations of Rwanda located in the Huye sector of Huye district for the AF plot located in the Arboretum of Ruhande.

Table 2: Location of meteo stations and used buckets for recording rainfall and temperature and estimated distances from study areas

#	Meteo station/bucket	Distance (station to forest main boundary in Km)	Geographic coordinates		
			Latitude	Longitude	Altitude
1	Nyakibanda meteo	6	9706200.6	799615.159	1614
2	Nyakabuye meteo	2.5	9716452.24	725343.765	1216
3	Bucket 2: Nyamubembe	2	9718721.86	724872.255	1394
4	Bucket 3: Njambwe	1	9716772.01	717278.161	1703
5	Bucket 1: Gatare	0.3	9718612	719682.008	1922

2.2.6 Tree variables measurement and wood biomass collection

For each tree species, the stem density, DBH, average height, WSD, total tree biomass, C stock, and Co_2e were estimated. In 2018 and 2019, the tree Diameter at Breast Height (DBH) and total height were measured to calculate the aboveground biomass for all trees ≥ 5 cm DBH. They were measured for seven AF species under study as described in 2.2.3. The three parameters were taken on 1,222 and 127 individual trees respectively from Cyamudongo and Ruhande, which make a total of 1,349 individual trees (Table 3). Vertex IV (Hypsometer) was used for tree heights and diameter tape for tree DBH.

The incremental borer with an inner diameter of the bit of 5.10 mm was used to collect wood biomass from the tree stems, electronic balance for fresh weights, and a ruler for sample heights. For each tree species, 3 samples were collected. For big size trees (> 10 cm DBH), the small pieces of wood were extracted from the tree to determine wood density in which samples were oven-dried at 105 ºC until the constant weight. For small tree species (<10 cm DBH), the Sector was used to cut off a small branch of regular shape which was weighted and measured its total length and the mean diameter for further indirect variables calculations. Thereafter, immediately the wood sample heights and diameters were bagged, labeled, and transported to the laboratory of the University of Koblenz-Landau for wood density and C determination. The study was conducted on 1349 individual trees which include 1222 in Cyamudongo and 127 in Ruhande study areas. The number of AF young tree species established by the Cyamudongo Project that has been the basis for this study was 676 while the existed AF tree species in the farms around Cyamudongo isolated rain forest was 546. These highlighted numbers of individual trees for various AF tree species varied with stand density (stems/ha). The differences also depended on which AF tree species have been appreciated by farmers because of the role they attributed to them considering the targets (eg. Firewood, stakes, fodder, erosion control, and timber among others). The more species appreciated by farmers, the more individual trees of that particular AF tree species are found on their lands.

Table 3. Recorded AF trees per species and location

Recorded AF trees per species and location

No	Tree species	Location					
		Ruhande	Cyamudongo (SS)		Cyamudongo (RS)		Total
			Established by project	Not established by the project	Established by project	Not established by the project	
1	*Cedrela serrata*	14	17	1	77	28	137
2	*Grevillea robusta*	53	246	171	183	77	730
3	*Maesopsis eminii*	7	66	33	13	3	122
4	*Polyscias fulva*	53	0	8	24	17	102
5	*Croton megalocarpus*	NA	0	2	4	0	6
6	*Markhamia lutea*	NA	6	155	30	47	238
7	*Podocarpus latifolius*	NA	10	0	0	4	14
	Grand Total	127	345	370	331	176	1349

2.2.7 Wood samples calculation

In this study, Huber's formula was used as the samples were short and the shape was different from the cone with little tapering. The green volume of each sample was calculated by the use of Huber's formula based on circumference measured in the middle of the log.

$$(V = \frac{\pi}{4} . D^2 . L) \quad \textit{(Equation 2)}$$

The term wood density has been used by Chave, (2006) to refer to "the ratio of the oven-dry mass of a wood sample divided by the mass of water displaced by its green volume". The volume without bark was taken to check data consistency during the calculation of tree wood density. It was calculated from measurements of oven-dry weight combined with measurement of green volume. The volume of a tree core was estimated by the dimensional method as described by Chave, (2006). Hence, the volume was calculated by assuming a regular cylindrical shape. This required measuring both the total length and its diameter, with a small caliper, avoiding the pressure of the caliper blades on wood. Oven dry weight was measured with a digital balance of precision of 0.01 g. The wood samples were put in the Oven-dried at 105^0c until constant weight and then milled for C and other nutrient contents (Ca, Mg, Na, and K) as described in 3.2.4.

2.2.8 Tree biomass calculation

Aboveground woody biomass was estimated from the volume of trees and the average oven-dry wood density of each species. Many models are used to calculate the aboveground tree biomass. In the literature, there are many examples of allometric equations to compute the AGB especially in the trees of a tropical location. The allometric equation suggested by Chave et al., (2014) was found to be the most improved model for various types of forest, AF, and in different environmental conditions and was used in this study, particularly for trees with DBH above 5 cm.

$$AGB = 0.0673 \times (\rho D^2 H)^{0,976} \quad \textit{(Equation 3)}$$

Where D (DBH) is in cm, H (tree height) is in m, and q (wood-specific density) is in g cm^{-3}. For young established AF tree species (trees < 5 cm diameter at 30 cm), we adopted an allometric equation developed by (Mokria et al., 2018).

$$Y = 0.2567(D * H)^{1.1213} \quad \textit{(Equation 4)}$$

Where Y, D_{30}, H, are aboveground biomass (kg/plant), diameter at stump height (30 cm), and total tree height (m), respectively.

The total biomass of individual trees was obtained by applying the biomass expansion factor (1.74) to the biomass of the stem as described by Brown and Lugo (1992). The following root-to-shoot ratio was indicated by the Krug et al. (2006) in IPPC (2006) and Sanquetta et al., (2011):

$$R = \frac{W\ root}{W\ aboveground} \quad \textit{Equation 5}$$

Where: R= the ratio between a tree and root while W root = Tree root dry weight (g).

Ponce-Hernandez R. *et al*., (2004) reported the factors to be used to estimate the BGB from AGB for different tree species categories. The factors of 0.25 and 0.3 are to be used for coniferous and broad-leaved species respectively.

The total annual biomass increment was determined by considering the data collected in 2018 and 2019 that was averaged. The obtained value was multiplied by the C concentration of the dry wood sample to obtain the C increment per hectare and year. The C stock has been computed following the procedure described by Pearson et al. (2014) where the dry wood C has to be multiplied by the wood biomass for getting the C per area unit and targeted species. The default of o.47 was used to estimate the CO_2e as reported by Krug et al., (2006) for IPCC (2006).

In this regard, the biomass value was converted into carbon concentration and carbon dioxide equivalent concerning the above procedure. The biomass stock (kg/m^2) of each sampling plot was obtained by summing up all the individual biomass weights (in kilograms) of the sampling plot area. The AGB value was converted to tones per hectare by considering the total number of plots.

Bismark et al., (2008) highlighted the method for estimating the C sequestration which takes into account the ratio between the molecular weight of C dioxide and the atomic weight of C (44/12) and followed in this study.

$$Sequestration\ of\ CO2\ = \left(\frac{Mr\ CO2}{Ar\ C}\right) \qquad Equation\ 6$$

$$Sequestration\ of\ CO2 = 3.67\ X\ C\ content \qquad Equation\ 7$$

Where:

Mr = molecule relative

Ar = atom relative

The laboratory analyses were done in the Soil Science Laboratories of the University of Koblenz-Landau/Germany. The analyzed chemical elements, materials, methods, and procedures are discussed in Table 4 in chap 3.3.4.

2.2.9 Statistical analysis

The R-software was used for the different statistical tests. A *Kruskal Wallis test (the* non-parametric equivalent of an *ANOVA)* was used to test AGB, C stock, and other nutrients for various tree species in time for different study areas. As the automatic contrast procedure, which exists for ANOVA, is not developed for *Kruskal Wallis tests*, a pairwise comparison between various variables of different tree species using a separate *Mann-Whitney Wilcoxon test* was used. The relationship among the variables of tree species was determined using the *Spearman correlation test.* The change with time about tree variables was detected by performing two analyses as the data were collected two times.

2.3 Results

2.3.1 Precipitation and temperature of the study areas

The monthly precipitations were summed up to make the annual precipitations for different weather stations located in different agro-ecological zones of Cyamudongo (Nyakabuye weather station) and Ruhande (Nyakibanda). For the Cyamudongo study area, the daily precipitations recorded from Nyakabuye local station were added to the daily collected ones through various buckets established in different locations of the study area (Table 3) which were averaged to increase the quality of the precipitation estimate. The annual precipitations were 1605.8 mm and 1436 mm respectively for 2018 and 2019 in Nyakibanda while they were 1835 mm and 1638 mm in Nyakabuye respectively for 2018 and 2019.

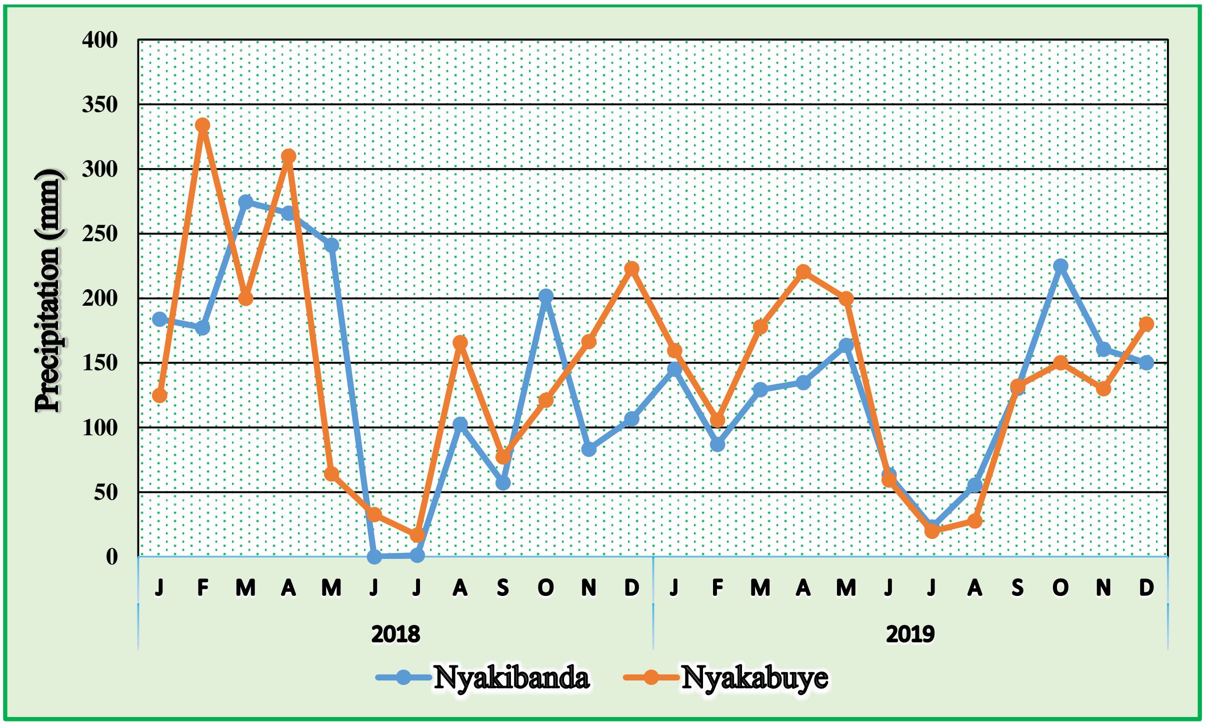


Figure 5. Monthly precipitation in Nyakibanda and Nyakabuye weather stations

Figure 6 shows, the mean temperature (T MEAN), minimum temperature (T MIN) and maximum temperature (T MAX) recorded in the various national local weather stations of Rusizi and Huye Districts in 2018 and 2019. For the Cyamudongo study area, the Kamembe aero station was used whereas the Nyakibanda weather station was used for the Ruhande study area. The mean temperature of 2019 was found to be higher than the mean temperature of 2018 for both stations and the records showed that the high-level temperature was found at Kamembe Aero station. The mean temperature was 20.8 ℃ and 20.9 ℃ in Kamembe Aero station in 2018 and 2019 respectively whereas the mean temperature was 19.8 ℃ and 20 ℃ in the Nyakibanda weather station in 2019 and 2019 respectively. The mean minimum annual temperature was 16.20℃ and 14.9 ℃ in 2018 for Kamembe Aero station and Nyakibanda weather station respectively. In 2019, the mean annual minimum temperature was 16.29℃ and 14.84℃ for Kamembe Aero station and Nyakibanda weather station respectively. Besides, the annual maximum mean temperature in 2018 was 25.50℃ and 24.82℃ for Kamembe Aero station and Nyakibanda weather station respectively whereas it was 25.52℃ and 25.26℃ for Kamembe Aero station and Nyakibanda weather station respectively. However, the month with the lowest mean minimum temperature was July with 15.04℃ and 13.4℃ for Kamembe aero and Nyakibanda weather stations while the month with the highest mean minimum temperature was May with 16.66℃ for Kamembe aero weather station and 15.68℃ for Nyakibanda weather station. Besides, the month with the lowest maximum mean temperature was May for all stations with 24.8ºC and 24.30ºC for Kamembe aero and Nyakibanda weather stations while the month with the highest maximum mean temperature was August with 26.42ºC for Kamembe aero and September with 26.5ºC and Nyakibanda weather stations.

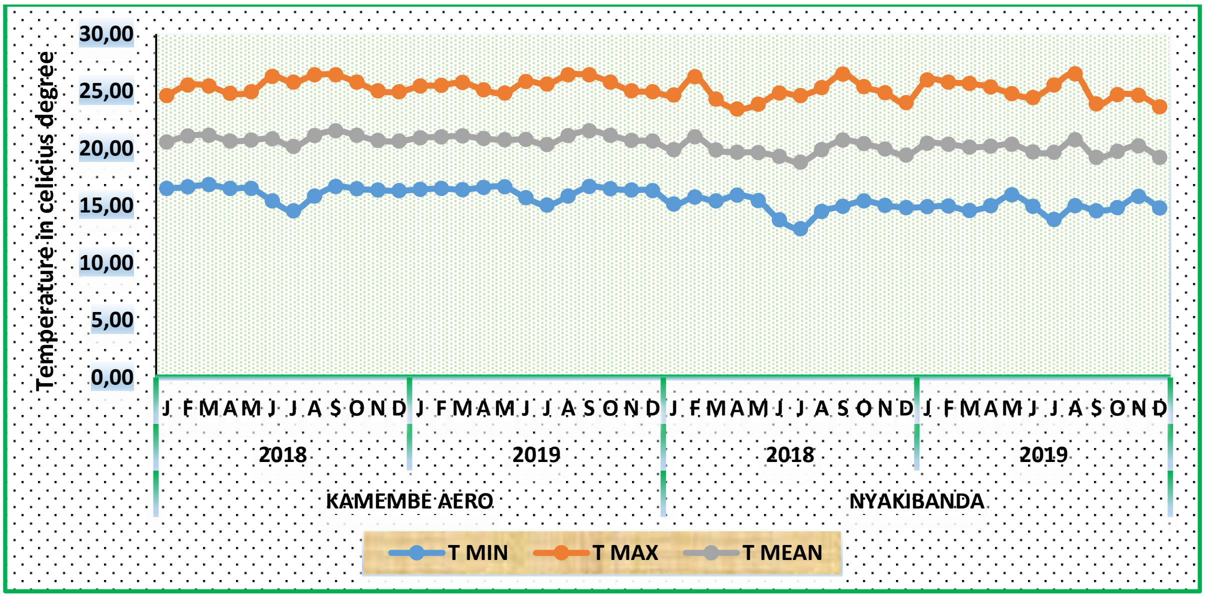


Figure 6. Annual and monthly maximum and minimum temperature per study area

2.3.2 Stand variables, wood biomass, and C content of different AF tree species

2.3.2.1 Stand variables, wood biomass, and C content of different AF tree species around Cyamudongo isolated forest

The AGB, BGB, ABGB, C stock, and CO_2e were estimated and compared between the existing AF species before the Cyamudongo Project and the species established by the project (Table 4). In 2 years of study (2018 and 2019), the existing AF species provided the highest values in terms of the aforementioned variables. Besides, the wood biomass accumulated in various AF species, C stock, and CO_2e were statistically different per category of recorded species ($p<0.05$). There was the marginal (close to being statistically significant) significance by comparing the two categories in time ($p= 0.054$). Therefore, the high amount of accumulated dry biomass and C for existing AF species is associated with the tree age, size (H and DBH), and species composition. By comparing the wood biomass for two years, the results showed the increase in terms of all estimated parameters, and the obtained values correspond to the current annual increment (CAI). The existing AF species were found to have higher CAI compared to the young AF species established by the Project. The average value of ABGB was

52.6 t ha^{-1} for existed AF tree species while it was 36.7 t ha^{-1} for young species. The CAI in terms of C stock was 24.4 t ha^{-1} and 16.6 t ha^{-1} for mature and young AF tree species respectively.

Table 4. Estimated biomass and C stock per species category of AF live trees in sustainable AF of communities around Cyamudongo isolated forest.

Category of recorded species	Year	AGB [t/ha]	BGB [t/ha]	ABGB [t/ha]	C stock [t/ha]	CO_2e [t/ha]
Existed AF species before project	2018	642.6	192.8	835.4	381.6	179.4
Existed AF species before project	2019	683.1	204.9	888.0	406.0	190.8
Established AF species by project	2018	16.5	4.9	21.4	9.6	4.5
Established AF species by project	2019	44.7	13.4	58.1	26.2	12.3
Total		1387	416	1803	823	387

Figure 7 compares the wood biomass, C stock, and CO_2e of AF tree species established by the Cyamudongo Project and existing AF tree species that were in the agriculture landscape before the Cyamudongo Project recorded in two different times of 2018 and 2019. The results showed that the existing AF tree species contribute more than the AF tree species established by the Cyamudongo Project in terms of all the above-mentioned variables and the change was pronounced as far as time is concerned. The change was found to depend on the tree age or year of establishment. Therefore, the newly established AF tree species showed low values compared to the mature AF tree species that existed before the implementation of the Cyamudongo Project.

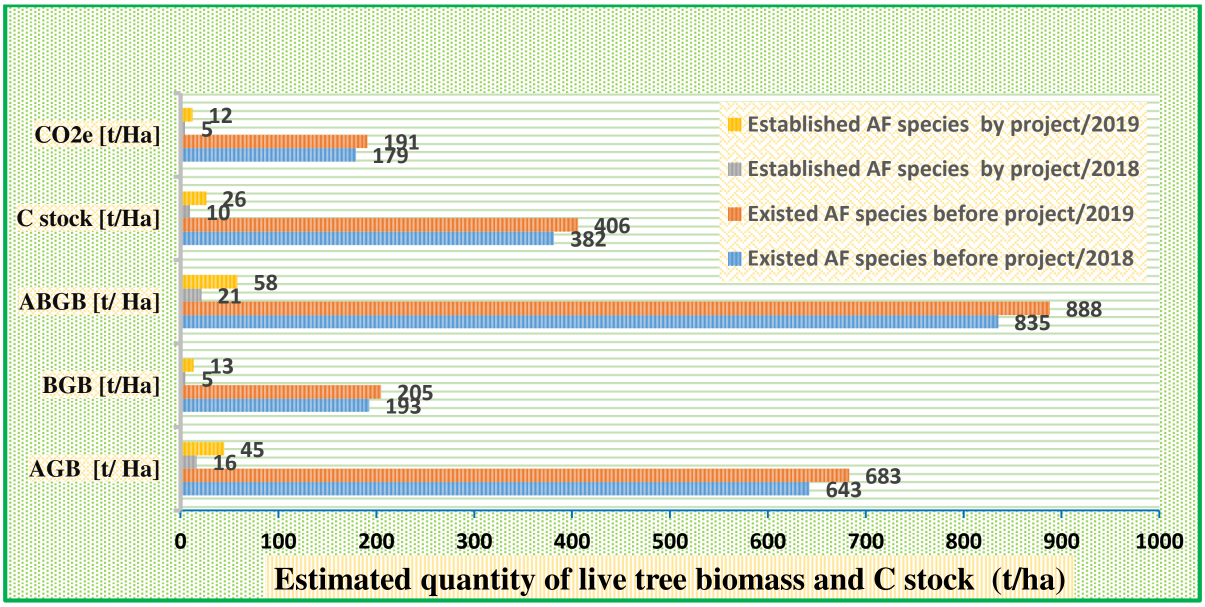


Figure 7. Comparison of the estimated quantity of biomass and C stock (t Ha-1) of AF live trees categories in sustainable AF of communities around Cyamudongo isolated forest.

Table 5 summarizes the averaged AGB, BGB, ABGB, C stock, and CO_2e per hector and AF tree species category of seven AF tree species scattered in the CL of the area around Cyamudongo isolated forest. By comparing the amount of dry biomass and C estimated for various AF species, the results show a statistically significant difference ($p< 0.05$). The tree biomass and C stock varied with species, species density, growth speed, and age. This result is following Agevi et al., (2017) who found that the tree biomass held in trees varies from one region to the other and is dependent on species density, age, climatic factors, and soil factors. The AF species established by the Project were chronologically ranked in terms of C stock as follows: *Grevillea robusta* > *Cedrela cerrata* > *Polyscias fulva* > *Markhamia lutea* > *Maesopsis eminii* > *Croton megalocarpus* > *Podocarpus latifolius*. Similarly, the existed AF species were also ranked as follows: *Grevillea robusta* > *Markhamia lutea* > *Maesopsis eminii* > *Cedrela serrata* > *Polyscias fulva* > *Croton megalocarpus*. The obtained C stock values were averaged for all AF species to further rank them as a general estimate of the ABGB and C stock in the study area. Hence, the *Grevillea robusta* (257 t ha^{-1}) was followed by *Markhamia lutea* (94.73 t ha^{-1}), *Maesopsis eminii* (26.8 t ha^{-1}), *Cedrela serrata* (22.95 t ha^{-1}), *Polyscias fulva* (9.64 t ha^{-1}), *Croton megalocarpus* (0.195 t ha^{1-}) and *Podocarpus latifolius* (0.19 t ha^{-1}). The density of individual species per ha was 210 trees and the density of every AF species was also determined. The *Grevillea robusta* was found to have more density compared to other species with 119 ha^{-1}, followed by *Markhamia lutea* 38 ha^{-1}, *Cedrela serrata* 22 ha^{-1}, *Maesopsis eminii* 19 ha^{-1}, *Polyscias fulva* 8 ha^{-1}, *Podocarpus latifolius* 3 ha^{-1} and *Croton megalocarpus* 1 ha^{-1}. However, *Grevillea robusta* contributed to the highest estimates for both AF species that existed before the Cyamudongo Project and were established by the project. In addition to that, it was found to grow faster compared to the other species under this study and the farmers willingly prefer to grow it with a high density among others because it provides them the stakes for climbing beans, firewood, constructing materials, and timbers.

The total amount of AGB, BGB, ABGB and C stock were 1387 t ha^{-1}, 416 t ha^{-1}, 1803 t ha^{-1}, and 823 t ha^{-1} respectively.

Table 5. Estimated quantity of live tree biomass and C stock per AF tree species and species category

Category of recorded species	Species	AGB [t/ ha]	BGB[t / ha]	ABGB [t/ha]	C stock [t/ha]	CO_2e [t/ha]
Established AF species by project	*Cedrela serrata*	9.51	2.85	12.36	5.53	2.6
	Croton megalocarpus	0.34	0.1	0.44	0.2	0.09
	Grevillea robusta	38.29	11.49	49.78	22.62	10.63
	Maesopsis eminii	3.81	1.14	4.96	2.2	1.03
	Markhamia lutea	4.37	1.31	5.69	2.42	1.14
	Podocarpus latifolius	0.32	0.09	0.41	0.19	0.09
	Polyscias fulva	4.57	1.37	5.94	2.67	1.26
Sub-total		61.21	18.35	79.58	35.83	16.84
Existed AF species before the project	*Cedrela serrata*	68.46	20.54	89	40.38	18.98
	Croton megalocarpus	0.33	0.1	0.42	0.19	0.09

	Grevillea robusta	819.96	245.99	1065.95	491.49	231
	Maesopsis eminii	86.92	26.08	112.99	51.4	24.16
	Markhamia lutea	321.87	96.56	418.43	187.04	87.91
	Polyscias fulva	28.14	8.44	36.58	16.62	7.81
Sub-total		1325.68	397.71	1723.37	787.12	369.95
Total		1387	416	1803	823	387

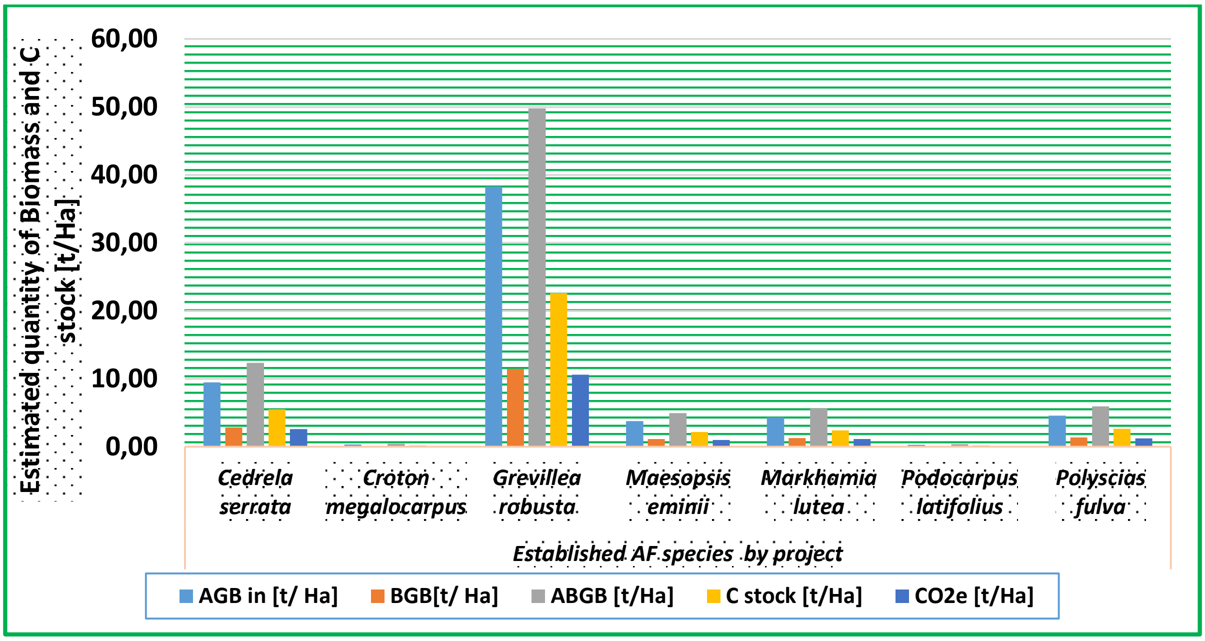


Figure 8. Estimated quantity of ABGB, C stock, and CO2e of AF trees established by Cyamudongo Project

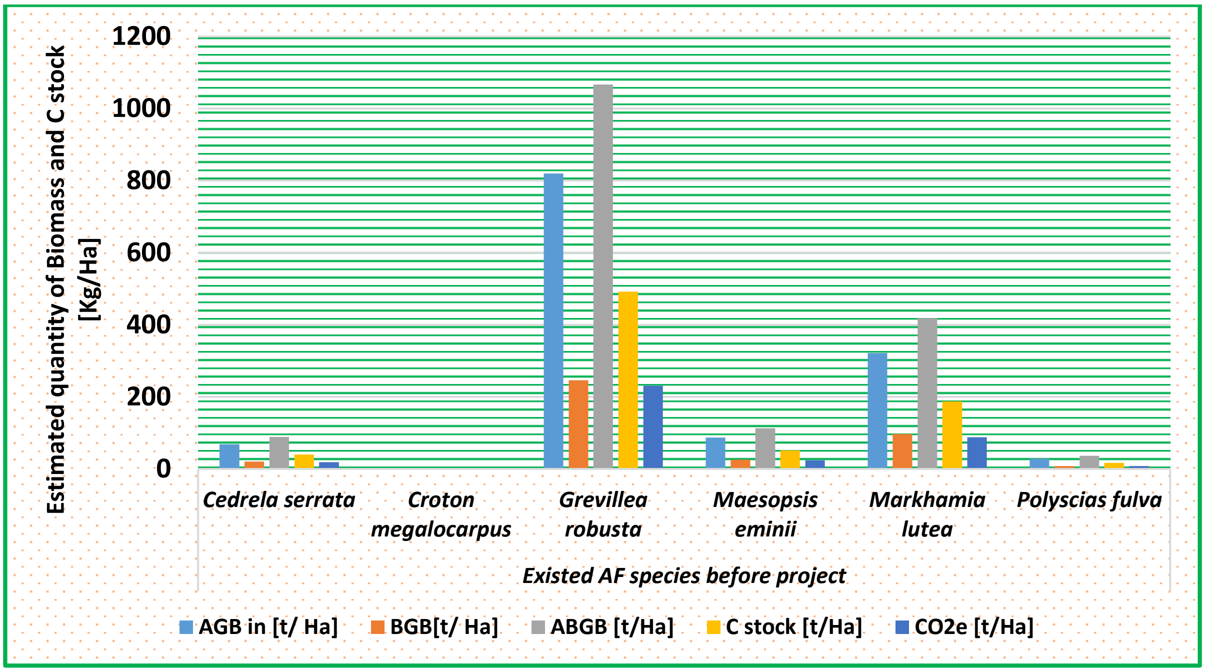


Figure 9. Estimated quantity of ABGB, C stock, and CO2e of existed AF trees before Cyamudongo Project

The amount of C sequestration estimated in t ha^{-1} $year^{-1}$ of established species varies with species, age, growth rate (both in height and diameter) and planting density as follow: *Grevillea* *robusta > Cedrela serrata > Polyscias fulva > Maesopsis eminii > Markhamia lutea > Croton megalocarpus > Podocarpus latifolius* with 8.67, 1.92, 0.85, 0.77, 0.76, 0.07 and 0.05 respectively. The total C sequestration rate of AF tree species established by the project is 13.11 t C ha $^{-1}$ yr^{-1} corresponding to 47.94 t CO_2 ha $^{-1}$ yr^{-1} centered on the young trees of 2 years old.

Table 6. C sequestration rate of AF species established by Cyamudongo Project

#	Species name	C stock[kg/ha]	C sequestration rate [t/ha/year]	No of individual trees	%
1	*Grevillea robusta*	17345.46	8.67	429	63.4
2	*Cedrela serrata*	3838.44	1.92	94	13.9
3	*Polyscias fulva*	1709.85	0.85	24	3.5
4	*Maesopsis eminii*	1548.06	0.77	79	11.6
5	*Markhamia lutea*	1520.15	0.76	36	5.3
6	*Croton megalocarpus*	139.03	0.07	4	0.5
7	*Podocarpus latifolius*	109.66	0.05	10	1.4
Total		26210.65	13.11	676	100

The tests showed differences in terms of WSD for various tree species. The WSD varied with tree species and age. The mature AF tree species were found to have more density compared to the young tree species of 2 years old. For mature trees, *Grevillea robusta* was found to have the highest density 494 kg m^{3-}, followed by *Markhamia lutea* 475 kg m^{-3}, *Cedrela serrata* 428 kg m^{3-}, *Maesopsis eminii* 385 kg m^{3-} and *Polyscias fulva* 262 kg m^{3-}. For the young AF tree species, *Croton megalocarpus* was found to have the highest WDS value (567 kg m^{3-}), followed by *Podocarpus latifolius* (487 kg m^{3-}), *Grevillea robusta* (442 kg m^{3-}), *Markhamia lutea* (431 kg m^{3-}), *Cedrela serrata* (412 kg m^{3-}), *Maesopsis eminii* (347 kg m^{3-}) and *Polyscias fulva* (211 kg m^{3-}).

Table 7. Comparison of WSD of young and old AF species recorded in Cyamudongo study area

Area	Species name	WSD [kg/m^3] (≥5 years old)	WSD[kg/m^3] for young species (2 years old)
Cyamudongo	*Cedrela serrata*	428	412
	Croton megalocarpus	NA	567
	Grevillea robusta	494	442
	Maesopsis eminii	385	347
	Markhamia lutea	475	431
	Podocarpus latifolius	NA	487
	Polyscias fulva	262	211

2.3.2.2 Stand variables, biomass, and C stock for different AF tree species of Ruhande

The mixture of AF trees was established on contour lines with a large spacing which resulted in a stand density of 426 stems ha^{-1}. *Polyscias fulva* dominate the other species in the stand with 183 stems ha^{-1}, followed by *Grevillea robusta* with 170 stems ha^{-1}, then *Cedrela serrata* with 53 stems ha$^{-1,}$ and finally, *Maesopsis eminii* with 20 stems ha^{-1}. Further, the analysis showed that *Grevillea robusta* has the highest SWD with 555 kg m^3 followed by *Cedrela serrata* with 427 kg m^3, *Maesopsis eminii* with 419 kg m^{3,} and *Polyscias fulva* with 342 kg m^3. This result showed a significant difference among different AF tree species (df = 3, p-value < 2.2e-16). Hereafter, there was a need to check between which AF tree species the difference exactly is significant. The analysis did not confirm any significant differences between *Cedrela serrata* and *Maesopsis eminii*, as far as WSD is concerned. The SWD was affected by tree species, size, and age. The obtained values are barely distinguishable from Kuyah et al., (2012) who found the high value (610 kg m^3) on large trees and low values (390 kg m^3) on small trees.

The C content was determined and on average, we found values for, *Grevillea robusta*, *Cedrela serrata, Maesopsis eminii,* and *Polyscias fulva*, which was 47.4%, 46.4%, 45.8%, and 45.8% respectively.

Further analysis showed that the C sequestration rate of the Ruhande AF plot is 6.85 t ha^{-1} yr^{-1} corresponding to 25.07 t CO_2 ha^{-1} yr^{-1}. The contribution of each AF species depends on its growth stage (both H and DBH), stand age, C content, and WSD. These species were ranked chronologically based on their contribution to C sequestration. *Grevillea robusta > Polyscias fulva > Cedrela serrata > Maesopsis eminii* with 5.18 t ha^{-1} yr^{-1}, 0.84 t ha^{-1} yr^{-1}, 0.81 t ha^{-1} yr^{1} and 0.01 t ha^{-1} yr^{-1} chronologically.

Table 8 shows the amount of living biomass and C stock of four different AF tree species of Ruhande AF plot located in Ruhande Arboretum. The *Grevillea robusta* contributes more than other species in terms of wood biomass (AGB& BGB), C stock, C sequestration, and CO_2e. The second AF tree species that were found to contribute more to the above-mentioned variables are *Polyscias fulva* followed by *Cedrela serrata* and the least was *Maesopsis eminii*. The variability in studied parameters was mainly due to the stand density (number of stems ha^{1}) and AF tree species.

Table 8. The estimated amount of living biomass and C stock of four AF species of Ruhande AF plot

#	Species name	Density (Stems/ha)	AGB (t/ha)	BGB (t/ha)	ABGB (t/ha)	C stock (t/ha)	C sequestration rate (t/ha/year)	CO_2e (t/ha)
1	*Cedrela serrata*	53	45.79	13.74	59.53	27.66	0.81	13
2	*Grevillea robusta*	170	284.99	85.5	370.49	176.13	5.18	82.78
3	*Maesopsis eminii*	20	32.99	9.9	42.89	0.45	0.01	0.21
4	*Polyscias fulva*	183	48.17	14.45	62.62	28.7	0.84	13.49
	Total	426	411.94	123.58	535.52	232.94	6.85	109.48

Figure 10 compares the total amount of wood biomass, C stock, and CO_2e of AF tree species of two years records of 2018 and 2019. The tests revealed that the computed variables in 2019 were higher than the recorded variables in 2018 and the differences were pronounced for all AF tree species under study.

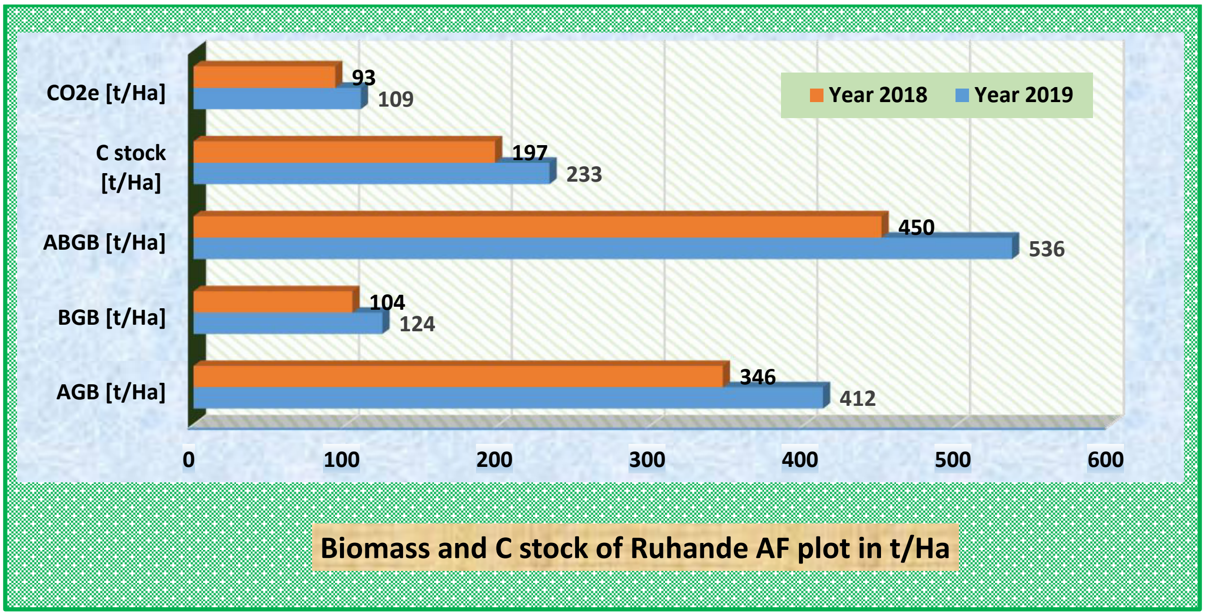


Figure 10. The estimated total amount of living biomass of AF trees of Ruhande AF plot in 2018 and 2019

WSD [kg/m^3] for old species 34 years old in Ruhande was studied and the highest value was found on *Grevillea robusta* (555 kg m^{3-}) followed by *Cedrela serrata* (427 kg m^{3-}). For the remaining variables, refer to Table 9. Generally, the comparison of WSD for mature AF trees for two regions indicates that the WSD was higher in Ruhande compared to Cyamudongo study areas.

Table 9. Wood density (WSD) of recorded AF species in Ruhande

Area	Species name	Year of establishment	WSD (Kg m^{3-})
Ruhande	*Cedrella serrata*	1986	427
	Grevillea robusta	1986	555
	Maesopsis eminii	1986	419
	Polyscias fulva	1986	342

2.3.2.3 Comparison of various tree variables, biomass, and C stock between different AF tree species of Cyamudongo and Ruhande AF plot study areas

It was found that the newly established AF species (2 years old) by the Cyamudongo Project sequester more C than the mature AF species (34 years) of Ruhande AF lot. Nair et al., (2009) affirmed that the extent of C captured by the AF system depends on various factors including edaphic, climatic, and the applied management practices.

The estimated quantity of sequestrated C for 2 years and 34 years AF species were 13.11 t C ha $^{-1}$ yr^{-1} which is equivalent to 48 t CO_2 ha $^{-1}$ yr^{-1} and 6.85 t ha^{-1} yr^{-1} which is equivalent to 25.1 t CO_2 ha $^{-1}$ yr^{-1} in Cyamudongo and Ruhande respectively. The amount of C fixed by AF tree species significantly varied among them and varied with the C concentration of each AF tree species, tree age, size, and the place it occupies to the overall stand density.

In Ruhande, the reported amount of AGB, BGB, ABGB, and C stock was highly affected by the number of stems per ha, WSD, and C contents of each species. The *Grevillea robusta* was found to have more biomass and store more C compared to the other AF tree species. The estimated quantity of C stored by the Ruhande AF plot is 232.94 t ha^{-1} and *Grevillea robusta* was found to contribute more than other AF tree species with 176.13 t ha^{-1} followed by *Polyscias fulva* (28.7 t ha^{-1}), *Cedrela serrata* (27.66 t ha^{-1}), and *Maesopsis eminii* (0.45 t ha$^{-1)}$.

In Cyamudongo, the overall C stored by the AF systems was 823 t ha^{-1} by both young tree species established by the Cyamudongo Project (35.84 t ha^{-1}) and C stored by existed AF species before the existence of the Project (787.12 t ha^{-1}). The amount of C stored by the AF tree species also varied with the time of measurement and category of AF tree species. The C estimated in 2019 was higher than that of 2018 and it was again higher for mature AF tree species compared to the young AF tree species.

The C stored by young AF tree species was 26.2 t ha^{-1} and 9.6 t ha^{-1} in 2019 and 2019 respectively while it was 406 t ha^{-1} and 381.6 t ha^{-1} in 2019 and 2018 respectively for the existed AF tree species before the Cyamudongo Project intervention. In the Cyamudongo study area, the *Grevillea robusta* was found to contribute more to the overall quantity of C stored in the region for both young AF species and mature ones with 22.26 t ha^{-1} and 491.49 t ha^{-1} respectively. The *Grevillea robusta* was found to store more C in all study areas and this showed its importance in the areas of Rwanda as a strategy to mitigate against climate change-related issues through C sequestration in addition to its contribution to the improvement of farmers wellbeing through the provision of multi-products such as fuelwood, stakes, timber and erosion control.

In Cyamudongo, *Markhamia lutea* was found to be the second AF tree species, which contribute more to the C storage with 187.4 t ha^{-1} and were recorded and counted among existed AF tree species before the project and this showed how the importance farmers attributed to it by integrating it in their farms. This AF tree species was mainly found to be planted in the demarcations and boundaries of the farms and nearest to the homesteads and sometimes scattered in the cropland (CL), for soil improvement and was used in the fabrication of wooden furniture such as handles, poles, spoons, and cabinets.

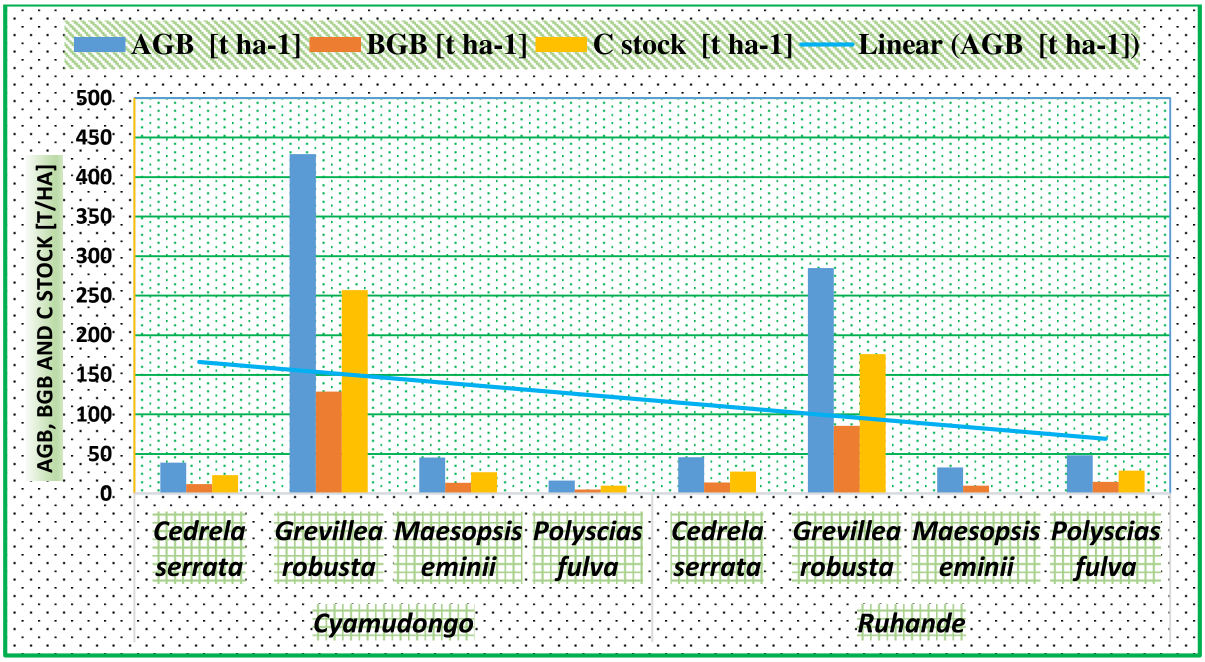


Figure 11. Comparison of AGB, BGB, and C stock in different study areas

The results highlighted differences in terms of WSD for various AF tree species from different study areas. Surprisingly, one of the AF tree species of the Cyamudongo study area was qualified to have more WSD value than other mature tree species. A 2-year-old *Croton megalocarpus* (567 kg m^3) was found to have a high value of WSD followed by a mature species of *Grevillea robusta* (494 kg m^3) and mature *Cedrela serrata* (428 kg m^3). In Ruhande, *Grevillea robusta* (555 kg m^3) was found to have more WSD value followed by *Cedrella serrata*, *Maesopsis eminii,* and *Polyscias fulva*. In all study areas, *Polyscias fulva* was qualified to have a small WSD among all seven AF tree species targeted by this study (Table 1).

Concerning the WSD tested for various AF species, it is clear to conclude that it varies with tree species, age, and environmental conditions.

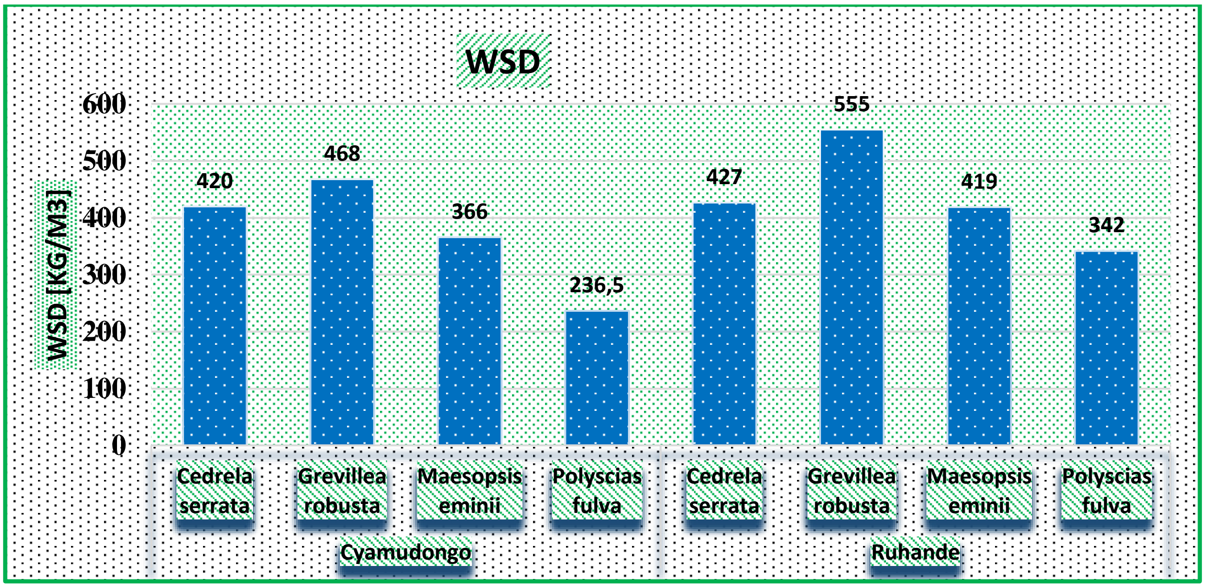


Figure 12. Comparison of WSD of AF tree species of Cyamudongo and Ruhande study areas

2.3.3 Relationship between various AF tree variables

The relationship between various parameters for different AF tree species of sustainable AF systems on the surroundings of Cyamudongo isolated rain forest and AF plot located in Arboretum of Ruhande was determined. The regressed variables were ABGB, tree diameters (DBH for large trees (>5 cm of diameter) and D30 for young tree species), G, and H.

The observed correlations, linear regression equations, p-values, and correlation coefficients or coefficients of determination (R) for each AF tree species are presented in Figures 13, 14,15,16,17,18,19,20, and 21. The obtained output for each functional dependency between various tree parameters or variables for each AF tree species was interpreted following correlation coefficients described by Schober et al., (2018), to know how much is correlation intensity.

2.3.3.1 Relationship between various AF tree variables for 7 species recorded in sustainable AF practices around Cyamudongo isolated forest

- **Existed AF tree species before the project**

Figure 13 shows the correlation between ABGB, DBH, DBH, G, and total H for existed species before the project. Firstly, the correlation was very strong for *Polyscias fulva* for all variables and species while it was strong between DBH and H for other remaining species. For DBH and ABGB, it was very strong except for *Grevillea robusta*, which shows a strong correlation. It was further strong between H and ABGB for all species except for *Polyscias fulva*, which was very strong as mentioned initially. Finally, the correlation between G and ABGB was similarly very strong for all species.

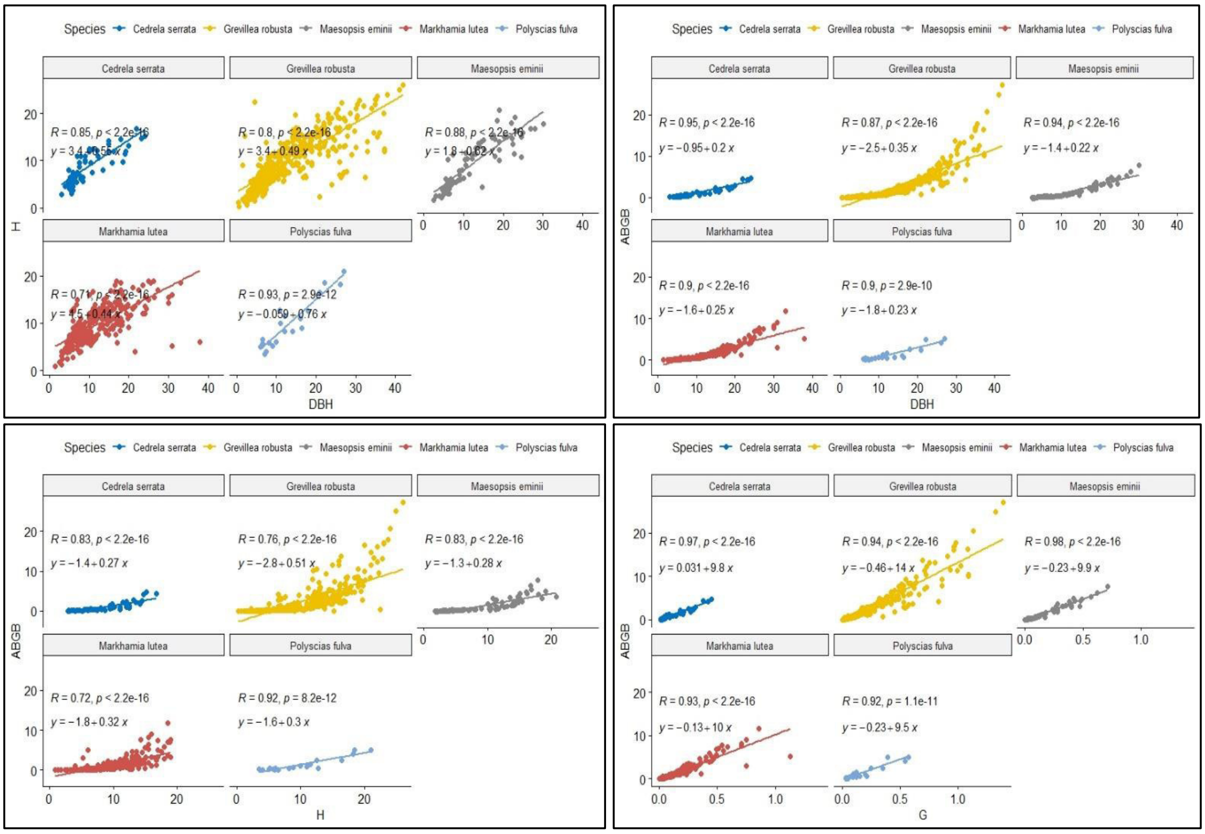


Figure 13. Regression analysis between ABGB, DBH, DBH, G, and total H for existed species before the project

- **AF tree species established by the project**

The outputs of regression analysis between ABGB, DBH, DBH, D_{30}, and total H for seven AF established by the project are presented in Figures 14, 15, 16 &17. Our results show that the tree height was strongly correlated with D_{30} for *Cedrela serrata, Grevillea robusta, Markhamia lutea, Podocarpus latifolius, and Polyscias fulva.* Besides, it was moderately correlated with D_{30} for *Maesopsis eminii* while the correlation was negligible for *Croton megalocarpus.* The D_{30} was strongly correlated with ABGB for all species except for *Croton megalocarpus* where it was moderately correlated.

Further, the analysis showed that the tree height was very strongly correlated with ABGB for *Cedrela serrata, Markhamia lutea, Podocarpus latifolius, and Polyscias fulva*, strongly correlated for *Croton megalocarpus* and *Maesopsis eminii* while it the correlation was moderate for *Grevillea robusta.* The correlation between G and ABGB was very strongly correlated for *Maesopsis eminii,* weakly correlated for *Croton megalocarpus* while the correlation was strong for all other remaining species.

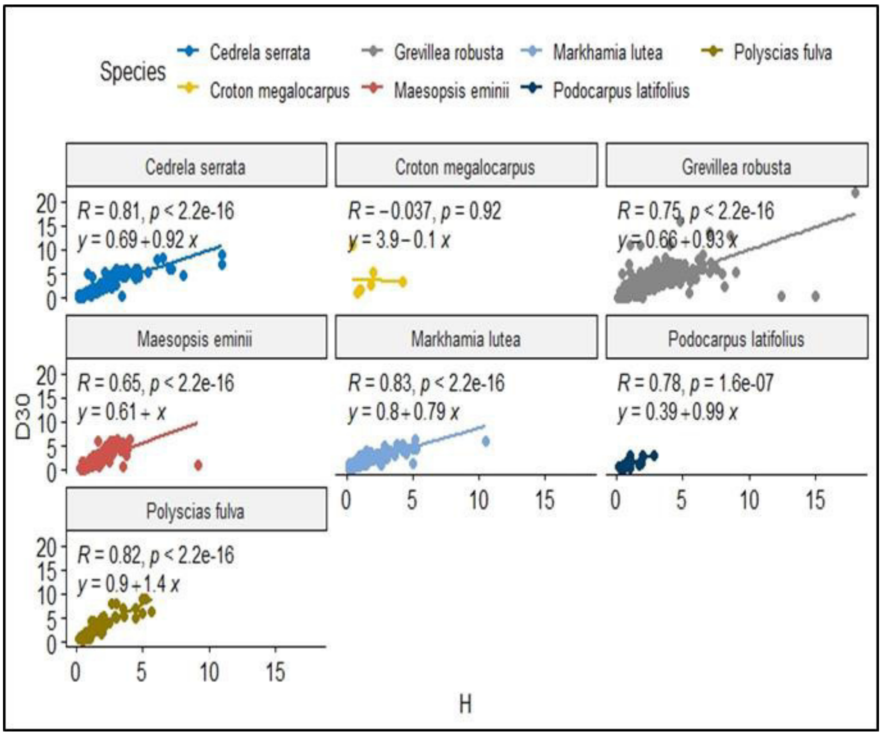


Figure 14. Regression analysis between H and D_{30} for seven AF species established by the project

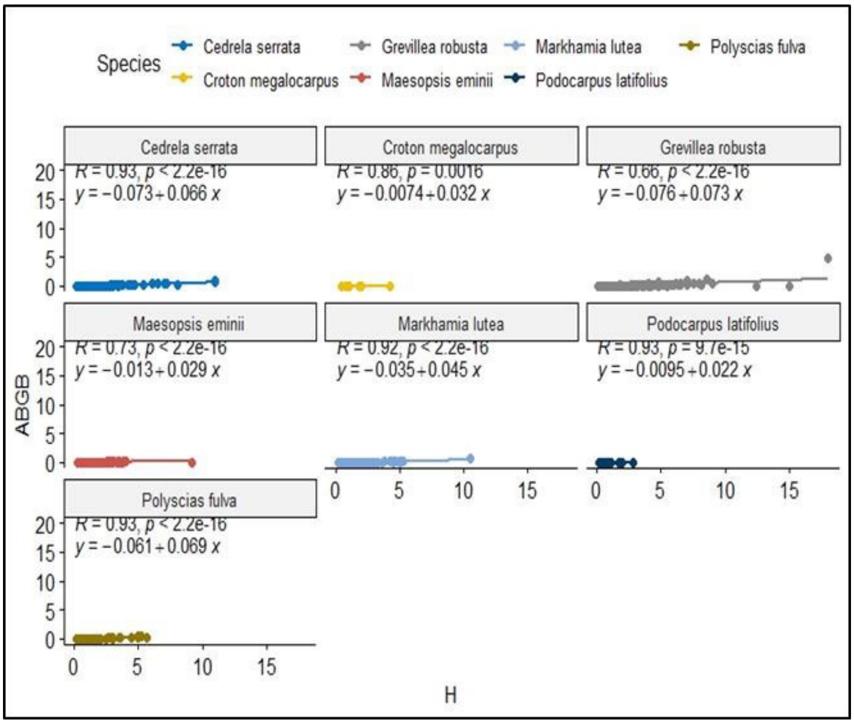


Figure 15. Regression analysis between D_{30} and ABGB for seven AF species established by the project

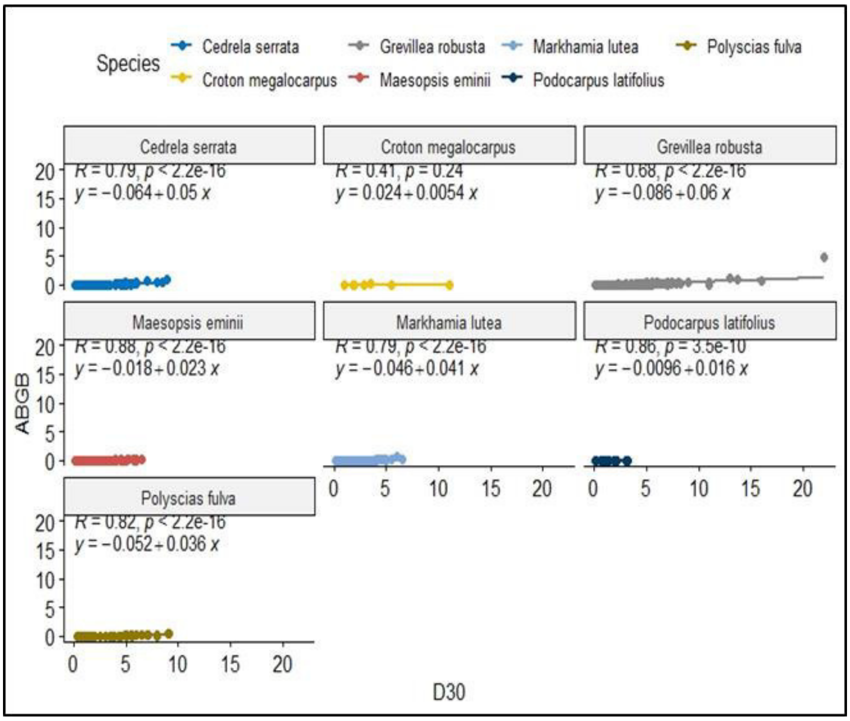


Figure 16. Regression analysis between H and ABGB for seven AF species established by the project

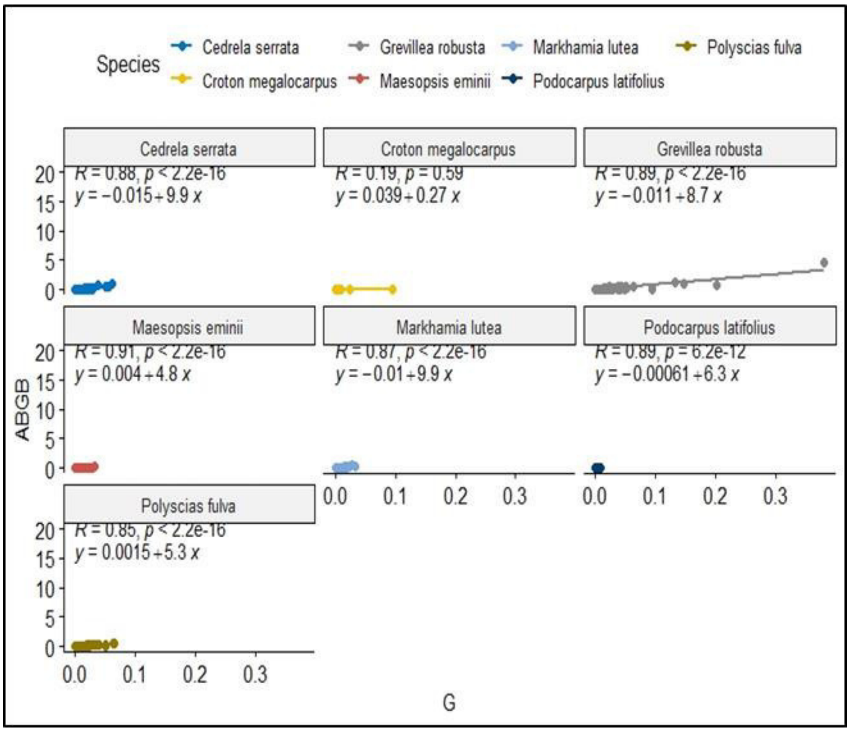


Figure 17. Regression analysis between G and ABGB for seven species established by the project.

2.3.3.2 Regression analysis between various AF tree variables for 4 species recorded in Ruhande plot

Different various variables (H, DBH, ABGB, and G) of AF tree species including *Cedrela serrata, Grevillea robusta,* and *Maesopsis eminii* were regressed to establish their relationships. The correlation between tree DBH and H for C*edrela serrata* and *Maesopsis eminii* was very strong while it was moderate for both *Grevillea robusta* and *Polyscias fulva*. The correlation between DBH and ABGB was very strong for all AF trees. For H and ABGB, the correlation was very strong for *Maesopsis eminii* while it was strong for *Cedrela serrata* and *Grevillea robusta*. On the other hand, the correlation was moderate for *Polyscias fulva*. Finally, the G and ABGB were very strongly correlated for all species.

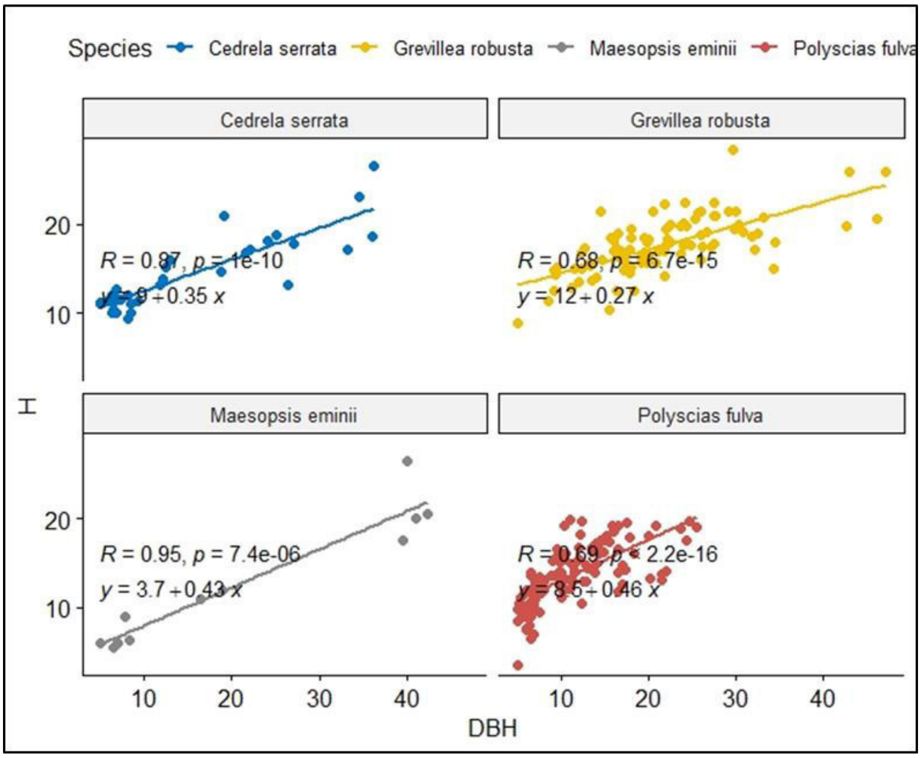


Figure 18. Regression analysis between DBH and H for four AF species of Ruhande AF plot

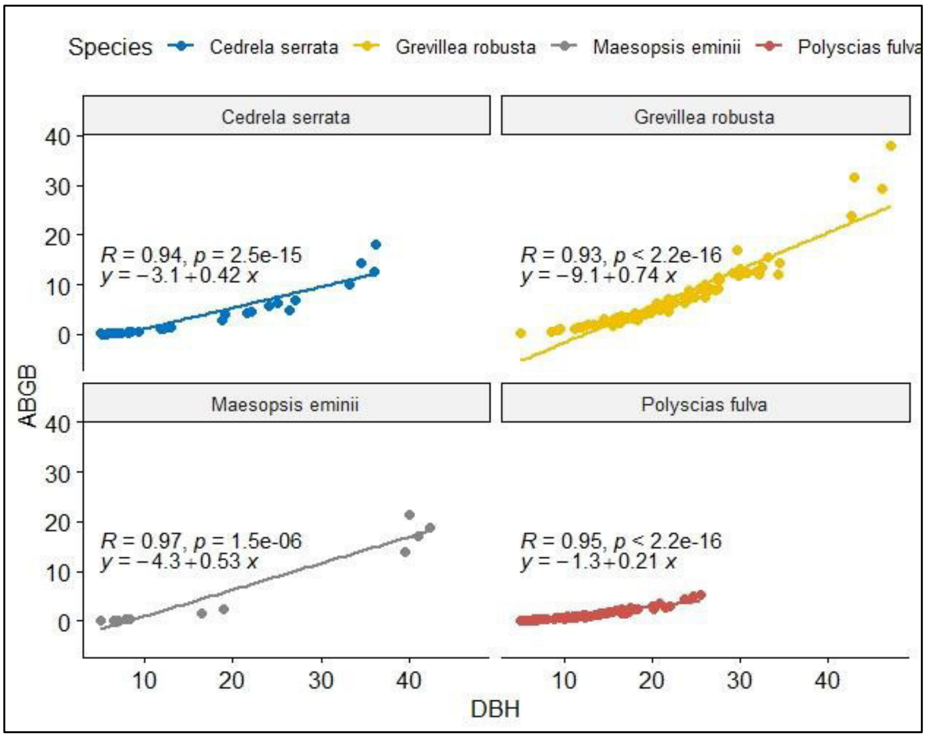


Figure 19. Regression analysis between DBH and ABGB for four AF species of Ruhande AF plot

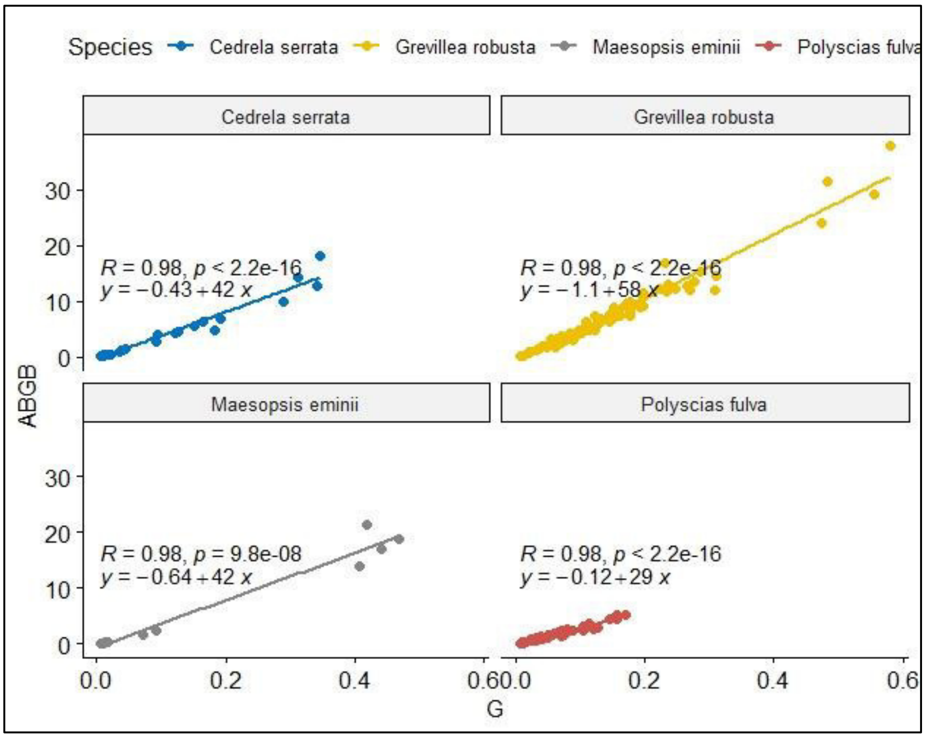


Figure 20. Regression analysis between H and ABGB for four AF species of Ruhande AF plot

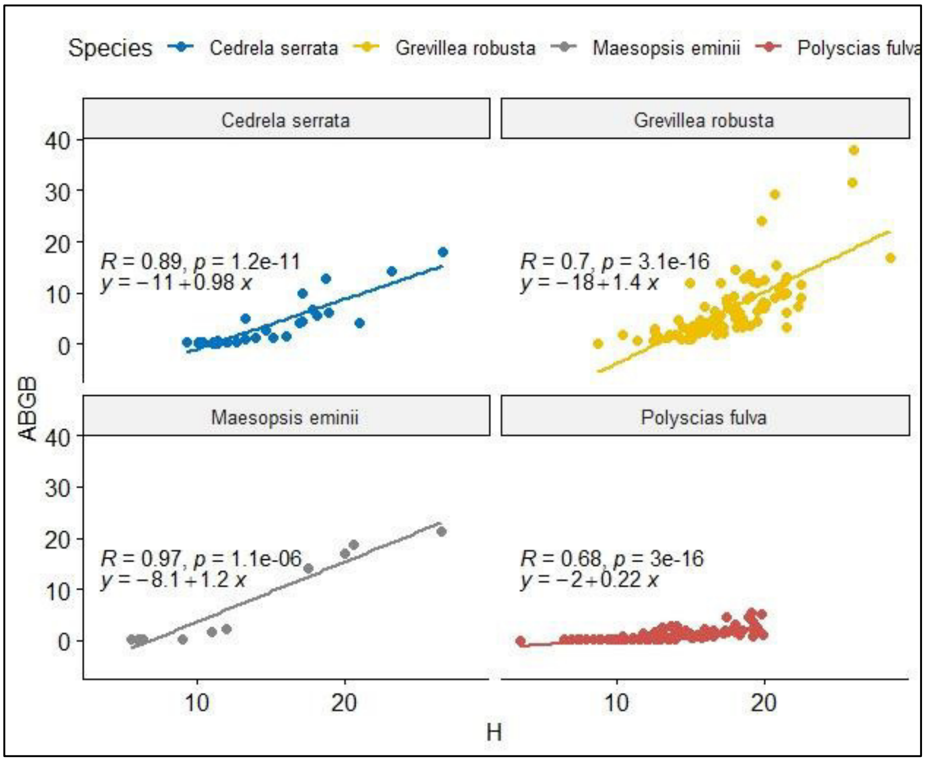


Figure 21. Regression analysis between G and ABGB for four AF species of Ruhande AF plot.

2.3.4 Nutrients content of AF tree species of study areas of Cyamudongo and Ruhande

2.3.4.1 Nutrient contents of seven AF tree species of Cyamudongo study area

Initially, the nutrient contents of seven species located in AF land use around Cyamudongo isolated forest were measured and compared. This result is significant only for Ca and Na with p-value = 0.01695 and p-value = 0.01717 respectively. No significant difference was highlighted between C, N, C: N ratio, K, Mg with, p-value = 0.2969, p-value = 0.2196, p-value = 0.2351, p-value = 0.3953 and p-value = 0.2173 respectively.

Henceforward, there was a need to check which species the difference is exactly significant. Thus, the AF tree species with a high mean value were compared to the other remaining species. The result did not show any significant difference between *Cedrela serrata* and *Croton megalocarpus, Markhamia lutea*, *Podocarpus latifolius* with p-value = 0.9097, p-value = 0.9803, p-value = 0.8052 and p-value = 0.8052 respectively as far as Ca is concerned. In reverse, there was a significant difference between *Cedrela serrata* and *Grevillea robusta*, *Maesopsis eminii*, *Polyscias fulva* with p-value = 0.03545, p-value = 0.02556, p-value = 0.02379.

In terms of Na, there was no significant difference between *Croton megalocarpus* and *Cedrela serrata, Grevillea robusta, Maesopsis eminii,* with p-value = 0.212, p-value = 0.1054 and p-value = 0.1159 correspondingly, whereas there was a marginal difference between *Croton megalocarpus* and *Markhamia lutea, Podocarpus latifolius* with p-value 0.05706 and p-value = 0.05743 correspondingly. This result is significant only between *Croton megalocarpus* and *Polyscias fulva* with a p-value = 0.007748.

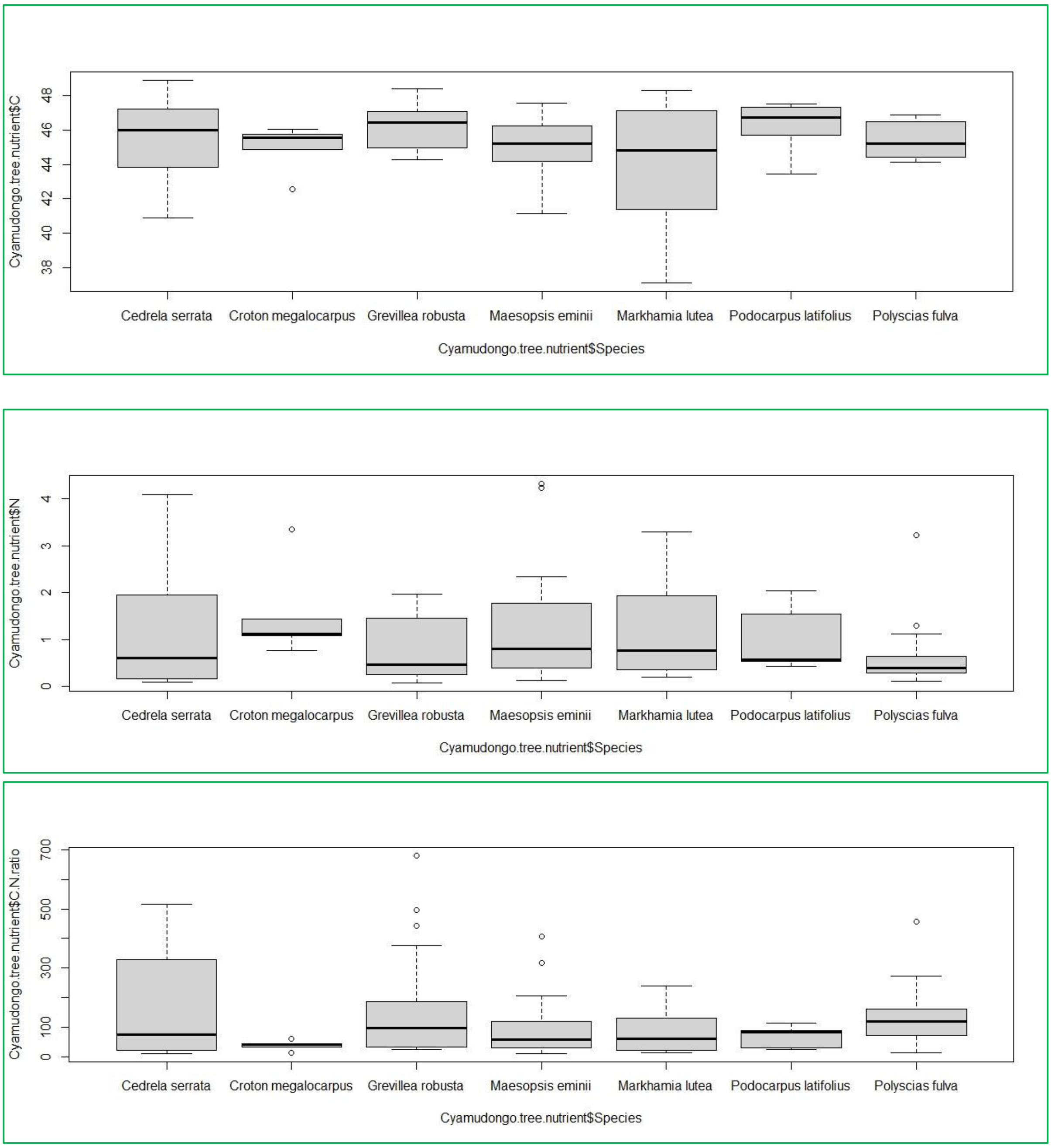


Figure 22. C, N, and C: N ratio for seven AF species of Cyamudongo study area

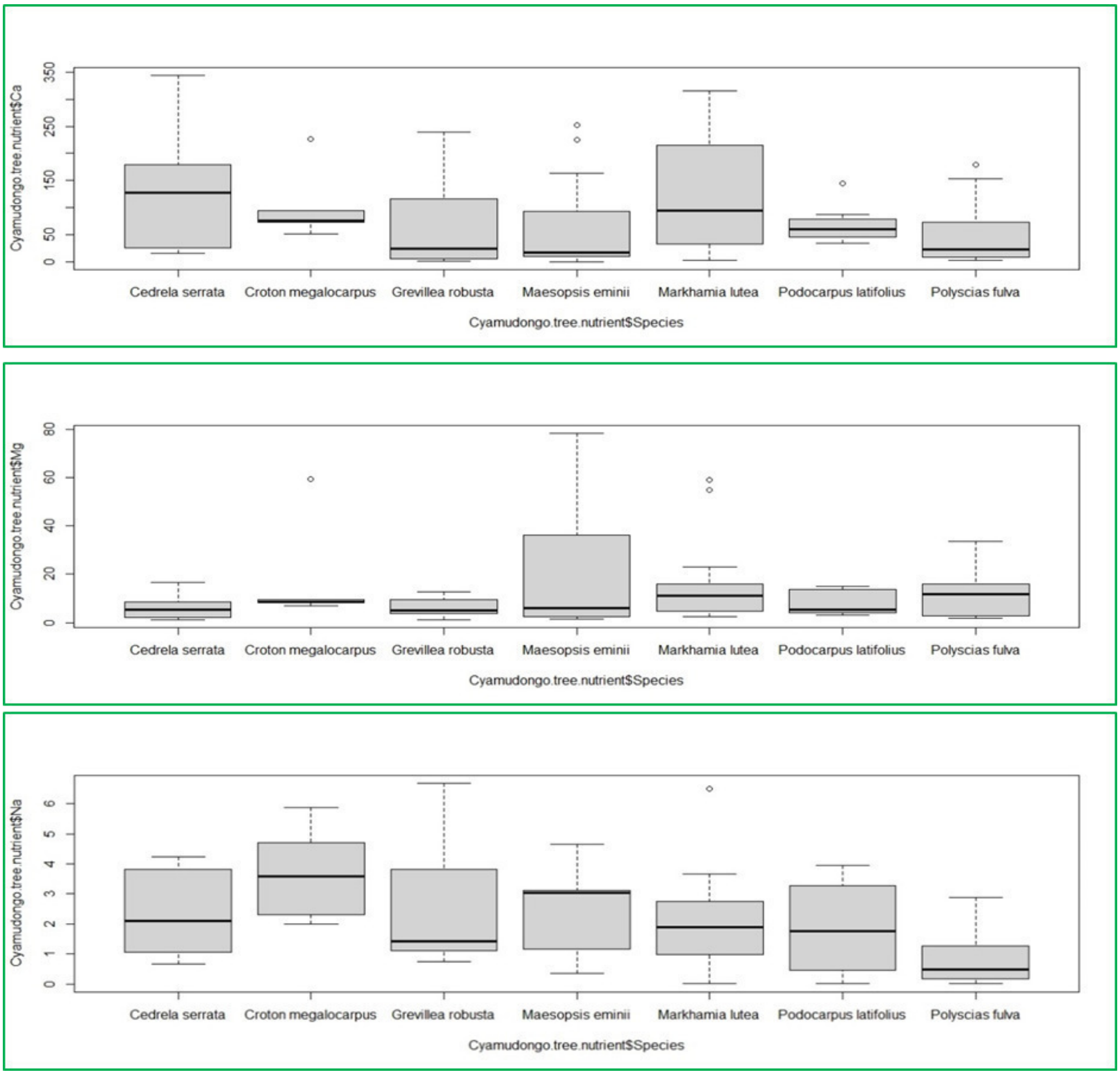


Figure 23. K, Ca, Mg, and Na ratio for seven AF species of Cyamudongo study area

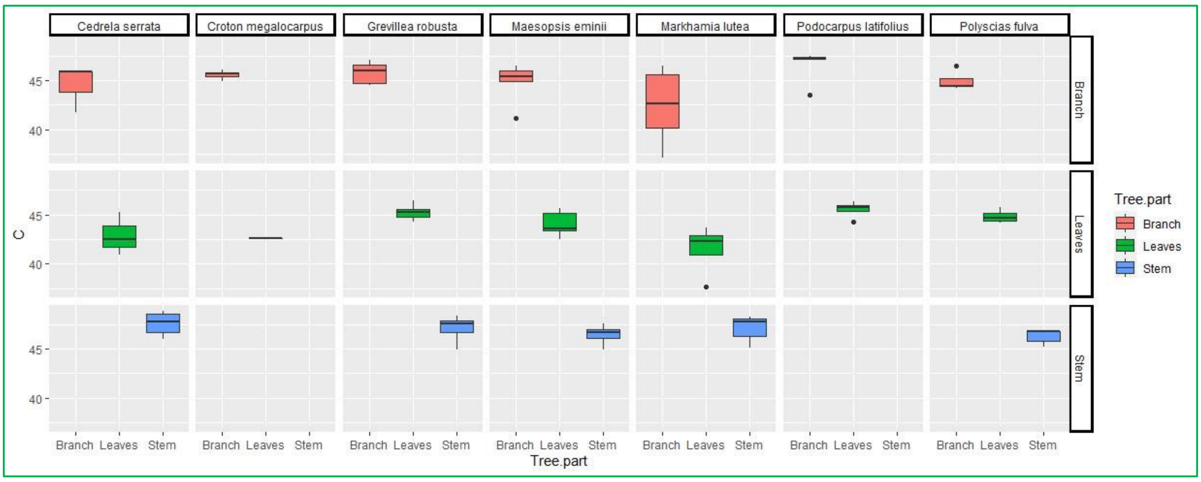
Besides, the mean values for various tree species were compared. Thus, the results showed that the species of *Podocarpus latifolius* contain more C than other species (46.21%), followed by *Grevillea robusta* (46.18%), *Cedrela serrata* (45.47%), *Polyscias fulva* (45.44%), *Maesopsis eminii* (45.03), *Croton megalocarpus (*44.96%) and *Markhamia lutea* (43.98%). Firstly, the nutrient contents were separately tested in stem, branch, and leaves for seven species. The C: N ratio was pronounced in the stem compared to other parts whereas the K and Ca were well noticeable in the leaves than in-branch and stem. All nutrients content in various tree parts for different tree species was presented in Table 10. Moreover, the change with the time of tree nutrients was also detected. The results have not shown any significant change in terms of C with p-value = 8.9e-08, whereas there was a significant change for N, C: N ratio, K, Ca, Mg and Na with p-value = 8.07e-07, p-value = 5.6e-07, p-value = 0.01, p-value = 0.0002, p-value = 0.01 and p-value = 0.03 respectively.

Table 10. Averaged values (mg/L) of nutrients content of seven AF species located around Cyamudongo isolated forest.

Species	Tree part		N	C	C: N ratio	K	Ca	Mg	Na
Cedrela serrata	Branch	Mean	1.12	44.52	49.67	35.86	177.77	5.70	2.76
		SD	0.64	2.43	26.38	2.82	6.87	0.71	1.82
	Leaves	Mean	3.03	42.87	15.49	90.93	272.03	14.17	1.77
		SD	1.02	2.17	6.10	47.39	125.00	3.18	0.53
	Stem	Mean	0.14	47.59	372.27	5.47	24.12	1.99	2.70
		SD	0.06	1.20	138.99	1.36	4.75	0.46	1.69
	Total	Mean	1.20	45.47	186.98	37.07	133.63	6.32	2.46
		SD	1.36	2.69	198.79	42.68	124.38	5.49	1.44
Croton megalocarpus	Branch	Mean	1.10	45.56	43.48	44.39	74.23	8.32	4.12
		SD	0.27	0.50	11.61	31.93	17.57	1.16	1.52
	Leaves	Mean	3.36	42.57	12.67	114.40	225.90	59.37	2.00
		SD	.	.	.	.	.	.	.
	Total	Mean	1.55	44.96	37.31	58.39	104.56	18.53	3.70
		SD	1.04	1.41	17.05	41.77	69.52	22.85	1.62
Grevillea robusta	Branch	Mean	0.49	45.76	96.02	35.27	31.40	4.36	3.29
		SD	0.10	1.07	19.36	10.62	20.78	2.95	2.37
	Leaves	Mean	1.70	45.26	26.86	56.10	167.80	11.47	1.47
		SD	0.18	0.75	3.25	16.38	43.15	2.00	0.56
	Stem	Mean	0.22	47.23	332.64	18.33	4.27	4.41	2.42
		SD	0.17	1.14	201.15	5.28	1.64	0.92	1.61
	Total	Mean	0.73	46.18	166.40	34.77	60.04	6.41	2.44
		SD	0.66	1.30	181.40	18.85	74.90	3.83	1.79
Maesopsis eminii	Branch	Mean	0.63	44.88	80.90	64.00	11.32	10.01	3.04
		SD	0.21	1.92	37.58	54.85	11.85	6.23	1.43
	Leaves	Mean	2.89	44.05	19.00	75.15	134.80	39.45	1.98
		SD	1.35	1.32	10.89	91.24	112.66	34.81	1.23
	Stem	Mean	0.41	46.47	242.32	13.97	50.28	15.51	1.97
		SD	0.50	1.10	158.17	17.59	69.99	26.01	1.38
	Total	Mean	1.32	45.03	103.31	54.37	62.87	21.29	2.40
		SD	1.38	1.74	119.05	64.65	88.08	26.21	1.37
Markhamia lutea	Branch	Mean	1.13	42.46	48.33	70.46	173.04	12.17	2.58
		SD	0.58	3.73	27.40	41.91	106.41	6.69	2.03
	Leaves	Mean	2.55	41.49	16.96	161.76	149.30	25.41	2.83

		SD	0.66	2.66	3.59	59.79	55.20	19.60	0.70
	Stem	Mean	0.30	47.17	171.95	22.58	55.10	12.71	0.71
		SD	0.09	1.36	55.87	7.62	84.31	22.75	0.90
	Total	Mean	1.17	43.98	86.85	75.33	122.87	15.68	1.94
		SD	1.01	3.65	78.01	66.59	98.91	17.26	1.65
Podocarpus latifolius	Branch	Mean	0.52	46.67	91.42	19.77	54.95	4.53	1.20
		SD	0.05	1.57	11.88	6.67	12.11	1.34	1.52
	Leaves	Mean	1.57	45.52	33.40	97.96	87.27	12.02	2.90
		SD	0.57	0.90	16.35	53.35	43.76	5.05	0.88
	Total	Mean	0.94	46.21	68.21	51.04	67.88	7.52	1.88
		SD	0.64	1.41	32.64	51.03	31.59	4.95	1.52
Polyscias fulva	Branch	Mean	0.60	44.96	88.57	43.94	52.79	20.25	0.94
		SD	0.31	0.93	33.24	9.83	34.78	8.61	1.18
	Leaves	Mean	1.63	44.83	57.62	119.98	112.70	11.07	1.73
		SD	1.46	0.82	58.51	99.64	94.11	7.80	1.36
	Stem	Mean	0.23	46.29	246.08	8.13	8.71	3.69	0.50
		SD	0.10	0.75	129.99	1.73	3.54	1.73	0.47
	Total	Mean	0.69	45.44	142.01	47.72	49.66	11.76	0.95
		SD	0.84	1.04	118.55	60.43	59.83	9.65	1.04
Total	Branch	Mean	0.75	45.00	74.64	45.33	74.32	9.25	2.52
		SD	0.41	2.27	31.62	32.90	74.23	7.04	1.93
	Leaves	Mean	2.25	44.06	26.52	96.09	154.12	21.19	2.08
		SD	1.03	1.96	22.44	66.16	88.75	20.78	0.97
	Stem	Mean	0.25	47.01	276.92	14.50	26.07	7.21	1.70
		SD	0.21	1.15	156.90	9.72	48.35	14.08	1.52
	Total	Mean	1.03	45.35	123.13	50.35	82.27	12.04	2.14
		SD	1.01	2.22	137.65	51.88	87.14	15.29	1.60

Figure 24 illustrates the variability of nutrients contents in various tree components for the tree species recorded in the Cyamudongo study area. The tests revealed differences in terms of C, N, and C: N ratio, K, Ca, Mg and Na in various tree components including stem, branches, and leaves.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Grevillea robusta
Maesopsis eminii
Markhamia lutea
Podocarpus latifolius
Polyscias fulva
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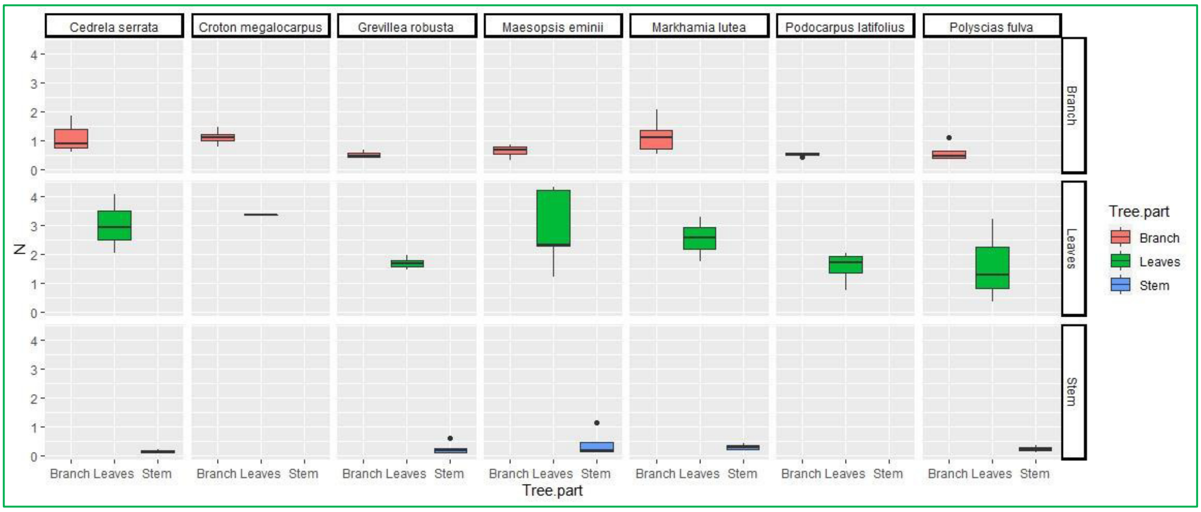
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Polyscias fulva
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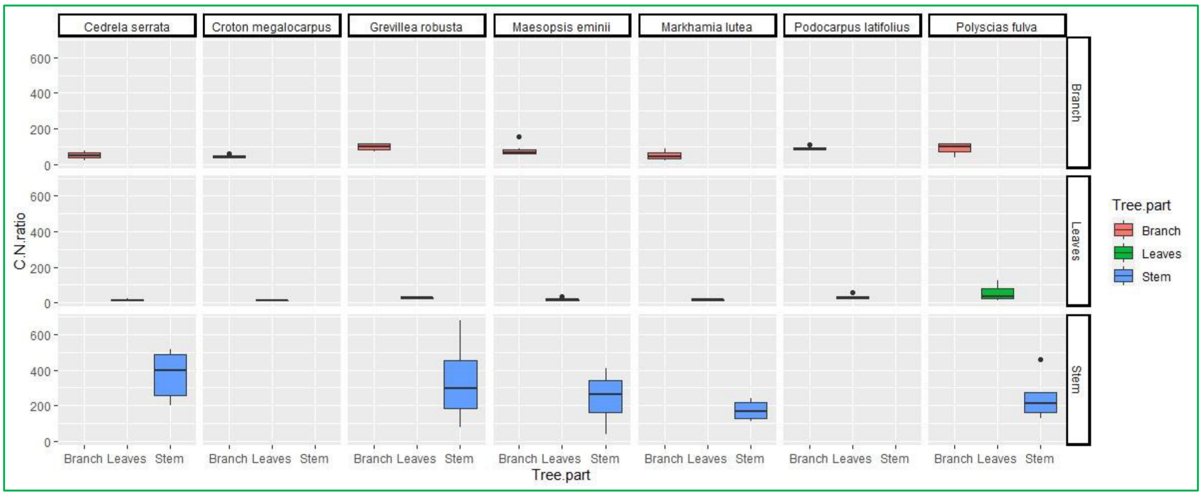
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Croton megalocarpus
Grevillea robusta
Maesopsis eminii
Markhamia lutea
Podocarpus latifolius
Polyscias fulva
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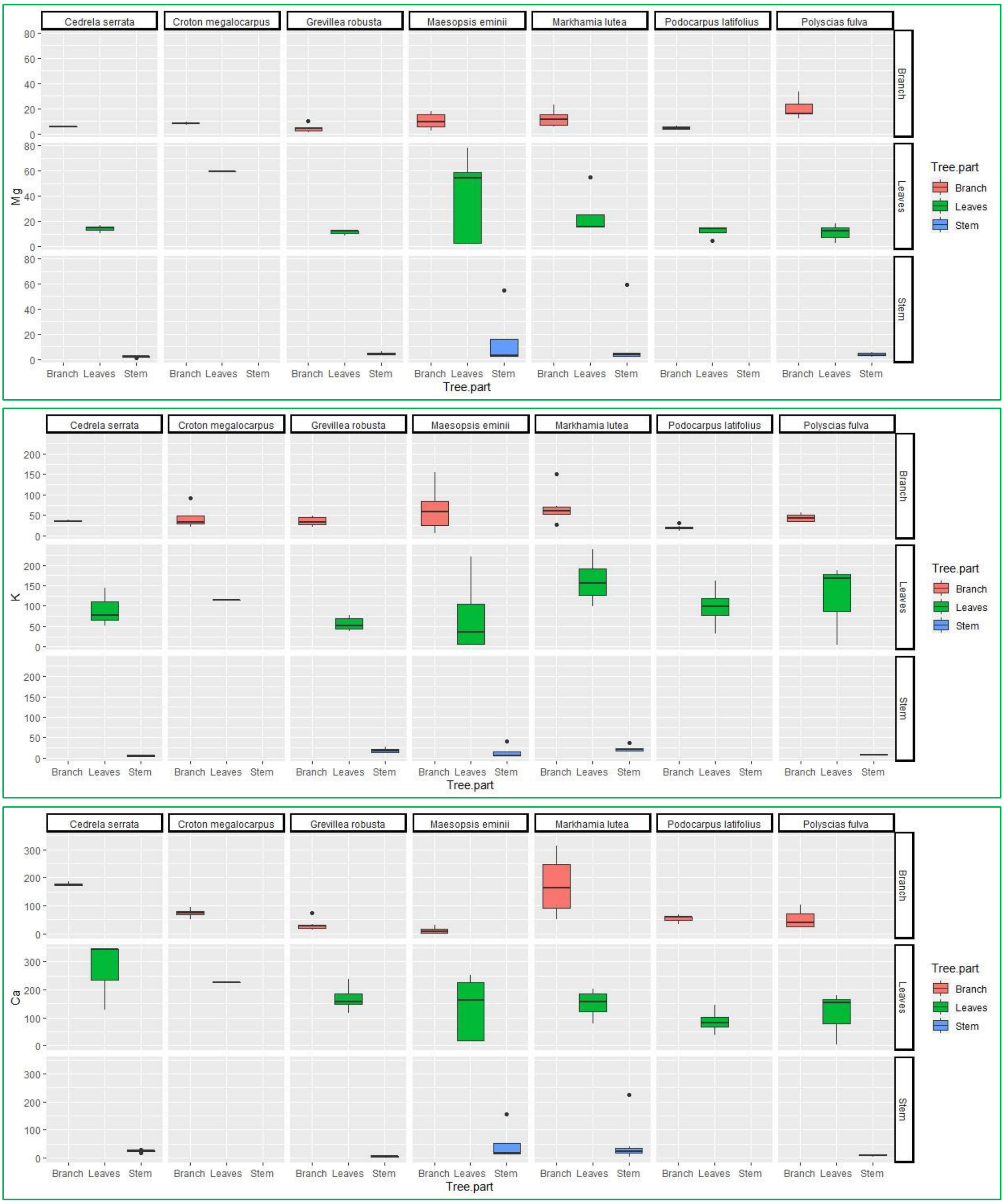


Figure 24. Comparison of nutrients content of different AF tree species in various tree components (stem, branches & leaves) of Cyamudongo AF tree species

2.3.4.2 Nutrients content for four AF tree species of Ruhande AF plot

Figure 25 shows the C, N, and C: N ratio of four AF tree species located at Ruhande plot. The analysis did not reveal any significant difference between various AF tree species with p-value = 0.1, p-value = 0.6, p-value = 0.5, p-value = 0.3, p-value = 0.1, p-value = 0.08 and p-value = 0.4 for C, N, C: N ratio, K, Ca, Mg and Na content respectively. The average C content including all tree parts was higher on *Grevillea robusta* (47.4%), followed by *Cedrella serrata* (46.4%), *Maesopsis eminii* (45.843%), and *Polyscias fulva* (45.8%). This result is significant for C, N, C: N ratio, K, Ca, Mg and Na for all tested AF tree species with p-value = 0.0002, p-value = 1.7e-06, p-value = 1.7e-06, p-value = 0.01, p-value = 0.009, p-value = 0.004 and p-value = 0.0006 respectively as far as the collection periods (2018 & 2019) are concerned.

Also, the nutrients were compared for stem and leaves. The result did not identify the significant difference for C and Na contained in the stem and leaves with p-value = 0.09845 and p-value = 0.6 respectively, whereas the result showed a significant difference in terms of N, C: N ratio, K, Ca and Mg with p-value = 2.9e-06, p-value = 2.9e-06, p-value = 1.5e-05, p-value = 4.7e-09, p-value = 4.7e-09 respectively. The results show that more C is found in the tree stem compared to tree leaves and the highest mean value was recorded in the stem of *Grevillea robusta* (48 %), followed by *Cedrela serrata* (47.49%), *Maesopsis eminii* (46.6%), and *Polyscias fulva* (46.1%). Significantly, the Na was higher in the leaves than in the stem.

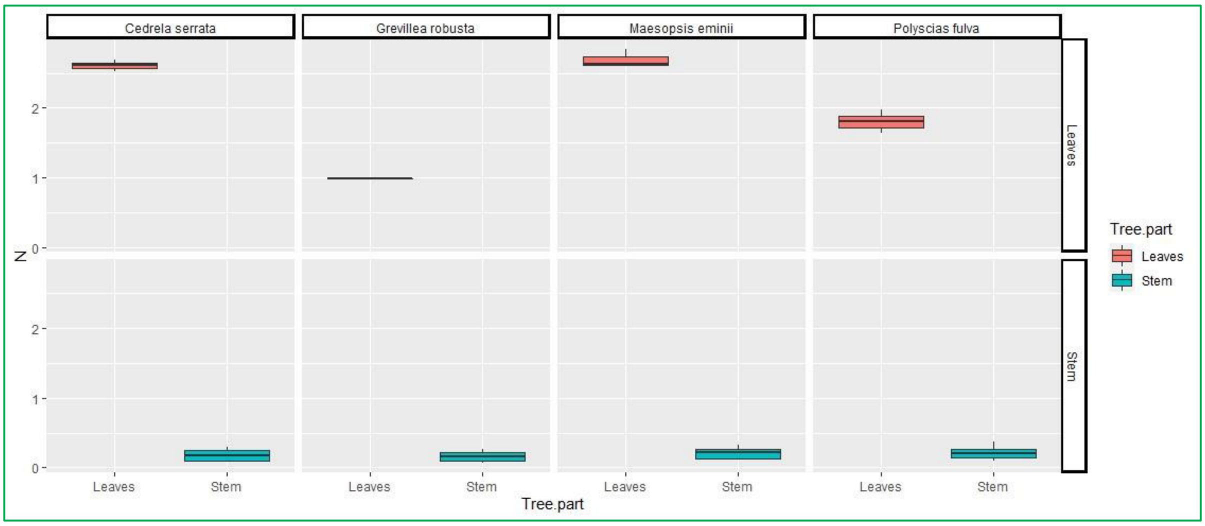
Therefore, the highest mean value was found in the leaves of *Masesopsis eminii* (2.69%) followed by C*edrela serrata* (2.61%), *Polyscias fulva* (1.8%), *and Grevillea robusta* (0.98%). Besides, the C: N mean values were higher in leaves of *Grevillea robusta* (390.1), followed by *Cedrela serrata* (341.5) while it was higher in the stems of *Maesopsis eminii* (265.8) and *Polyscias fulva* (263.4). Considering the overall C: N mean values (stem and leaves), all the species are ranked as follows: *Grevillea robusta* (276.4) > *Cedrela serrata* (260.3)> *Polyscias fulva (*184.1)> *Maesopsis eminii* (182.6).

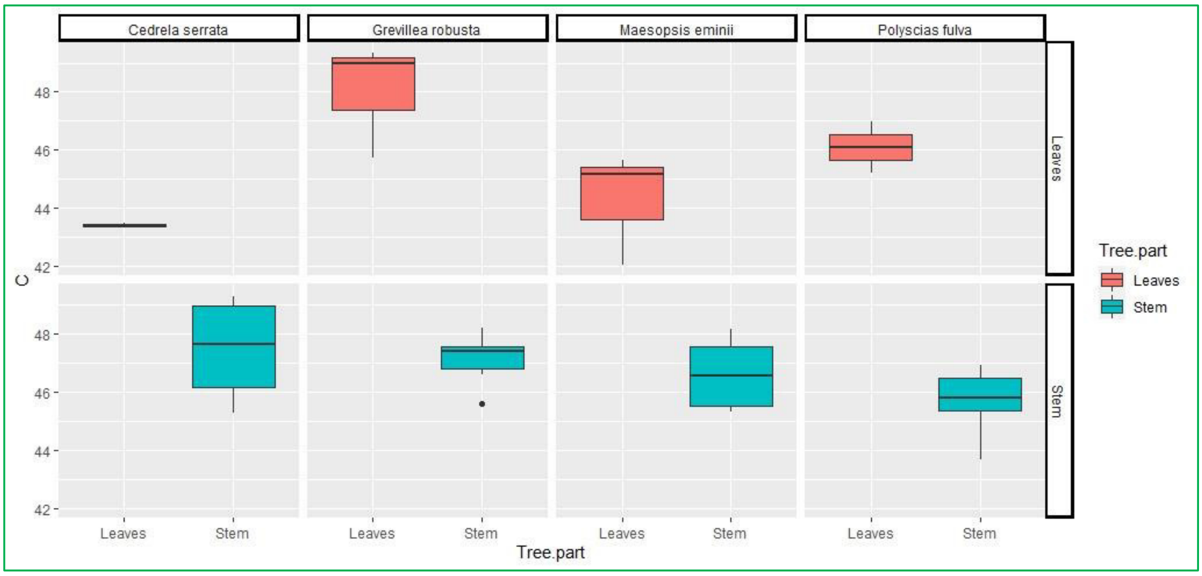
A high amount of K was recorded in the leaves than stem for all tested AF species. The more K mean values were recorded in *Maesopsis eminii* (8.08 mg/L), followed by *Cedrela serrata* (6.76 mg/L), *Polyscias fulva* (6.63 mg/L), and *Grevillea robusta* (5.41 mg/L). For Na, more values were recorded in tree leaves compared to the tree stem. The results show that the *Polyscias fulva* contain a high Na mean value (4.05 mg/L), followed by *Cedrela serrata* (78.54 mg/L), *Maesopsis eminii* (78.14 mg/L), and *Grevillea robusta* (38.89 mg/L). The Mg, was higher in *Maesopsis eminii* (19.7 mg/L) followed by *Polyscias fulva* (18.59 mg/L), *Cedrela serrata* (9.31 mg/L), and *Grevillea robusta* (6.76 mg/L). Finally, the averaged values of Na were more in the tree stem than in leaves. The averaged values (stem and leaves) show that *Grevillea robusta* stores more Na than other species with (2.15 mg/L), followed by *Cedrela serrata* (1.94 mg/L), *Maesopsis eminii* (1.46 mg/L), and *Polyscias fulva* (0.49 mg/L).

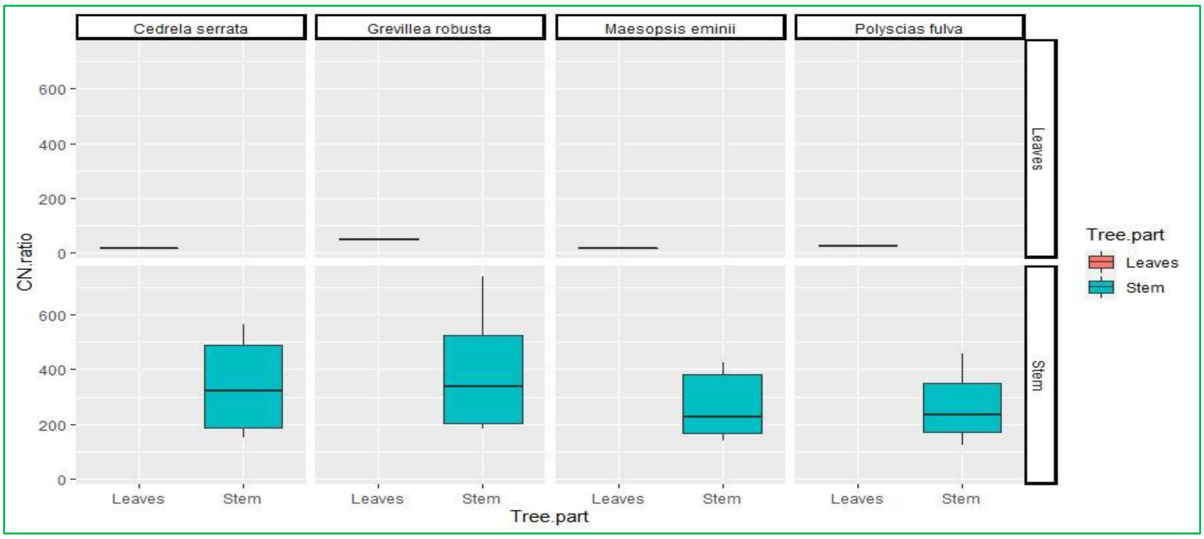
Table 11. Averaged values (mg/L) of four AF tree nutrients content of Ruhande AF plot

Species	Tree part		N	C	CN ratio	K	Ca	Mg	Na
Cedrella serrata	Leaves	Mean	2.61	43.40	16.65	21.26	192.20	33.31	0.85
		SD	0.11	0.12	0.77	3.10	55.72	24.81	0.26
	Stem	Mean	0.18	47.49	341.54	1.94	40.66	1.31	2.32
		SD	0.09	1.77	184.92	1.11	7.65	0.37	2.78
	Total	Mean	0.79	46.47	260.32	6.77	78.55	9.31	1.95
		SD	1.13	2.41	216.90	9.07	73.53	17.53	2.45
Grevillea robusta	Leaves	Mean	0.98	48.03	48.84	5.62	103.85	10.99	0.15
		SD	0.01	1.99	1.93	3.45	45.94	5.30	0.13
	Stem	Mean	0.16	47.14	390.20	5.31	6.42	4.64	3.15
		SD	0.08	0.92	230.05	1.47	2.62	1.32	2.28
	Total	Mean	0.44	47.44	276.41	5.42	38.90	6.76	2.15
		SD	0.42	1.31	249.42	2.08	53.90	4.27	2.35
Maesopsis eminii	Leaves	Mean	2.70	44.29	16.43	19.74	194.40	55.48	0.93
		SD	0.13	1.96	0.75	5.96	36.18	6.49	0.18
	Stem	Mean	0.21	46.62	265.81	2.26	20.02	1.91	1.73
		SD	0.09	1.24	128.83	0.98	7.72	0.37	1.63
	Total	Mean	1.04	45.84	182.68	8.08	78.15	19.77	1.47
		SD	1.25	1.81	161.00	9.27	89.25	26.99	1.35
Polyscias fulva	Leaves	Mean	1.81	46.10	25.64	10.44	228.10	49.03	0.73
		SD	0.17	0.88	1.92	4.89	23.25	2.62	0.21
	Stem	Mean	0.21	45.69	263.44	4.74	12.03	3.37	0.38
		SD	0.10	1.17	130.66	2.39	4.39	1.25	0.22
	Total	Mean	0.74	45.83	184.17	6.64	84.05	18.59	0.50
		SD	0.81	1.04	157.50	4.20	108.71	22.89	0.27
Total	Leaves	Mean	1.97	45.64	27.82	13.63	178.50	37.56	0.65
		SD	0.74	2.25	14.12	7.77	60.21	20.69	0.37

Stem	Mean	0.19	46.74	315.25	3.56	19.78	2.81	1.90
	SD	0.09	1.41	171.00	2.12	14.40	1.59	2.11
Total	Mean	0.75	46.39	224.91	6.72	69.66	13.73	1.50
	SD	0.93	1.76	195.36	6.58	82.43	19.89	1.84






Cedrela serrata
Grevillea robusta
Maesopsis eminii
Polyscias fulva
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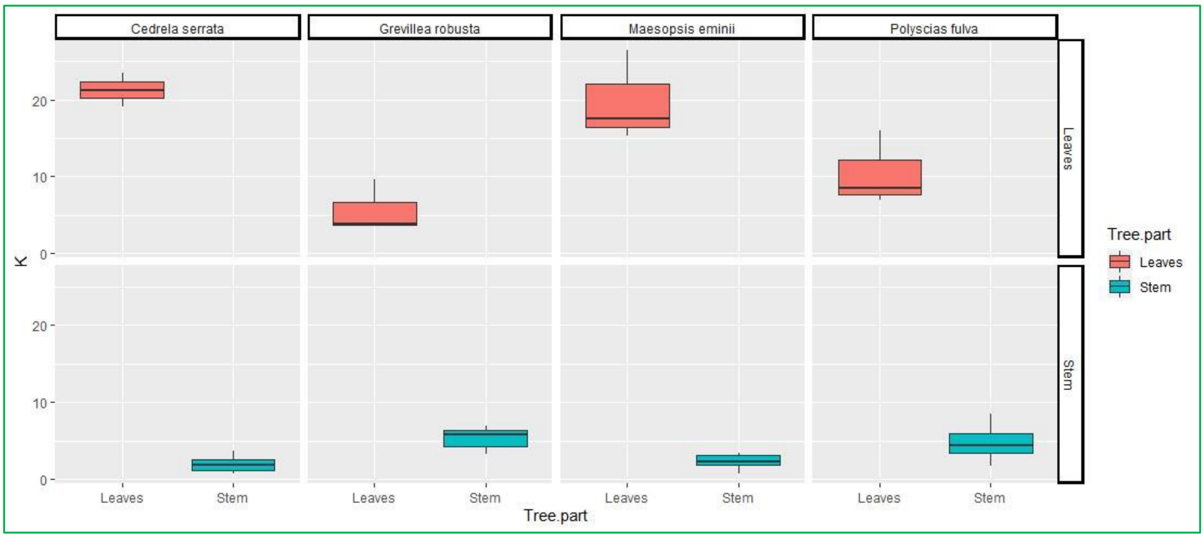
600
400
200
0
Leaves
Stem
Tree.part
Leaves
Stem


Cedrela serrata
Grevillea robusta
Maesopsis eminii
Polyscias fulva
K
20
10
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Leaves
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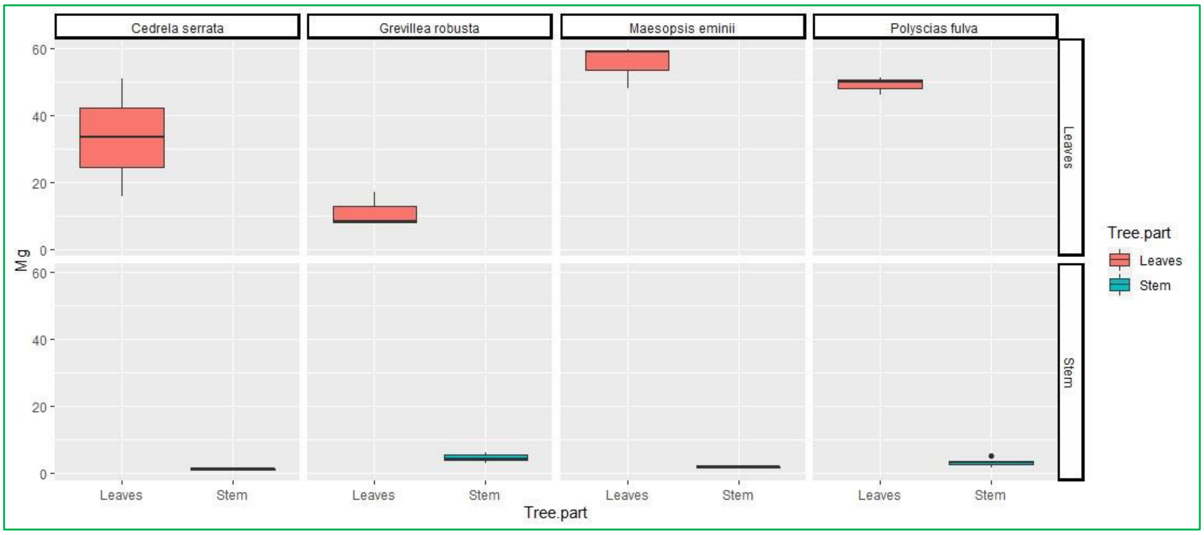
Tree.part
Leaves
Stem


Cedrela serrata
Grevillea robusta
Maesopsis eminii
Polyscias fulva
Mg
60
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Leaves
Stem
Tree.part
Leaves
Stem

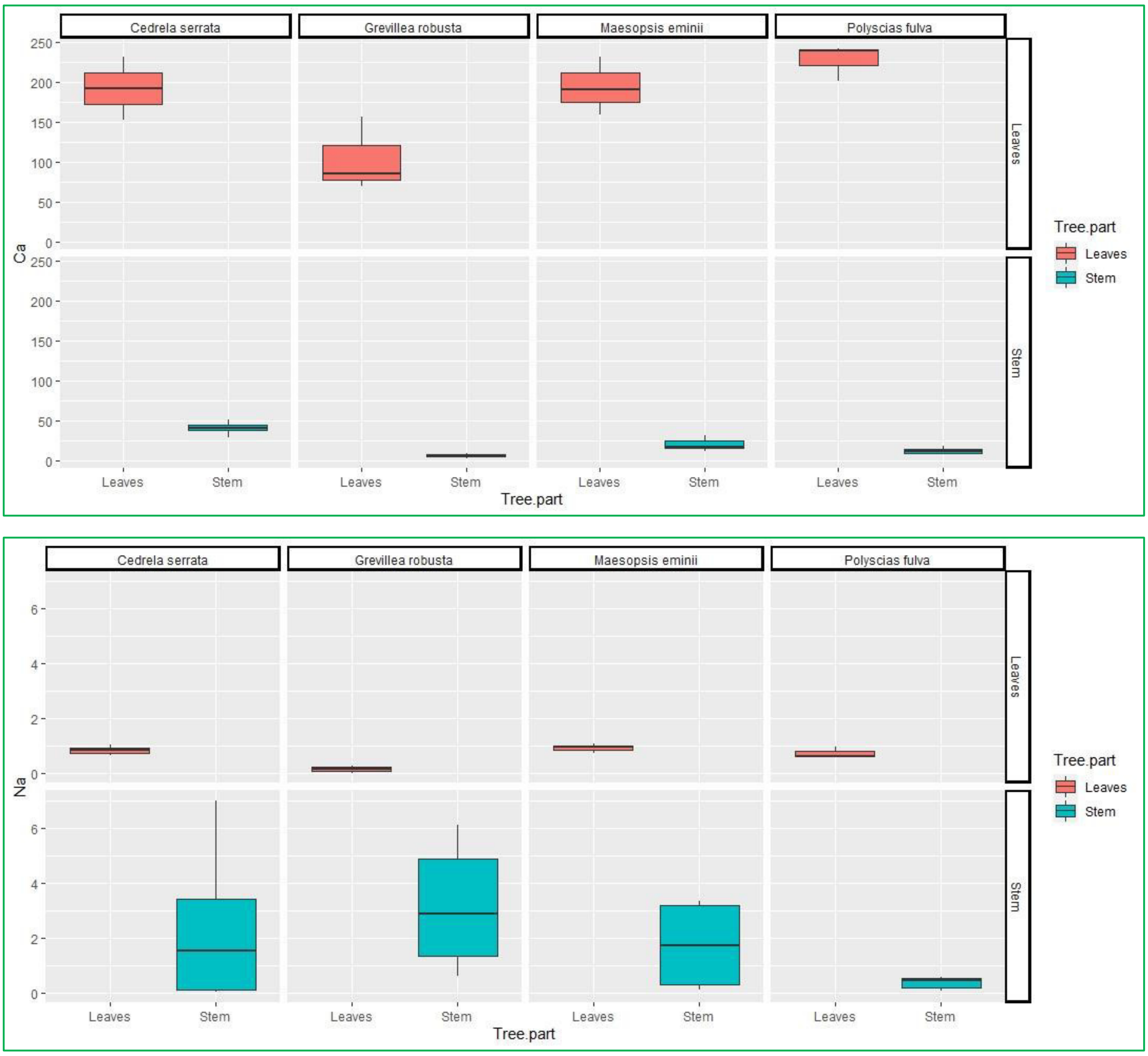


Figure 25. Comparison of nutrients content of AF tree species in different components (stem & leaves) of Ruhande AF plot

2.3.4.3 Comparison of various nutrients content of various AF tree species of Cyamudongo and Ruhande study areas

The tests revealed differences in terms of nutrient contents (C, N, C: N ratio, K, Na, Ca, and Mg) for various AF tree species of Cyamudongo and Ruhande study areas. As expected, the estimated C content in trees varied with species, tree components, and WSD. The species with high WSD were found to have more C contents.

The *Grevillea robusta* was found to have more C content with 47.4% and 46.16% as the averaged percentage from stems, branches, and leaves in Cyamudongo and Ruhande respectively. The recorded C percentage for various components/ parts of AF tree species was found to vary not only among species but also with tree parts. For example, more C was recorded in the leaves of *Grevillea robusta* (48.03%) followed by the stem (47.16%) while the stem of *Cedrela serrata* contains more C in its stem with 47.49 % followed by its leaves (43.40%) for Ruhande AF tree species. These values were higher than those obtained in the Cyamudongo study area for the same AF tree species. In Cyamudongo, the recorded C content was 47.23 % in the stems, 45.76 % in the branches, and 45.26% in the leaves of *Grevillea robusta*. For *Cedrela serrata*, more C was recorded in the stems (47.59%), branches (44.52%), and leaves (42.87%). All the values for various nutrient contents across study areas are shown in tables 10&11.

Despite that, the N content did not confirm any significant difference between tree species but showed a significant difference between tree components for tested AF tree species. The N values for various tree species in both Cyamudongo and Ruhande were different even though not significant. The N value for Cyamudongo AF tree species was found to be higher on *Croton megalocarpus* (1.55 %) followed by *Maesopsis eminii* (1.32 %), *Cedrela serrata* (1.2 %), *Markhamia lutea* (1.17%), *Podocarpus latifolius* (0.94 %), *Grevillea robusta* (0.73 %) and *Polyscias fulva* (0.69 %). For Ruhande, the N value was higher on *Maesopsis eminii* (1.04%), followed by *Cedrela serrata* (0.79%), *Polyscias fulva* (0.74%), and *Grevillea robusta* (0.44%). For all study areas, the Grevillea robusta was found to be the least in terms of N content.

Concerning the tree parts/ components, the averaged N value was found to be higher in leaves (1.97%) than stems (0.19%) for Ruhande AF tree species. Similarly, the leaves of Cyamudongo AF tree species stored 2.25% and the stems followed by branches (0.75%) and stems (0.25%). The overall N stored by AF tree species of Cyamudongo was 1.03%, which was higher than the amount of N stored by the Ruhande AF plot (0.75%). The results showed that the amount of N varied with AF tree species, tree parts, growth stage or age of AF tree species, and climatic conditions in terms of rainfall and temperature that were different across the study areas.

Generally, this result did not show any significant difference for seven AF tree species of the Cyamudongo study area as far as the C: N ratio is concerned. Inversely, the tests revealed significant differences for four AF tree species established in the Ruhande AF plot. The tests highlighted significant differences among various tree parts and were higher in stem while the lowest ratio was found in leaves for all study areas (Table 10 and 11). The C: N ratio also varied with AF tree species, tree parts, and the region. The *Grevillea robusta* was found to have more

C: N ratio value in Ruhande with 276.4, followed by *Cedrela serrata* (260.3), *Polyscias fulva* (184.1), and *Maesopsis eminii* (182.6). *Cedrela serrata* (186.9) was found to have more C: N ratio value for the Cyamudongo study area followed by *Grevillea robusta* (166.4), *Polyscias fulva* (142), *Maesopsis eminii* (103.3), *Markhamia lutea* (86.8), *Podocarpus latifolius* (68.2), and *Croton megalocarpus* (37.3). This result appears to be well supported by Zhang et al., (2020) who reported a significant variation in the C: N ratio in different component plants. In its findings, the C: N ratios were 21.05 ± 0.14, 57.85 ± 0.48, 319.04 ± 6.23, and 49.81 ± 0.58 in the leaf, branch, trunk, and root, respectively. Furthermore, this result also follows the reported C: N ratio of Lebedev et al., (2017) for different plant structures. The obtained results also corroborate with Cools et al., (2014) who reported the variability of the C: N ratio among different tree species under their study.

The tree content in terms of K was significantly different among AF tree species and tree components and the highest amount was recorded in leaves compared to the other components (Table 10 and 11). The young species of AF were found to contain more K than the mature AF species. This the reason why more values were recorded on the small species of Cyamudongo while the values were low in the old AF trees of the Ruhande AF plot.

For Ruhande AF tree species, the K value was found to be higher on *Maesopsis eminii* (8.08 mg/l) followed by *Cedrela serrata* (6.77 mg/l), *Polyscias fulva* (6.64 mg/l), and *Grevillea robusta* (5.42 mg/l). For Cyamudongo, *Markhamia lutea* was found to have more K value (75.33 mg/l) compared to other AF tree species. The second species was *Croton megalocarpus* (58.39 mg/l) followed by *Maesopsis eminii* (54.37 mg/l), *Polyscias fulva* (47.72 mg/l), *Cedrela serrata* (37.07 mg/l), and *Grevillea robusta* (34.77 mg/l).

By comparing the K value in stems, branches, and leaves, the leaves were qualified to have more K content compared to the other tree components. The tests revealed the small K values in leaves of AF species of Ruhande compared to the K values recorded in the Cyamudongo study area. The high value was recorded on *Cedrela serrata* (21.26 mg/l), followed by *Maesopsis eminii* (19.74 mg/l), *Polyscias fulva* (10.44 mg/l), and *Grevillea robusta* (5.62 mg/l). For Cyamudongo, *Markhamia lutea* (161.75 mg/l) followed by *Polyscias fulva* (119.98 mg/l), *Podocarpus latifolius* (97.97 mg/l), *Maesopsis eminii* (75.15), *Cedrela serrata* (35.86 mg/l), and *Grevillea robusta* (35.27 mg/l).

For Ruhande AF tree species, *Polyscias fulva* was found to contain the highest amount of Ca with 84.05 mg/l followed by *Cedrela serrata* (78.55 mg/l), *Maesopsis eminii* (78.15 mg/l), and *Grevillea robusta* (38.9 mg/l). In Cyamudongo, *Cedrela serrata* was found to have the highest value with 133.6 mg/l followed by *Markhamia lutea* (122.8 mg/l), *Croton megalocarpus* (104.5 mg/l), *Podocarpus latifoliu*s (67.88 mg/l), *Maesopsis eminii* (62.8 mg/l), and *Grevillea robusta* (60.04 mg/l). The overall values of recorded Ca for leaves and stems were 178.5 mg/l and 19.78 mg/l respectively for the AF tree species recorded in Ruhande. The overall Ca values were 154.12 mg/l, 74.32 mg/l, and 26.07 mg/l for leaves, branches, and stems respectively. The overall Ca averages were 82.27 mg/l and 69.66 mg/l for Ruhande and Cyamudongo respectively.

The Mg concentration in various AF tree species was found to vary with tree species, tree parts, and region. In Ruhande, the highest value was recorded on *Maesopsis eminii* with 19.77 mg/l followed by *Polyscia fulva* (18.59 mg/l), *Cedrela serrata* (9.3 mg/l), and *Grevillea robusta* (6.76 mg/l). Similarly, *Maesopsis eminii* was found to have the highest amount (21.29 mg/l) for Cyamudongo, followed by *Croton megalocarpus* (18.53 mg/l), *Markhamia lutea* (15.68 mg/l), *Polyscias fulva* (11.76 mg/l), *Podocarpus latifolius* (7.52 mg/l), *Grevillea robusta* (6.41 mg/l), and *Cedrela serrata* (6.32 mg/l). Globally, the leaves of Ruhande contain more Mg with 37.56 mg/l compared to the leaves of AF tree species in Cyamudongo (21.19 mg/l). By comparing the Mg recorded in the stems, the tests revealed more Mg in the stems of Cyamudongo (7.21 mg/l) while it was 2.28 mg/l for the stems of the Ruhande study area.

On the other hand, the Na did not show any significant difference among tree species and tree parts while it was significant with time. Besides, the highest amount of Na was recorded in the stem (Table 10 and 11).

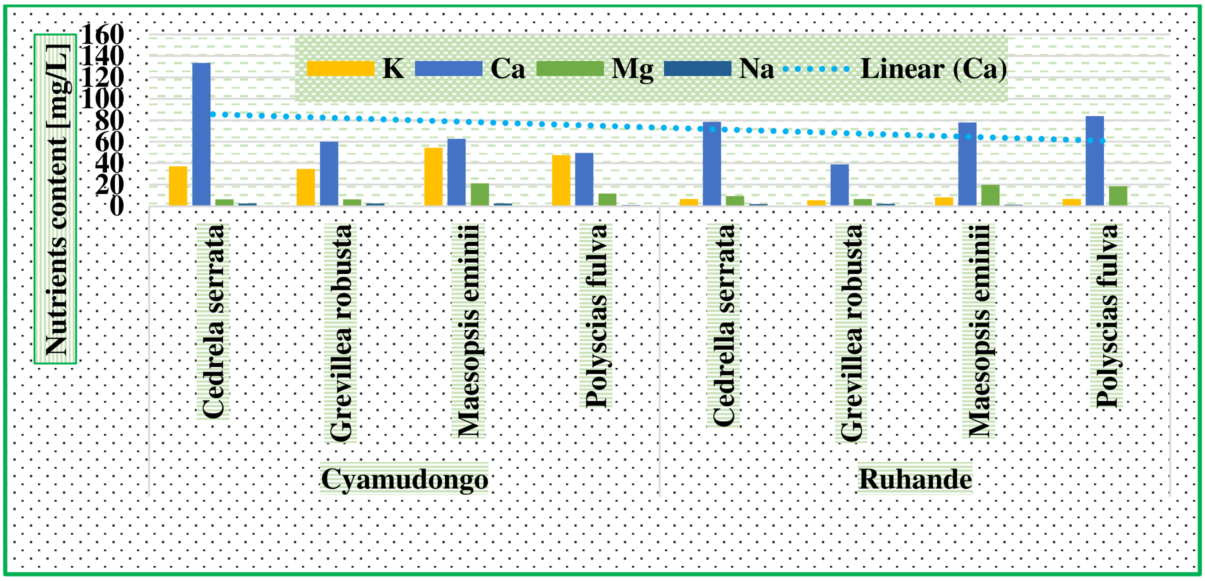


Figure 26. Comparison of K, Ca, Mg, and Na of AF tree species of Cyamudongo and Ruhande study areas

The results highlighted differences in terms of WSD for various AF tree species from different study areas. Surprisingly, one of the AF tree species of the Cyamudongo study area was qualified to have more WSD value than other mature tree species. A 2-year-old *Croton megalocarpus* (567 kg m^3) was found to have a high value of WSD followed by a mature species of *Grevillea robusta* (494 kg m^3) and mature *Cedrela serrata* (428 kg m^3). In Ruhande, *Grevillea robusta* (555 kg m^3) was found to have more WSD value followed by *Cedrella serrata*, *Maesopsis eminii,* and *Polyscias fulva*. In all study areas, *Polyscias fulva* was qualified to have a small WSD among all seven AF tree species targeted by this study (Table 1).

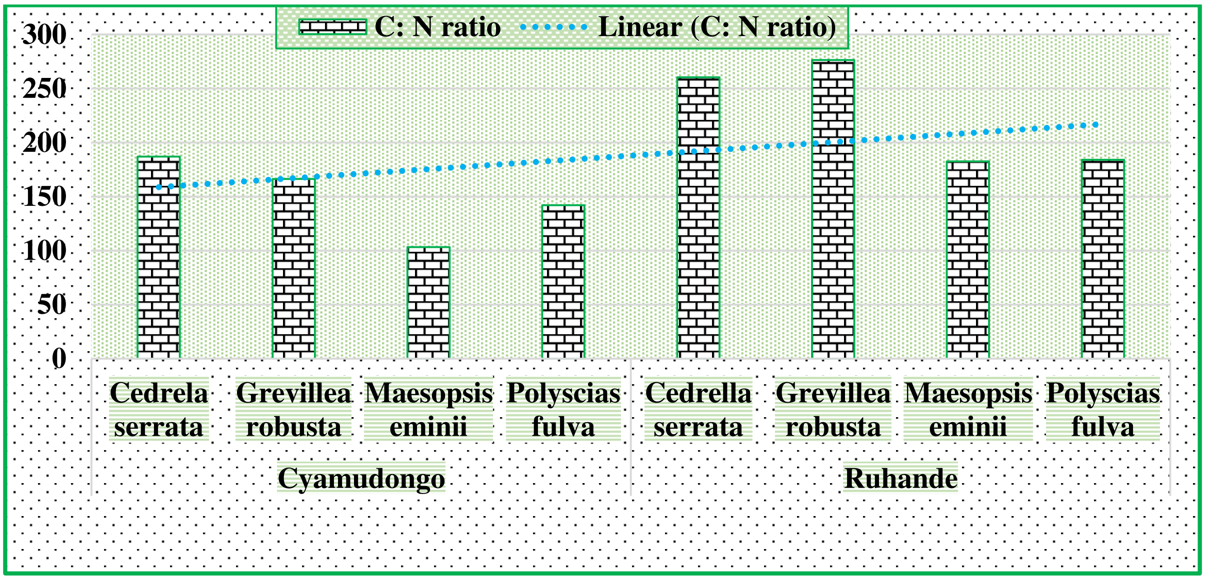


Figure 27. Comparison of C: N ratio of AF tree species of Cyamudongo and Ruhande study areas

2.4 Discussion

It was found that the amount of C sequestered and stored by various AF tree species and their mixture in various study areas was affected by tree species, stand density, age and tree size, and environmental conditions in terms of rainfall and temperature. A lot of rainfall with small temperature levels was recorded in Cyamudongo while the less intensive rainfall with higher temperature was recorded in the Ruhande study area (Figures 5 & 6). Nair et al., (2009) affirmed that the extent of C captured by the AF system depends on various factors including edaphic, climatic, and the applied management practices.

The obtained C stock values are in good agreement with Hu et al., (2015) who reported more C stock on big size trees than small trees. They further found differences in terms of biomass C that varied with the composition of tree species and their arrangement within the stand. The young trees were found to grow fast than mature ones and this has an impact on the C sequestration. The tests highlighted that the total C sequestration rate recorded for young AF tree species established by the project in the surroundings of Cyamudongo isolated rain forest is 13.11 t C ha $^{-1}$ yr^{-1} corresponding to 47.94 t CO_2 ha $^{-1}$ yr^{-1} centered on the young trees of 2 years old whereas the analysis further showed that the C sequestration rate of the Ruhande AF plot of 34 years old is 6.85 t ha^{-1} yr^{-1} corresponding to 25.07 t CO_2 ha^{-1} yr^{-1}. This indicates the capacity of young tree species to mitigate climate change-related issues through the removal of CO_2 from the atmosphere. This is in the line with Hairiah et al., (2010) who reported more C sequestration rate for young species compared to mature trees. The growth stage was found to contribute to the C stored by various AF tree species. By comparing the C stored by the young tree species to the quantity of C stored by mature or old AF tree species, the tests revealed a high amount of C in mature trees than that of young AF tree species across all study areas. This result is following Agevi et al., (2017) who found that the tree biomass held in trees varies from one region to the other and is dependent on species density, age, climatic factors, and soil factors.

In Cyamudongo, the existing tree species stored 787.12 t ha^{-1} while the tree species that were established by the Project stored 35.83 t ha^{-1}. The old AF tree species of Ruhande stored 232.94 t ha^{-1}. The high amount of C stored by mature species found in Cyamudongo may be attributed to the favorable environmental conditions in terms of rainfall, temperature, and other factors such as tree age, growth stage, WSD, and applied management practices including the number of trees per hector (density). This concurs well with Arora et al., (2014) who reported more wood biomass and C stock on trees with more ages than young species. They further stated that the tree biomass and C stock increased with age. This fits also with Hairiah et al., (2010) who stated that mature AF trees have the potential to have more C stock than newly established tree species and also confirms with previous findings of Slik et al., (2010) and Wassihun et al., (2019) who stated that the AGB is affected by stand density. They further clarified that the AGB and stand density are strongly correlated with each other.

Concerning the WSD tested for various AF species, it is clear to conclude that it varies with tree species, age, and environmental conditions. This result lends support to Mukuralinda et al., (2021) who reported various wood densities for different tree species under their study conducted in Ruhande arboretum, Rwanda.

The tests revealed differences in terms of nutrient contents (C, N, C: N ratio, K, Na, Ca, and Mg) for various AF tree species of Cyamudongo and Ruhande study areas. The obtained values of C concentration in different AF tree species across study areas are in good agreement with Watson, (2015) who also reported the average C close to 50%, which is a value mostly used to compute the amount of C stored by a kind of forest. The 50% C has become a central value and suggested as important in the determination of C stock (Lamlom and Savidge, 2003). As expected, the estimated C content in trees varied with species, tree components, and WSD. The species with high WSD were found to have more C contents.

The *Grevillea robusta* was found to have more C content with 47.4% and 46.16% as the averaged percentage from stems, branches, and leaves in Cyamudongo and Ruhande respectively. The recorded C percentage for various components/ parts of AF tree species was found to vary not only among species but also with tree parts. This result shares a number of similarities with Chouhan et al., (2009) findings on the variability of C content that varied with tree species and parts. This result also lends support to previous findings in the literature. Matthews, (1993) confirmed the variations of C content between different parts of a tree. Lamlom and Savidge, (2003), reported that C contents significantly varied among species and with wood density comparing softwood and hardwood.

Despite that, the N content did not confirm any significant difference between tree species but showed a significant difference between tree components for tested AF tree species. The N values for various tree species in both Cyamudongo and Ruhande were different even though not significant. The results showed that the amount of N varied with AF tree species, tree parts, growth stage or age of AF tree species, and climatic conditions in terms of rainfall and temperature that were different across the study areas. This result is in the line with previous study results. Kostecki et al., 2015 recorded the total N content in leaves and bark, which was much higher than in the wood of the tested tree species. Besides, Northup et al., (2005) found that the leaves have generally higher N than stems across species. Besides, Özcan and Makineci, (2020), found that the averaged N contents in the biomasses of the tree components, the foliage had the highest N content (1.32%), followed by the bark (0.7%), branch (0.68%), and stem (0.35%) components.

Generally, this result did not show any significant difference for seven AF tree species of the Cyamudongo study area as far as the C: N ratio is concerned. The tests highlighted significant differences among various tree parts and were higher in stem while the lowest ratio was found in leaves for all study areas (Table 10 and 11). This result appears to be well supported by Zhang et al., (2020) who reported a significant variation in the C: N ratio in different component plants. In its findings, the C: N ratios were 21.05 ± 0.14, 57.85 ± 0.48, 319.04 ± 6.23, and 49.81 ± 0.58 in the leaf, branch, trunk, and root, respectively. Furthermore, this result also follows the reported C: N ratio of Lebedev et al., (2017) for different plant structures. The obtained results also corroborate with Cools et al., (2014) who reported the variability of the C: N ratio among different tree species under their study.

The tree content in terms of K was significantly different among AF tree species and tree components and the highest amount was recorded in leaves compared to the other components (Table 10 and 11). The young species of AF were found to contain more K than the mature AF species. By comparing the K value in stems, branches, and leaves, the leaves were qualified to have more K content compared to the other tree components. This result appears to be well substantially supported by Board et al., (2017) who found a significant difference between leaves and other tree components with a remarkable amount in leaves as far as K is concerned.

As anticipated, similar results were also observed for Mg and Ca content, which leaves, had significantly the highest amount compared to the other components and among tree species. This is in complete agreement with Tůma et al., (2004) who recorded the highest content of Mg in the leaves. It is logical because the leaves are the main location of photosynthesis, chlorophyll is usually in the highest concentration here, and magnesium is its building stone. Tůma et al., (2004) further highlighted that Mg and Ca, are accumulated in the leaves especially in the vacuole, and progressively supplied into metabolic reactions.

For Cyamudongo species, the correlation between tree height and diameter at 30 cm from the ground (D_{30}) for the small tree species widely varied from negligible to very strong due to the variability in terms of the growth performance of different tree species at the young stage, and their shapes. Different tree species of different families, biological and physiological characteristics may not have the same growth rate though established in the same environmental conditions. Therefore, this resulted in a high variation of the relationship between tree height and D_{30}. Among the studied tree species at the young stage (1-2 years old), some start to provide the multiple stems with irregular shapes at ground level (even below 30 cm from the ground) where the main stem was taken for regressing between tree height and D_{30}, and this was observed on *Croton megalocarpus*, and the reported correlation coefficient was negligible (R=0.031). Besides, the remaining tree species (*Cedrela serrata, Grevillea robusta, Markhamia lutea, Podocarpus latifolius,* and *Polyscias fulva*) showed a strong correlation (R=0.70-0.89) except for *Maesopsis eminii* that showed a moderate correlation (R=0.40-0.69). This is in good agreement with Mugasha et al., (2013) who reported a variation relationship between tree height and diameter due to the high variability of tree species.

In terms of ABGB and D_{30}, the correlation was moderate to very strong for different species. For basal area and ABGB, the correlation was strong to very strong. The studied young AF trees showed statistically significant ($P<0.05$) differences in terms of WSD and D_{30}, which affected their biomass (ABG&BGB). The regression results showed that correlation was very strong for all species except for *Croton megalocarpus*, which showed a moderate correlation due to differences in terms of WSD (ranging from 567 kg/m^3 to 211 kg/m^3) and D_{30} where the highest WSD value was observed on *Croton megalocarpus* with 567 kg/m^3 compared to the other AF tree species. For mature AF tree species, the correlation varied from strong to very strong for various tree species as far as DBH and H are concerned where many of the species showed a strong correlation except for *Polyscias fulva* that showed a very strong correlation (R=0.90-1.00).

For DBH and ABGB, many species showed a very strong correlation except for *Grevillea robusta*. For H and ABGB, the correlation was strong for *Grevillea robusta* while it was very strong for other species. The correlation between G and ABGB was very strong for all species. This concurs well with Otukei & Emanuel, (2015) who reported a higher correlation between DBH and AGB than the correlation between tree height and AGB, and DBH was found to contribute more than tree height.

For Ruhande species, the correlation between tree DBH and H for C*edrela serrata* and *Maesopsis eminii* was very strong while it was moderate for both *Grevillea robusta* and *Polyscias fulva*. This result corroborates with Buba, (2013) and Kumar & Bhatt, (2016) who reported the stronger correlations between DBH and H for tree species under their studies. The correlation between DBH and ABGB was very strong for all AF trees. This lends support to Chambers et al., (2001) who reported a similar relationship between various tree species as far as DBH and biomass are concerned for mature trees. As reported by Slik et al., (2013), the evidence we found points to the correlations between DBH and AGB which was strongly positive which is an indicator of the contribution of big diameter to the biomass allocation in wood. For H and ABGB, the correlation was very strong for *Maesopsis eminii* while it was strong for *Cedrela serrata* and *Grevillea robusta*. On the other hand, the correlation was moderate for *Polyscias fulva*. Finally, the G and ABGB were very strongly correlated for all species. This last fits well with Slik et al., (2010) and Wassihun et al., (2019) who reported a significant positive correlation between AGB and basal area (G) for big tree species.

By comparing the correlation coefficients for various tree variables for young and mature AF tree species, the results showed a high correlation variability for young species than mature or old species recorded in different environmental conditions of Cyamudongo and Ruhande. The young tree species have a high growth rate, which affects rapidly some of the tree variables such as tree height and diameter, and these variables together with the WSD affect the overall tree biomass.

For mature trees, the change in terms of height and diameter is not remarkable. These were found to be the main reasons for the low variability of correlation coefficients for mature tree species compared to young tree species. This substantiates previous findings in the literature where the wood biomass was found to expressively increased with the size in terms of diameter and age of trees (Healey et al., 2016). This is in complete agreement with Slik et al., (2013) who reported a very strong correlation between AGB and wood density for big trees and the wood density contributes more to the AGB. Otukei & Emanuel, (2015) stated that the variability of wood biomass is due to both tree diameter and height, and diameter contributes more than tree height. These results share a number of similarities with Hanson et al., (2001)' findings where they reported that the young tree species develop faster and are easily affected by management practices and ecological conditions compared to the mature tree species. These results are also consistent with Marziliano et al., (2019) who stated that the relationship between tree height and diameter varies with age. The old and mature trees may contain a big amount of biomass and C stock but their C sequestration rate may be low due to their slow growth rate in comparison to young tree species (Ligot et al., 2018).

CHAPTER THREE

AGROFORESTRY FOR SOIL EROSION CONTROL, SOIL PROPERTIES IMPROVEMENT, AND NUTRIENTS AVAILABILITY

3.1 Introduction

There is a vast amount of literature on land degradation and its management strategies in different parts of the world, especially in Rwanda. The poor agriculture practices on high mountains together with substantial precipitations have caused serious land degradation in Rwanda (Karamage et al., 2016). It has been reported that above 500 million tonnes of soil are lost every year in Rwanda as a result of the poor land use management activities where most of the soil is lost due to poor agricultural activities (Karamage et al., 2016). Soil erosion has been indicated as being the major cause of the soil poor fertility resulting from inappropriate management practices and the people are aware of various control measures (Nahayo et al., 2016).

More recent evidence from Nambajimana et al., (2020) shows that the erosion problem is observed in various corners of the country but seriously in Rusizi and Nyamasheke with more than 80 t ha^{-1} y^{-1} while the records in Nyaruguru, Nyamagabe, and Rutsiro show that more than 60 t ha^{-1} are lost annually. Physical, chemical, and biological processes can cause land degradation. Physical degradation is the deterioration and breakdown of soil structure leading to crusting, compaction, accelerated water runoff, and soil erosion. Significant chemical processes include acidification, leaching, salinization, decrease in cation retention capacity, and fertility depletion whereas biological processes include a reduction in total and biomass carbon, and a decline in terrestrial biodiversity (Nair et al., 2011). Nambajimana et al., (2020) recommended that reforestation schemes targeting fast-growing multipurpose tree species be therefore recommended as an important feature for erosion control, particularly in the highland areas with a mean slope exceeding 30%.

The soil erosion can be effectively controlled by AF (Lundgren and Nair, 1985). It has been reported by Shi, (2018) that AF has multiple roles including climate change mitigation through C sequestration, improvement of soil productivity, and biological resources enhancement among others. AF through both the service and production functions of trees, therefore, has the potential to alleviate or, in some instances, remove completely many of the principal constraints recognized by farmers which result directly from land degradation (Cooper et al., 1996). According to König, (1992), the sole integration of trees is far from being the solution to erosion problems on farmland. There should be supplementary erosion control measures such as hedgerows or grass strips planted along contour lines to make the system sustainable in terms of soil conservation. König further concluded that AF systems are not only useful for onsite soil protection but can also slow down the rapid deforestation and thus contributing to soil erosion control even beyond the cultivated land.

Soil fertility is defined 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 land such as hydrology, landforms, vegetation, and fauna". The appropriate land use management is recommended to address the soil productivity-related issues (Udawatta et al., 2019). Agevi et al., (2017) reported various factors contributing to the variability of organic carbon in the soil, including the depth of soil, AF practices applied, and ecological conditions of the area. AF has been proved to enrich the soil in terms of organic C better than mono-cropping systems. AF practices enhance soil fertility, soil biological function, and can uptake the leached nutrients from the soil deep layers (Dollinger and Jose, 2018).

This study assessed the impacts of sustainable AF land use on the soil 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 (Soil C, pH, Nitrogen, Phosphorus, Cation Exchange Capacity) and physical parameters {bulk density (BD) and texture} 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 physical and chemical properties in different soil depths, land uses, altitude ranges, and throughout the time in the study area. The following research questions were formulated in line with the aforementioned objective:

- What is the status of the soil's chemical and physical properties in the study area?
- What are the factors, which affect the soil pH of the study area?
- How different soil chemical elements change with time in the study area?
- How various chemical and physical soil properties vary with soil depths, land uses, and altitude ranges?
- How selected soil chemical elements are they correlated with the soil pH?

3.2 Materials and Methods

3.2.1 Description of the study area

The Rusizi has been selected to assess the impact of sustainable AF on the soil's chemical and physical properties and their changes with time. Rusizi District is located in the South-East of Rwanda and is one of seven districts of the Western Province. The area of the Rusizi district is 959 km^2. 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-}. Most of the people (>89%) own < 2 ha which compromises the development of agriculture productivity. Several crops are mixed and grown on one ha (GOR-KD, 2019).

The Rusizi district has both public and private forests which occupy a total area of 357 km^2. The private forest occupies the largest percentage with 64 % corresponding to 35% of the total district area and it is followed by state forest with 35% and the least is 1% of total district area. High demographic pressure combined with a large number of people who rely on agriculture and intensive precipitation, resulted in land degradation, especially on high slopes. Therefore, land protection measures are needed for sustainable district land management (District, 2013).

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).

3.2.2 Sampling design

The sampling technique used in this study is a clear advance on current methods. The most commonly used sampling design for many field studies is systematic sampling using either transects or grids (Scrimgeour, 2008).

In this study, four transects were consistently 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 3).

By using the transect method, it was possible to approach the same landscape by randomly selecting four representative transects wherein observations were made at fixed intervals along the transects. The transect method provides a statistically sound system for soil sampling and observation and the soil information collected by the transect method is distributed on a landscape without bias, and therefore a better estimate is determined of the real range of the variation of the soil (Wang, 1982).

The initial point of the transect was randomly selected. The four km transect corresponds to the radius 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 m^2 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 28). The distance between and within transects was respected. The sampling plots were established on 3 transects constituting the undisturbed forest by human activity. The first transect (on the right of Figure 28) was not considered as it is made by both natural trees and exotics of pins which were established by human intervention (i.e the soil was disturbed and altered in its natural composition). 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.

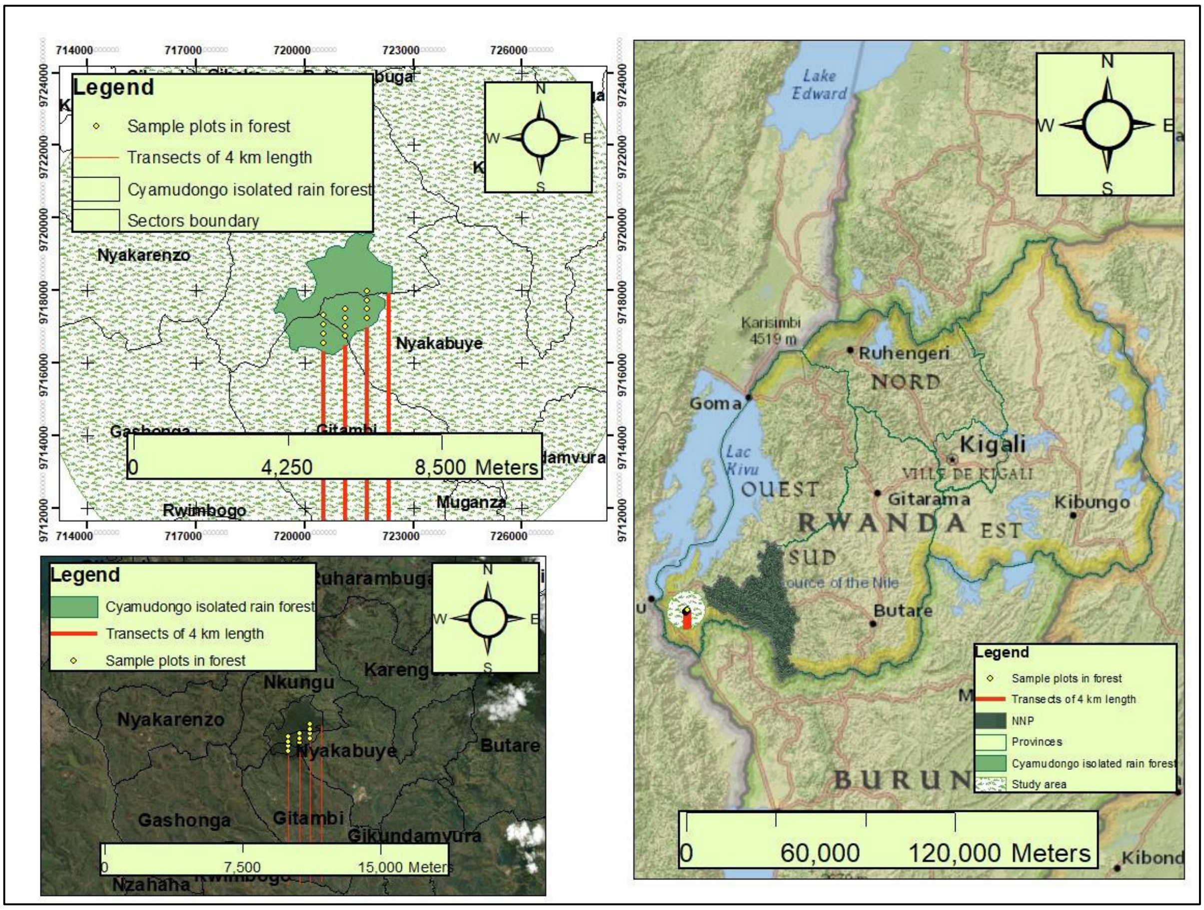


Figure 28. Soil sampling design both in and outside Cyamudongo fragmented rain forest

3.2.3. 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.

Having the soil core ring of a well-defined volume (98.125 cm^3) enabled me to gather the uninterrupted samples of the soil to be used for testing the selected physical variables of the soil. The soil sampling inside the forest was performed to get the samples which helped to control and detect the long-term change of soil in terms of both physical and chemical variables. 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. Table 12 shows the number of collected soil samples in different soil depths every year for both inside and outside Cyamudongo fragmented rainforest

Table 12. Number of collected soil samples every year per site

Collected samples		Sampling sites			
		Outside Cyamudongo isolated rain forest		Inside Cyamudongo isolated rain forest	
Soil depth (Cm)		2018	2019	2018	2020
Disturbed	0-20	61	61	0	12
	20-40	61	61	0	12
	40-60	61	61	0	12
Total		183	183	0	36
Undisturbed	0-20	0	61	0	12
Grand total		183	244	0	48
		475			

3.2.4 Description of laboratory work

I used innovative techniques based on the recommendations of the specific laboratory of soil science of the University of Koblenz-Landau. The soil samples were sieved and dried through the oven at about 105°C for the selected chemical variables as aimed in this study. Both soil and wood nutrients were analyzed using applications of automated procedures as required by the International Organization for Standardization (ISO) and Deutsches Institut für Normung (DIN).

To analyze soil physical properties, the specific laboratory methods of soil and plant analysis described by Okalebo et al., 2020 were used whereas the hydrometer method was used to perform the soil particle size analysis as described by Bouyoucos, 1962 and Beretta et al., 2014.

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 and Mulvaney, (1982).

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

$$[C: N = (Soil\ organic\ C: Total\ N)]$$ *Equation 8*

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. The extracted phosphorus was measured calorimetrically based on the reaction with ammonium molybdate and the development of the 'Molybdenum Blue' color. The absorbance of the compound was measured at 882 nm in a spectrophotometer and directly proportional to the amount of phosphorus extracted from the soil (Okalebo et al., 2002).

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. After color development, absorbance was read at 419 nm. The exchangeable bases were analyzed following Chapman, (1965). The CEC was determined using a similar procedure as for exchangeable bases.

Furthermore, the soil physical analyses were performed according to Okalebo et al., (2002). Besides, the soil particle size analysis was performed using the hydrometer method as described by Bouyoucos, 1962 and Beretta et al., 2014. The soil particle content (clay, silt, and sand) was determined in compliance with Anderson and Ingram, (1993). The BD of the soil was determined following Anderson and Ingram, (1993). Eventually, the determination of potassium, calcium, and magnesium in plant tissues was determined according to Anderson and Ingram, 1993 as further described by Okalebo et al., 2002. The Plant available P was analyzed by the Olsen method (Horta, 2007). The C content and N were determined following the same procedure applied to soil C and N determination. The soil dry weight per hectare was calculated using the formula as stated by Hairiah et al.,(2010).

$$Soil\ weight\ per\ ha\ (in\ t) = 100 * 100 * BD * D$$ *Equation 9*

Where BD is a soil bulk density and D is the soil sampling depth. Then, the soil weight was multiplied by the soil C concentration to get the estimated value of soil C stock per ha expressed in tonnes in the study area. C stock for each layer was calculated by multiplying the C stock obtained by Equation 11 by the total area after its multiplication with averaged C content in that particular layer. This formula provides the same result as Oladele & Braimoh, (2011) who suggested the following formula:

$$Soil\ C\ stock\ (Kg/ha) = BD * D * C * 10{,}000 \qquad \textit{Equation 10}$$

Where C is the averaged C concentration in each layer or targeted soil sampling depth. Afterward, C stock contained in 0-60 cm depth, was obtained by considering the C content of all soil layers. The protocol of the laboratory for different chemical elements analyses was used as shown in the following table.

Table 13. Materials and procedure for analysis of various chemical elements

Chemical element	Equipment	Chemicals	Procedure
pH	PE- Bottle 200 ml, Volumetric Pipette 12 ml, and pH Electrode	$CaCl_2$ = 0.01 mol	• Weight in 2 g of soil in 15 ml PE-bottle • Add 5 ml calcium chloride solution • Close the lid and shake for about a minute • Wait 30 min and shake again • Wait another 60 min and shake afterward • Wait 30 more min and measure the pH value with the pH electrode
N	PE-Bottle 200 ml, Funnel, Folded Filter (Satorius 3HW) and Volumetric Pipette 100 ml	$CaCl_2$ = 0.01 25 mol	• Weigh-in 10 g of fresh and sieved soil • Add 40 mol calcium chloride solution • Put on the shaker for about 1 h • Filter it into another 50 PE-bottle • Throw away the filter keep the filtrate
Inorganic Carbon (C)	Watch glass, Planetary Ball Mill, and Glass Pipette	Hydrochloride acid, б(HCl) = 10%	• Mill a part of the dried soil in the planetary ball mill and put a small amount of milled soil on the watch glass • Add some drops of Hydrochloride acid • See and hear if gas is generated
C: N ratio	Balance (0.000001 g = 0.01 mg		• Only for samples that are positive for inorganic carbon, put a small part of sample material into a

	accuracy), Muffle Furnace, Tin boats, and Porcelain Crucible		porcelain crucible and heat it to 550 °C in the muffle furnace for at least 3h • Weigh in approximately 20 mg of milled soil into a tin boat. Do 2 repetitions per sample. If necessary, do the same for the heated samples.
Available P	PE-Bottle 100 ml + 250 ml, Aluminum Foil, Funnel, Folded Filter (Sartorius 3HW) and Volumetric Pipette	CAL (Calcium acetate, Calcium lactate) solution: Dissolve 15,4 g/l Calcium acetate in enough, warm demineralized water. Add 7.9 g Calcium acetate. Let cool to room temperature and add 17.9 ml Acetic acid. Adjust to pH 4.1 using Acetic acid or NaOH solution. Active charcoal.	• Weigh-in 5g of sieved, dry soil in a 250 ml PE Bottle and add 0.5 g of active charcoal • Cover the bottles with aluminum foil • Add 100 ml of CAL solution • Put on the shaker for 90 min • Filtrate and keep the filtrate • Throw away the filter

3.2.5 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, and altitude ranges were considered as independent variables and various variables (chemical and physical) of soil as dependent factors. The analysis was done twice according to the number of times the data were collected to determine the change of various soil parameters in time.

3.3 Results

3.3.1 Comparison of soil chemical variables in different soil sampling depths

The soil chemical variables were studied in various soil depths (0-20 cm, 20-40 cm, and 40-60 cm). After testing the normality of data, we realized that they are not normally distributed which supports the use of the non-parametric test. A Kruskal-Wallis rank-sum test was used to detect whether differences in soil attributes (pH, C, N, C: N ratio, OM, ECEC, PO_4^{3-}, NH_4^+, NO_3^- and NO_2^-) between sampling depths are significant.

Figure 29 shows clear trends of selected chemical variables in different soil depths. 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. In general, the average value of each of the soil chemical properties decreased as the soil depth increased in the 0–60 cm soil profile with 20 cm intervals. The averaged pH values are 4.51, 4.41, and 4.34 in 0-20 cm, 20-40 cm, and 40-60 cm respectively. The averaged pH value in all soil depths is 4.42.

There was a significant difference in pH value among soil layers (p-value = 0.022). Hence, there was a need to check in which layers exactly it was significant. Consequently, the Wilcoxon rank-sum test with continuity correction was used to determine the significant level for different soil depths. As result, with pairwise comparison, the surface (0-20 cm) & medium (20-40 cm) layers and medium and dipper layers (40-60 cm) did not show any significant difference with p-value = 0.087 and p-value = 0.37 respectively. The result was only significant between surface and dipper layers with a p-value = 0.0054.

The result showed a significant difference (p-value = 0.0013) between soil depths as far as a soil C content is concerned. Specifically, the surface & medium, surface & dipper; and medium & dipper layers showed a significant difference with a p-value = 0.024, P-value= 0.0001 and P-value = 0.085 respectively. The averaged C percentage values are 2.73, 2.35, and 2.13 in 0-20 cm, 20-40 cm, and 40-60 cm respectively. The mean C value in all soil depth is 2.4. The tests highlighted that the C mean value decreased with the increase of soil depth.

The averaged estimated C stock in all soil depths was 16848 t ha^{-1}. The recorded C stocks in various sampling depths were 19164.6 t ha^{-1}, 16497 t $ha^{-1,}$ and 14952.6 t ha^{-1} in 0-20 cm, 20-40 cm, and 40-60 cm respectively. The C stock was declined with the increase of soil depth. The high amount of C stock on the surface layer is due to the high concentration of organic C, which resulted from the decomposition of accumulated organic materials at the surface.

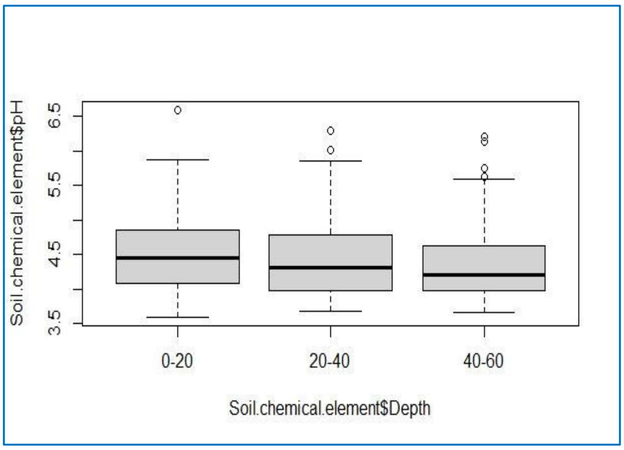
For soil N, there was a significant difference in N among soil layers (p-value = 2.159e-05). Similarly, to the C, all layers between them showed a significant difference among them with p-value = 0.007239, p-value = 0.03416 and p-value = 5.968e-06 for the surface & medium, surface & dipper; and medium & dipper layers respectively. No significant difference (p-value = 0.0013) observed between soil depths. 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.

The result showed a significant difference (p-value = 0.00043) between soil depths in terms of OM. By comparing the level of OM in various soil depths, the finding showed a significant difference between surface and middle (p-value = 0.02443) and dipper layers (p-value = 0.0001005) whereas no significant difference (p-value = 0.08564) was detected between the middle and dipper layers. The averaged OM (%) mean values are 4.7, 4.1, and 3.7 in 0-20 cm, 20-40 cm, and 40-60 cm respectively. The averaged OM mean value in all soil depths is 4.1.

Both NO_3^-+NO_2^- and NH_4^+ show a significant difference for sampling depths with p-value = 5.165e-08 and p-value = 0.0083 respectively. A significant level was also identified for NO_3^- +NO_2^- in different soil depths. The test revealed a significant difference between the surface and medium layers; surface and dipper layers; and medium and dipper layers with p-value = 0.001295, p-value = 2.323e-08 and p-value = 0.002975 respectively. Nevertheless, the result was significant between the surface and dipper layers with p-value = 0.002489 for NH_4^+ while the surface and medium layers; whereas the result was not significant between medium and dipper layers with p-value = 0.0758 and p-value = 0.1549 respectively. The NO_3^- + NO_2^- and NH_4^+ mean values decreased with the increase of soil depth. The averaged NO_3^- + NO_2^- mean values (mg/L) are 19.06, 13.20, and 10.65 in 0-20 cm, 20-40 cm, and 40-60 cm respectively. The averaged NO_3^- + NO_2^- mean value in all soil depths is 14.29. The averaged NH_4^+ mean values are 2.85, 1.85, and 1.73 in 0-20 cm, 20-40 cm, and 40-60 cm respectively. The averaged NH_4^+ mean value in all soil depths is 2.14.

Furthermore, the PO_4^{3-} was tested in various soil depths and its averaged mean value was 2.1 mg/L. The results showed a significant difference with a p-value = 0.0006554. Besides, with pairwise comparison, there was a significant difference between the surface layer and middle layers with p-value = 0.009303, surface and dipper layers with p-value = 0.0002431 whereas comparison between middle and dipper layers did not show any significant difference with p-value = 0.1866. It was found that the PO_4^{3-} averaged values decreased with the rise of soil depth with 2.8 mg/L, 1.8 mg/L, and 1.7 mg/L in (0-20 cm), middle (20-40 cm), and dipper (40-60 cm) respectively.

Ultimately, the soil CEC was tested and compared in different sampling depths. As result, there was a significant difference with p-value = 0.00232 and 49.2 mg/L averaged mean value. Besides, with pairwise comparison, there was a significant difference between surface and middle layers with p-value = 0.03992, surface and dipper layers with p-value = 0.0005666 while the middle and dipper layers did not show any significant difference with p-value = 0.151. The CEC average values also reduced with the increase of soil depths with 56.1 mg/L, 48.3 mg/L, and 43.4 mg/L in the surface, middle, and dipper layers respectively. Moreover, the Al^{3+} did not show any significant difference (p-value = 0.08403) in different soil depths.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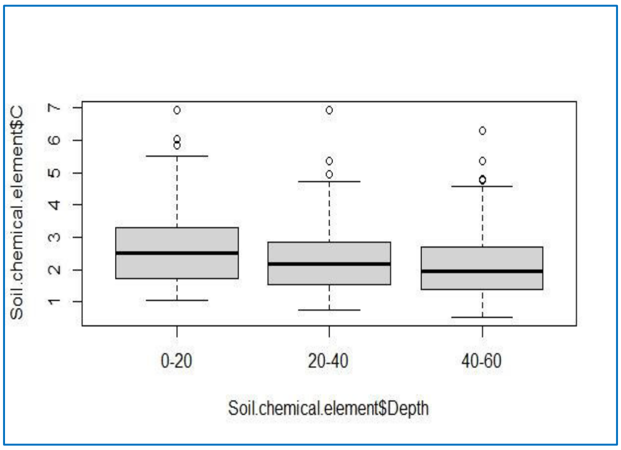
40-60
Soil.chemical.element$Depth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40-60
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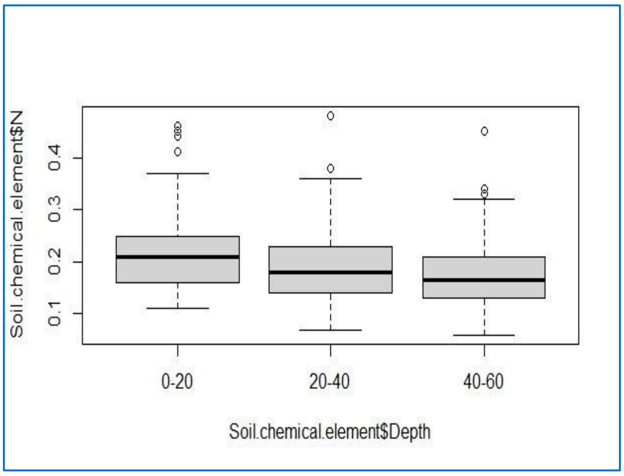
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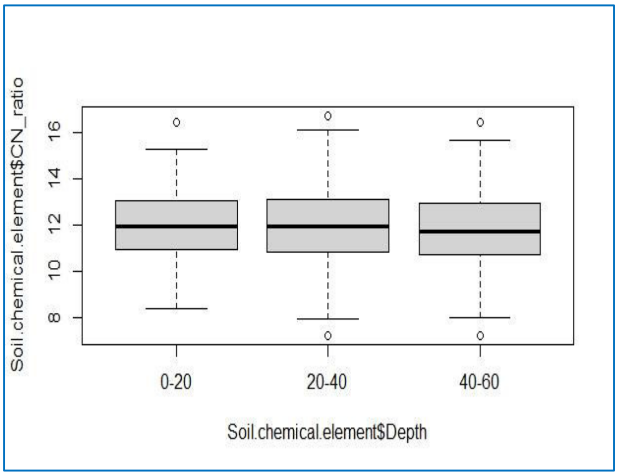
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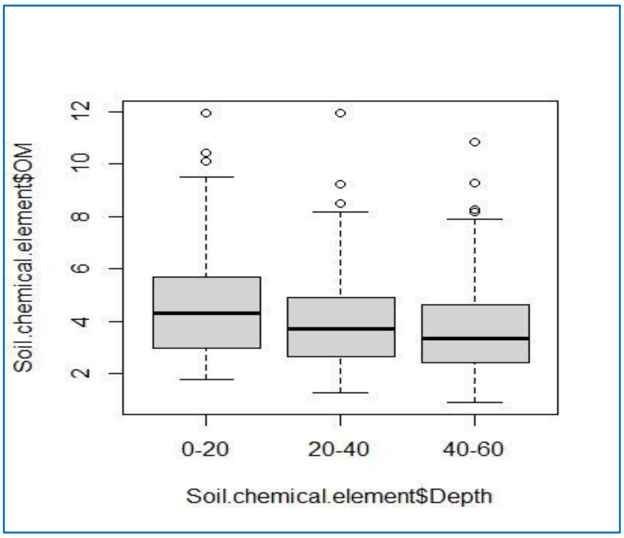
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20-40
40-60
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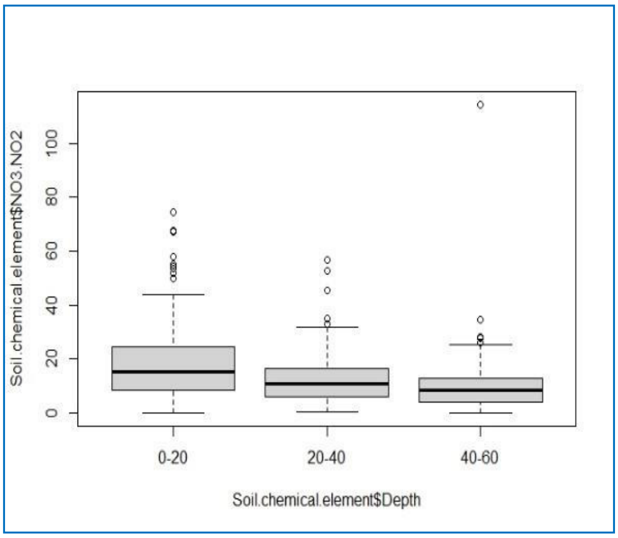
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40-60
Soil.chemical.element$Depth

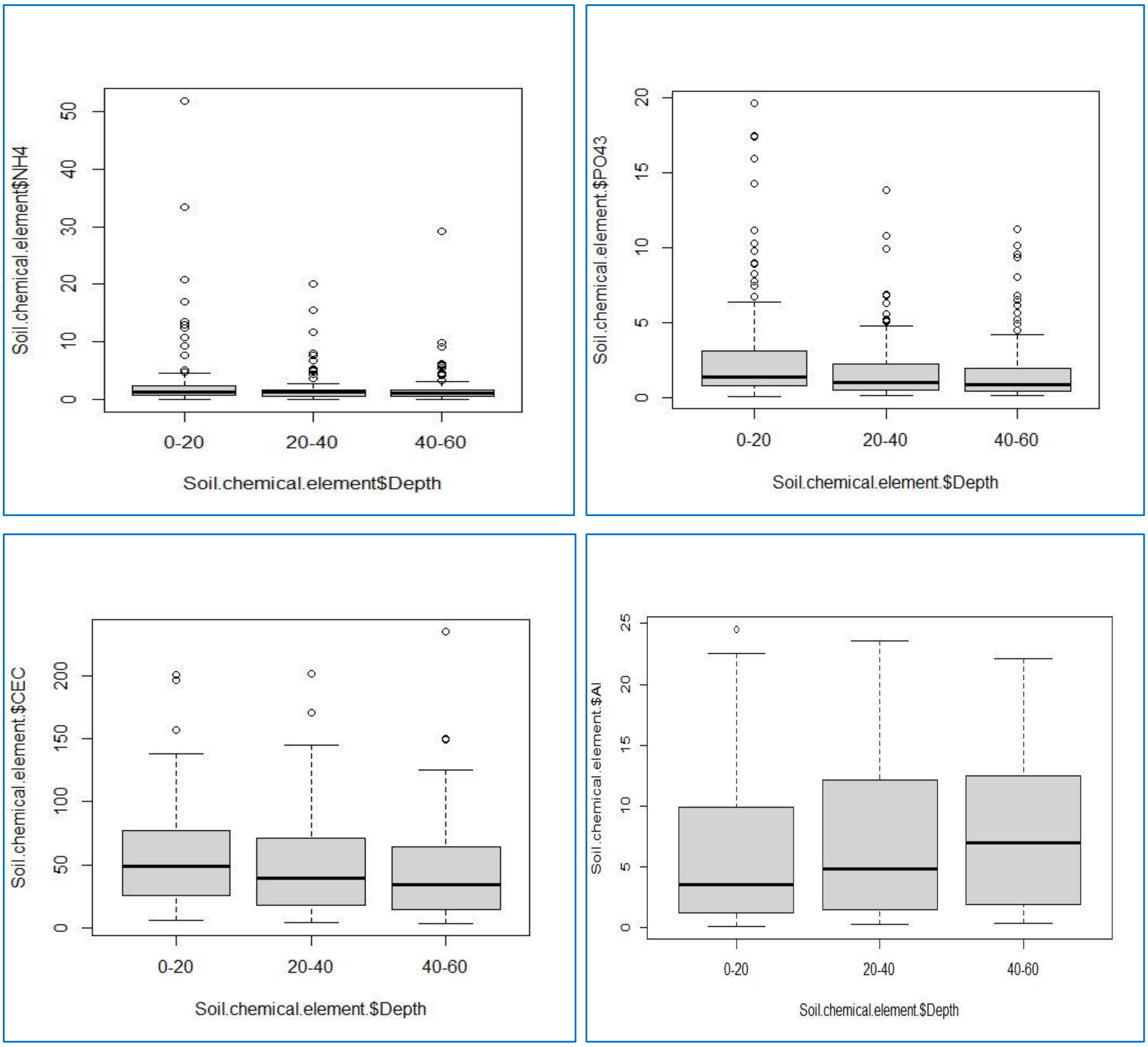


Figure 29. Assessment of soil pH, C, N, C: N ratio, OM, NO_3^- + NO_2^-, NH4+ and PO_4^{3-}, CEC, and Al $^{3+}$ in different soil depths

Table 14. Averaged values, SD, Min, and Max of different chemical elements in various soil depths

Depth		pH	N[%]	C[%]	C: N ratio	OM[%]	Na[mg/L]	K[mg/L]	Ca[mg/L]	Mg[mg/L]	CEC[mg/L]	PO43[mg/L]	NH4[mg/L]	NO3-.NO2- [mg/L]
0-20 cm	Mean	4.51	0.23	2.73	11.8	4.7	1.30	7.6	38.65	8.49	56.1	2.78	2.85	19.06
	SD	0.57	0.09	1.20	1.6	2.1	3.78	9.6	26.43	8.05	37.5	3.61	5.91	14.93
	Min	3.26	0.11	1.04	8.1	1.8	0.04	1.7	0.64	1.03	5.7	0.10	0.01	0.00
	Max	6.59	0.70	7.29	16.5	12.6	44.12	108.8	146.40	50.74	200.5	19.63	51.85	75.00
20-40 cm	Mean	4.41	0.20	2.35	11.8	4.1	0.94	5.8	33.90	7.63	48.3	1.84	1.85	13.20
	SD	0.56	0.07	1.08	1.8	1.9	0.57	5.9	27.45	8.08	36.4	2.10	2.71	9.84
	Min	3.20	0.07	0.73	7.2	1.3	0.11	1.1	0.01	0.63	4.6	0.19	0.02	0.00
	Max	6.30	0.48	6.93	16.7	11.9	3.83	61.6	149.90	51.28	201.0	13.85	20.03	57.00
40-60 cm	Mean	4.34	0.18	2.13	11.6	3.7	0.99	5.2	30.24	6.92	43.4	1.71	1.73	10.65
	SD	0.54	0.07	1.08	1.8	1.9	0.69	5.7	27.29	8.16	36.4	2.13	2.96	11.58
	Min	3.66	0.05	0.35	7.2	0.6	0.14	1.0	0.02	0.58	3.8	0.13	0.01	0.00
	Max	6.21	0.51	6.30	16.4	10.9	5.63	58.1	177.90	50.07	234.8	11.26	29.21	114.00
Total	Mean	4.42	0.20	2.40	11.7	4.1	1.08	6.2	34.26	7.68	49.2	2.11	2.14	14.29

	SD	0.56	0.08	1.14	1.7	2.0	2.24	7.3	27.21	8.10	37.1	2.75	4.15	12.76
	Min	3.20	0.05	0.35	7.2	0.6	0.04	1.0	0.01	0.58	3.8	0.10	0.01	0.00
	Max	6.59	0.70	7.29	16.7	12.6	44.12	108.8	177.90	51.28	234.8	19.63	51.85	114.00

3.3.2 Comparison of soil chemical variables in different altitude ranges

Figure 30 shows the averaged means of pH in different altitude ranges obtained from the analysis using the boxplot. The tests showed a significant difference (p-value < 2.2e-16) between altitude ranges in terms of pH. In all altitude levels, the soil pH was ranging from strongly acidic (pH <5.1) to slightly acidic (pH= 6.1–6.5) according to the soil test interpretation guide of Horneck, et al., 2011. The reported lowest pH value was 3.6 corresponding to the highest altitude range (>2000-2100 m asl) whereas the highest pH value was 6.5 which was recorded in the low altitude range (>1300-1400 m asl). The pH mean values are presented in Table 15. The results confirmed that the average pH was reduced with altitude augmentation. Hence, the strong acidic values were recorded between >1800-2100 m asl whereas it was moderately to slightly acidic in low altitude ranges especially ranging from >1200 to 1800 m asl.

Hereafter, with a pairwise comparison between >1300-1400 and all other altitude ranges and tests showed a significant difference (p-value <0.05) for >1400 to 2100 m asl. Contrarily, there was no significant difference between >1300-1400 and >1200-1300 with p-value = 0.2821.

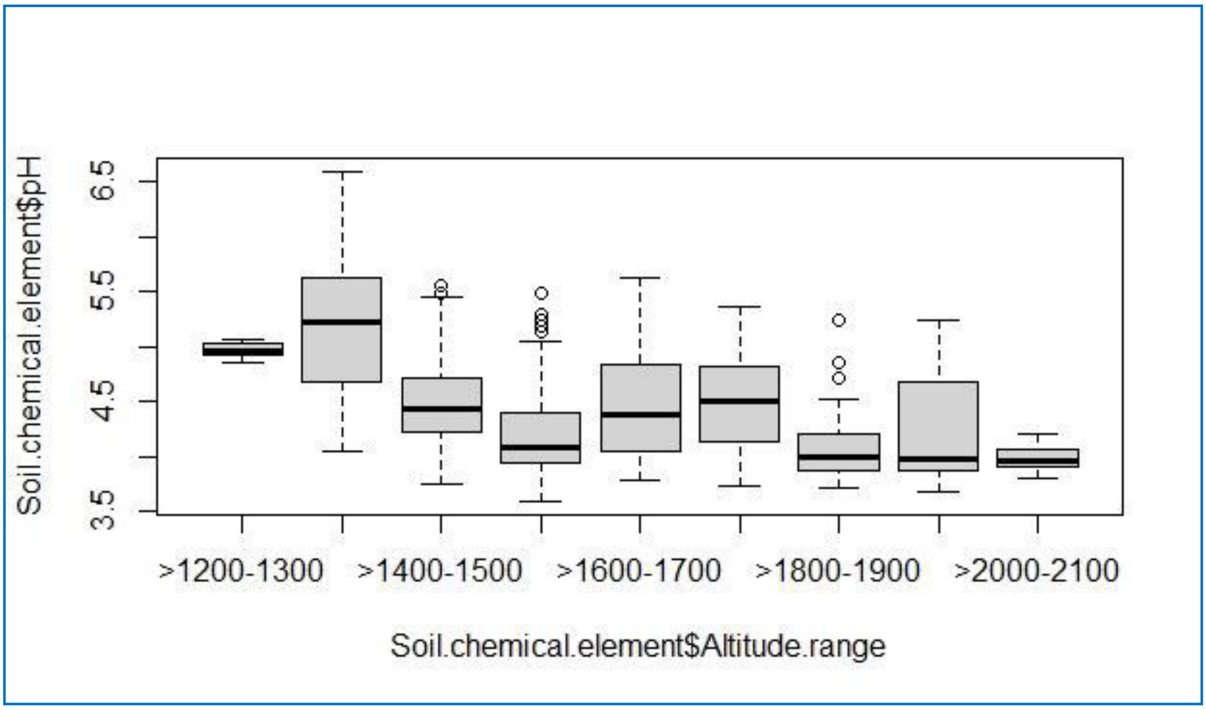


Figure 30. Comparison of soil pH in various altitude ranges

Figure 31 shows the averaged means of C in different altitude ranges obtained from the analysis using the boxplot. There was a significant difference in C for different altitudes ranges with a p-value < 2.2e-16. The C value increased with the increase of altitude and consequently the soil C 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). The minimum C was 0.35 percent and was found in the lowest altitude range (>1200-1300 m asl) whereas the maximum C value (7.29 percent) was found in the high altitude range (>1900-2000 m asl). The C mean values are presented in Table 15

Furthermore, the significance level between the altitude range with highest C value and other altitude ranges by the use of Wilcoxon rank-sum test with continuity correction was determined. Hereafter, with pairwise comparison, the result showed a significant difference only between >1900-2000 m asl and different altitude ranges such as > 1200- 1300, >1300-1400, >1400-1500, >1600-1700 and >1800-1900 with p-value = 0.00035, p-value = 4.73e-09, p-value = 2.126e-08, p-value = 2.126e-08, p-value = 0.0085 and p-value = 0.0054 respectively. There were no significant difference between >1900-2000 and >1500-1600, >1700-1800 and >2000-2100 with p-value = 0.39, p-value = 0.94 and p-value = 0.2618 respectively.

The soil C stock was estimated in different altitude ranges and the highest value was found in the high altitude levels (> 1900-2000 m asl) that correspond to the NF with 21832.2 t ha-1 followed by 20849.4 t ha-1 (>1700-1800 m asl), 19234.8 t ha-1 (>1500-1600 m asl), 18883.8 t ha-1 (>2000-2100 m asl), 17128.8 t ha-1 (>1800-1900 m asl), 16567.2 t ha-1(>1600-1700 m asl), 11372.4 t ha1-(>1400-1500 m asl), 10459.8 t ha-1 (1300-1400 m asl) and 9547.2 t ha-1(>1200-1300 m asl). The tests highlighted that the smallest quantity of soil C stock was recorded in the lowest altitude range of the study area.

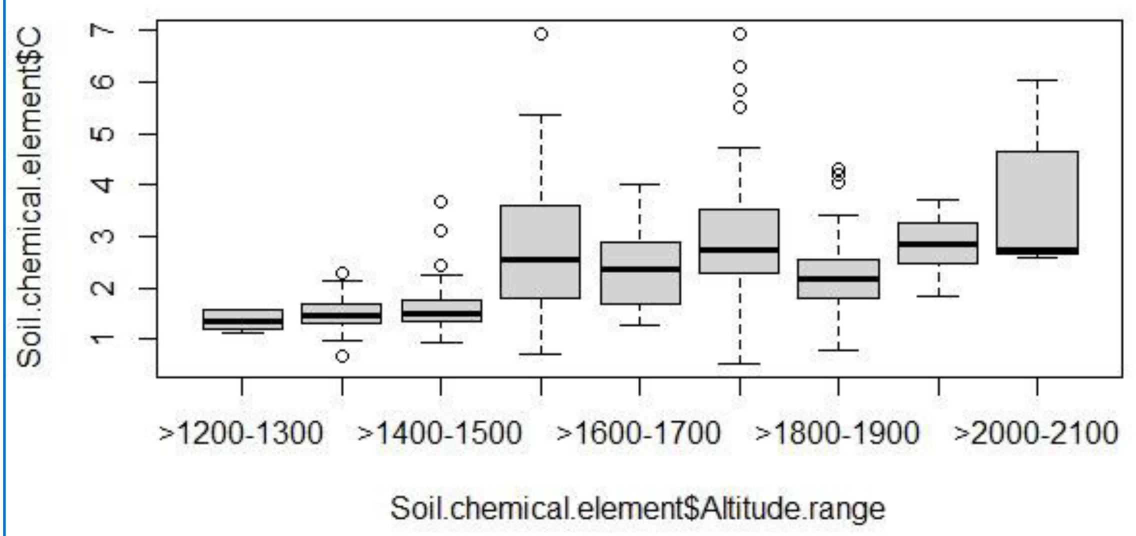


Figure 31. Comparison of soil C in various altitude ranges

Figure 32 shows the averaged means of N in different altitude ranges obtained from the analysis using the boxplot. There was a significant difference (p-value < 2.2e-16) between altitudes ranges with regard to N. The N value increased with the increase of altitude and consequently the soil N lowest mean value (0.06 percent) was found in the lowest altitude range (>1200-1300 m asl) whereas the highest N value (0.48 percent) was found in the highest altitude range (>2000 – 2100 m asl). The N mean values are presented in Table 15.

Additionally, the significance level between the altitude range with highest N value and other altitude ranges by the use of Wilcoxon rank-sum test with continuity correction was determined. Henceforward, with pairwise comparison, there was a significant difference between >2000-2100 m asl and different altitude ranges including >1200-1300, >1300-1400, >1400-1500, >1500-1600, >1600-1700 and >1700-1800 with p-value = 0.00083, p-value = 1.532e-07, p-value = 4.308e-07, p-value = 0.0054, p-value = 6.387e-05, p-value = 0.0001539 respectively whereas there was no significant difference between >2000-2100 m asl and >1700-1800, >1900-2000, with p-value = 0.06262 and p-value = 0.0975 respectively.

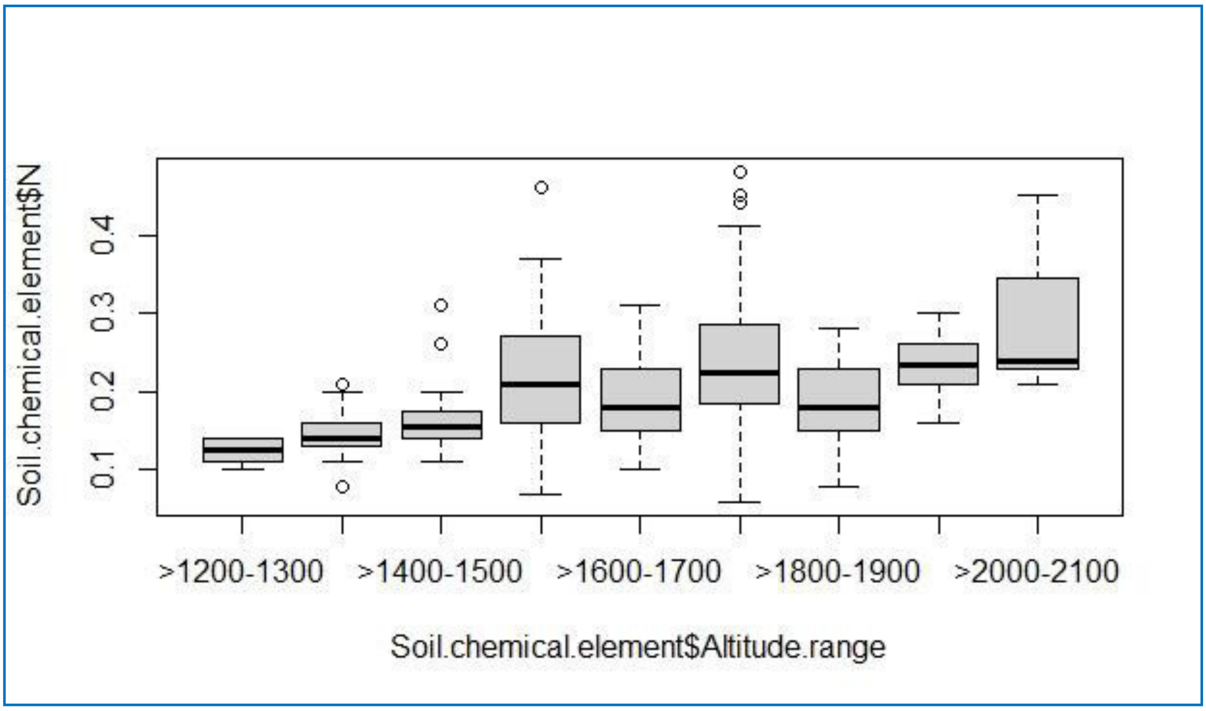


Figure 32. Comparison of soil N in various altitude ranges

Figure 33 shows the averaged means of C: N ratio in different altitude ranges obtained from the analysis using the boxplot. The test showed a significant difference for different altitudes ranges with a p-value < 2.2e-16 in terms of in C: N ratio. There was no trend to increase or decrease with altitude. The highest C: N ratio value (16.74) was obtained from the >1500-1600 while the lowest value (7.21) was found in the > 1400-1500 m asl. The C: N ratio mean values are presented in Table 15.

Moreover, the significance level between the altitudes range with highest C: N ratio value and other altitude ranges by the use of Wilcoxon rank-sum test with continuity correction was determined. Hereafter, with pairwise comparison, there was a significant difference between >1500-1600 m asl and different altitude ranges including >1200-1300, >1300-1400, >1400-1500 with p-value = 0.03082, p-value = 4.718e-12 and p-value = 7.206e-13 respectively. Whereas for many altitude ranges, there was no significant difference between >1500-1600 m asl and >1600-1700, >1700-1800, >1800-1900, >1900-2000 and >2000-2100 with p-value = 0.8318, p-value = 0.85, p-value = 0.1347, p-value = 0.2783 and p-value = 0.8174 respectively.

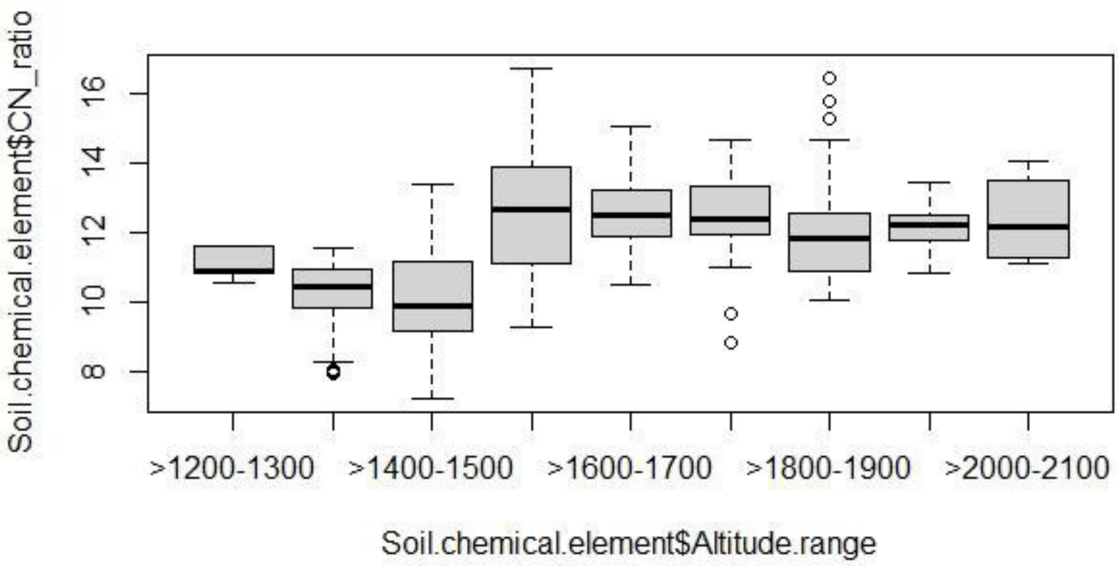


Figure 33. Comparison of soil C: N ratio in various altitude ranges

Figure 34 shows the averaged means of OM in different altitude ranges obtained from the analysis using the boxplot. There was a significant difference in OM for different altitudes ranges with a p-value < 2.2e-16. The average mean value of OM had a trend to significantly increase with the increase of altitude. Despite the fact that there was some inconsistency, the low average values of soil OM were observed in low altitude levels (>1200-1500 masl) whereas the high average values were recorded in high altitude ranges (>1500 – 2100 m asl). The minimum OM was 0.62 and was found in the lowest altitude range (>1200-1300 m asl) whereas the maximum OM value (12.54) was found in the high altitude range (>1900-2000 m asl). The OM mean values are presented in Table 15.

Furthermore, the significance level between the altitude range with the highest OM value and other altitude ranges by the use of the Wilcoxon rank-sum test with continuity correction was determined. Hereafter, with pairwise comparison, there was a significant difference between >1900-2000 m asl and different altitude ranges taken in meters above sea level. These include > 1200- 1300, >1300-1400, >1400-1500, >1600-1700 and >1800-1900 with p-value = 0.00035, p-value = 4.73e-09, p-value = 2.126e-08, p-value = 2.126e-08, p-value = 0.0085 and p-value = 0.0054 respectively whereas there was no significant difference between >1900-2000 and >1500-1600, >1700-1800 and >2000-2100 with p-value = 0.39, p-value = 0.94 and p-value = 0.2618 respectively.

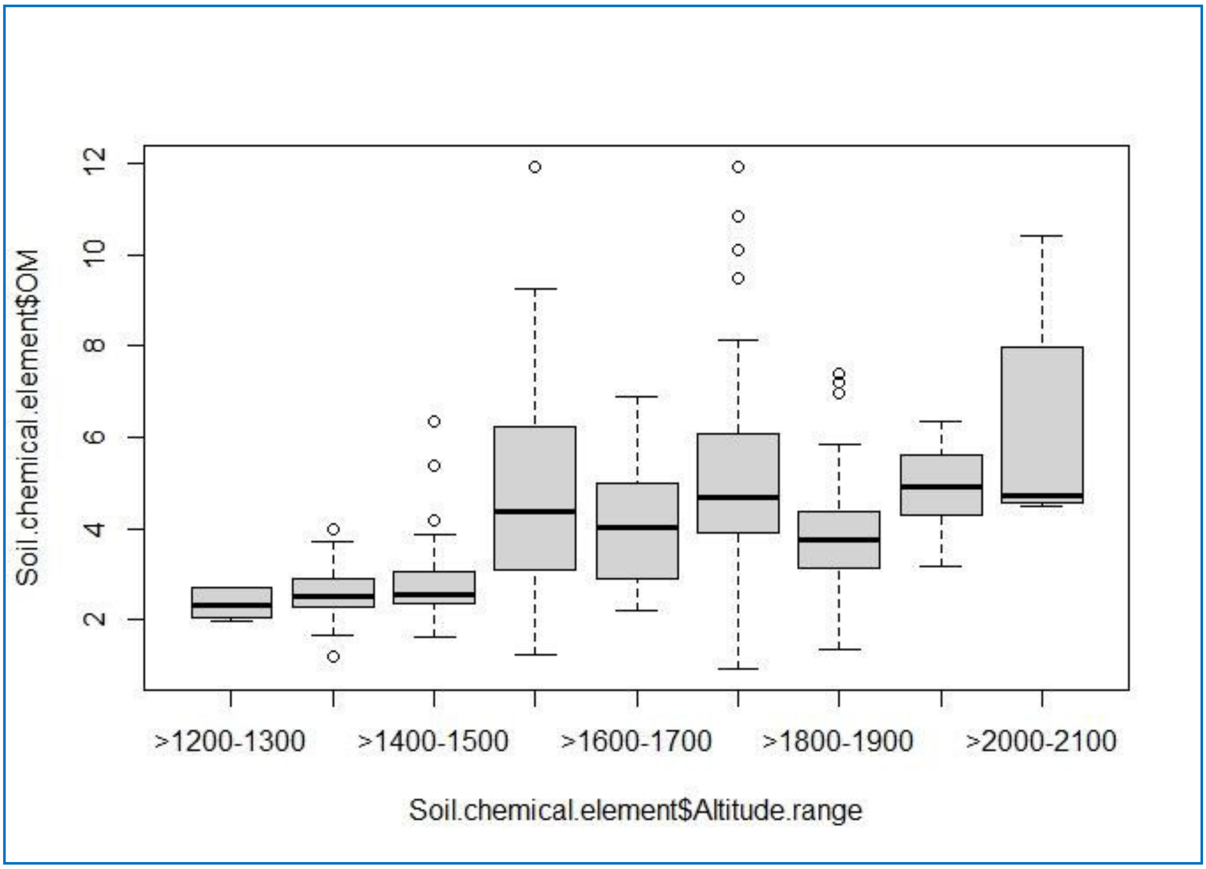


Figure 34. Soil OM in various altitude ranges

Figure 35 shows the averaged means of $NO_3^- + NO_2^-$ in different altitude ranges obtained from the analysis using the boxplot. There was a significant difference in $NO_3^- + NO_2^-$ for different altitudes ranges with p-value = 1.675e-05. The altitude range of high averaged value (>1700-1800) was compared with other altitude ranges. The result was significant only between >1700-1800 and >1300-1400, >1400-1500 with p-value = 0.03436 and p-value = 0.0006236 respectively. The analysis did not confirm any significant difference between >1700-1800 and >1200-1300, >1500-1600, >1600-1700, >1800-1900, >1900-2000 and >2000-2100 (p-value >0.05). The $NO_3^- + NO_2^-$ mean values are presented in Table 15.

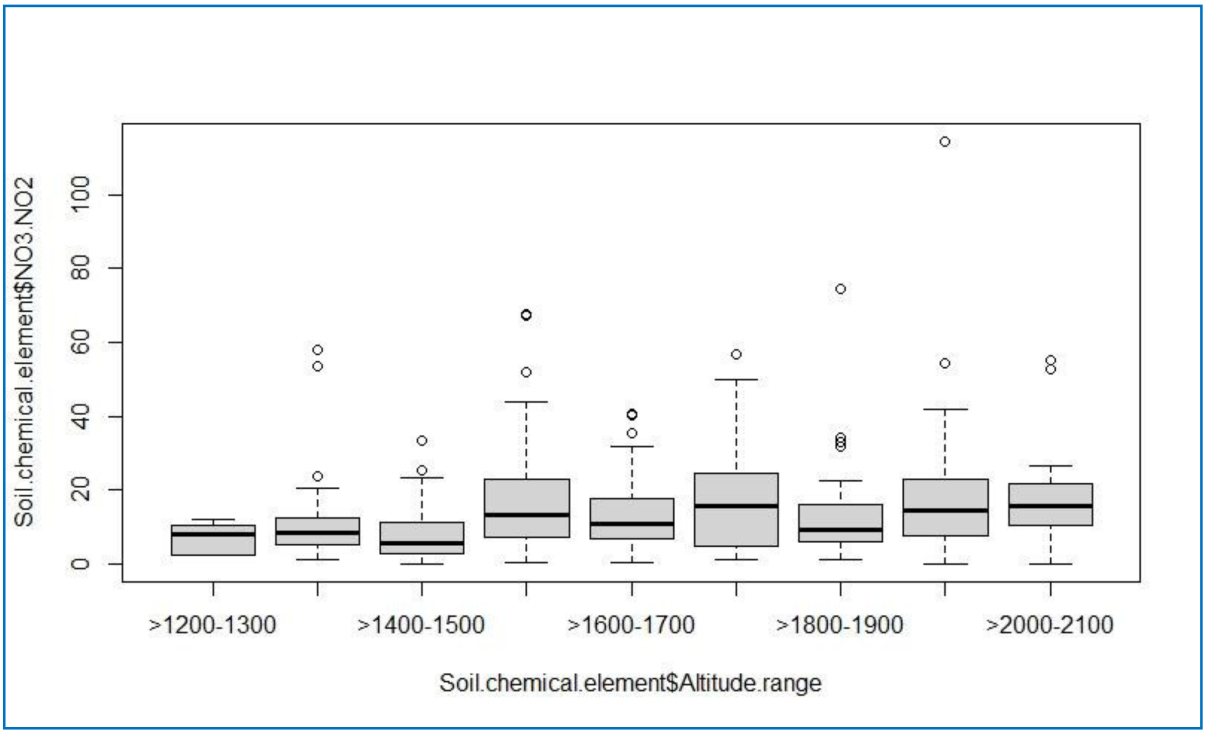


Figure 35. Soil $NO_3^-+NO_2^-$ in various altitude ranges

Figure 36 shows the averaged means of NH_4^+ in different altitude ranges obtained from the analysis using the boxplot. There was a significant difference in NH_4^+ for different altitudes ranges with a p-value < 2.2e-16. The pairwise comparison between altitude range with the highest mean value (>2000-2100) which correspond to the highest altitude range and other altitude ranges, the result did show a significant difference between them from the lowest altitude range (>1200-1300) up to >1900-2000 which is the range closer to the highest range with $P<0.05$. However, there was no significant difference between >2000-2100 and >1900-2000 with p-value = 0.07753. The mean value of NH_4^+ increased significantly and consistently with the increase of altitude. The NH_4^+ mean values are presented in Table 15.

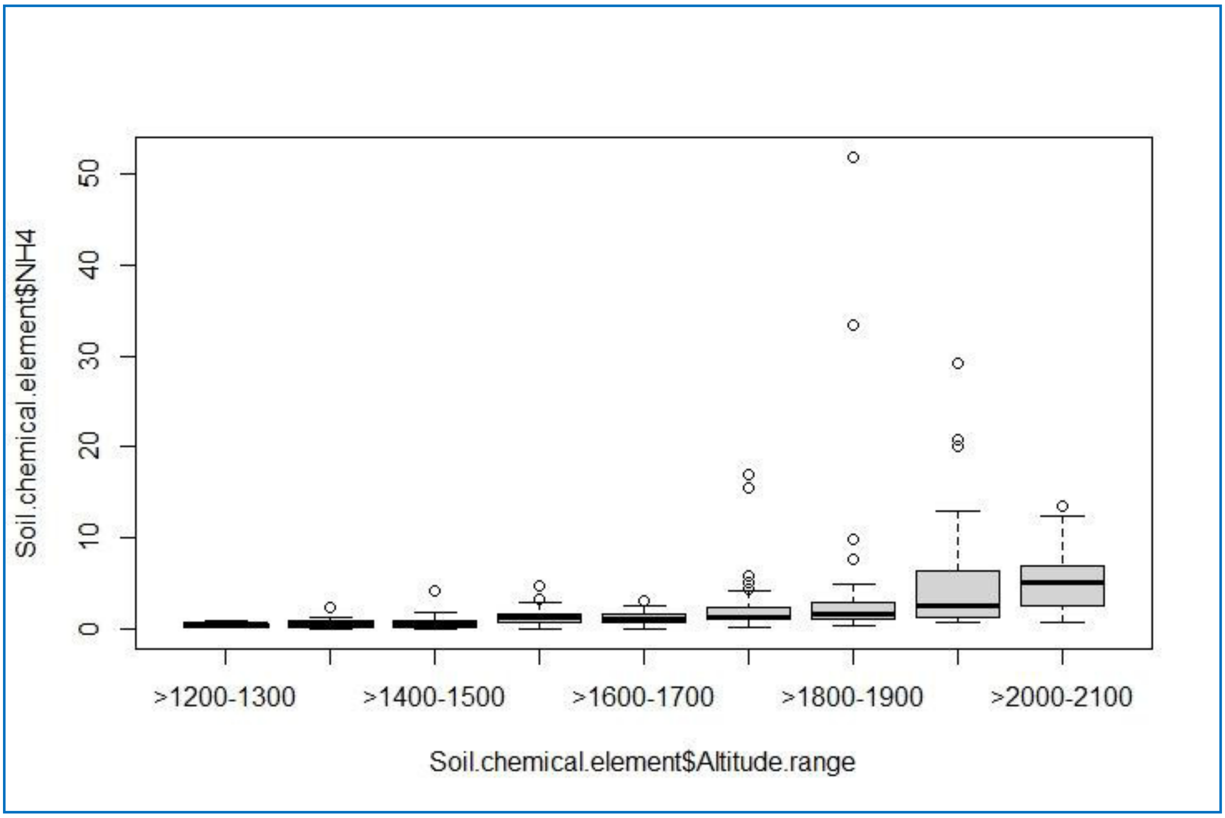


Figure 36. Soil NH_4^+ in various altitude ranges

Figure 37 illustrates the PO_4^{3-} mean values change with altitudinal gradient. The results showed a significant difference (p-value = 3.905e-06) between different altitude ranges and the averaged mean value was 2.1 mg/L. The soil PO_4^{3-} level has neither decreased nor increased with the altitudinal gradient. The highest mean value was recorded in >1600-1700 m asl with 2.9 mg/L. The PO_4^{3-} mean values are presented in Table 15.

With pairwise comparison, was performed to test the significance level between the altitude ranges with the highest mean value and other altitude ranges. The difference between >1600-1700 m and >1200-1300 m, >1300-1400 m, >1400-1500 m, >1500-1600 m, >1700-1800 m, >1800-1900 m, >1900-2000 m, >2000-2100 m was significant with p-value = 0.007126, p-value = 0.0004434, p-value = 7.335e-06, p-value = 2.312e-06, p-value = 2.312e-06, p-value = 1.774e-05, p-value = 8.98e-05 and p-value = 0.02223 respectively.

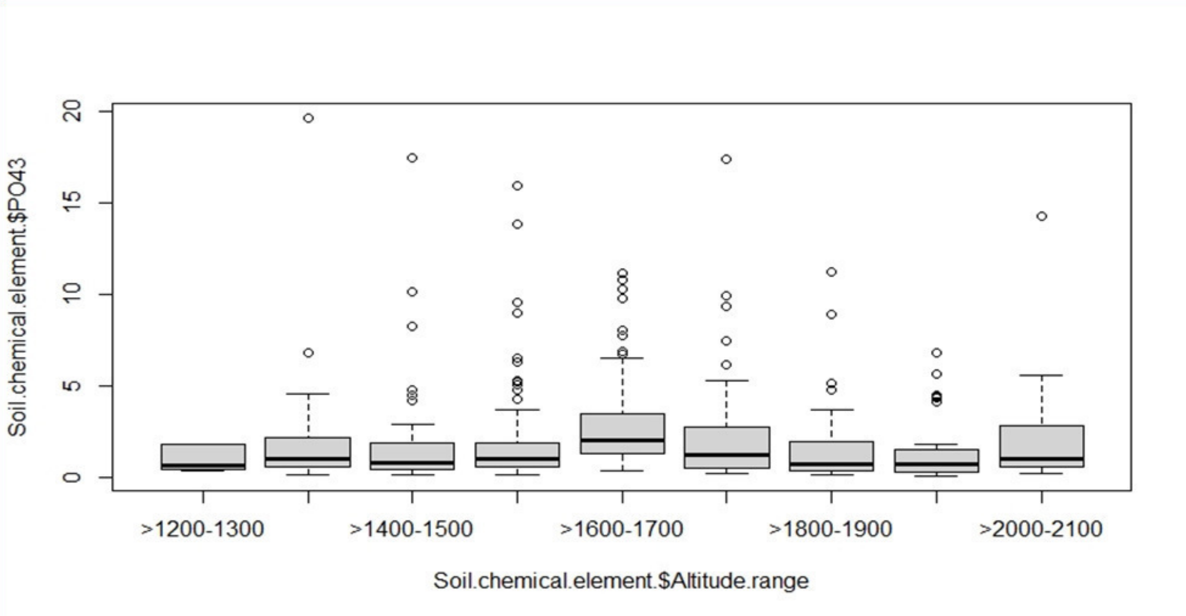


Figure 37. Soil PO_4^- in various altitude ranges

The figure 38 shows the CEC mean value in different ranges of altitude and the test showed a significant difference (p-value < 2.2e-16) and the averaged mean value was 49.24 mg/L. The altitude range of >1300-1400 m asl showed a peak mean value. Generally, the CEC mean value decreased with the increase of altitude even though it was not consistent. The CEC mean values are presented in Table 15.

With pairwise comparison, the altitude with highest mean value was compared with other altitude ranges. As the results, there was a significant difference between it with >1600-1700 m with p-value = 0.0004434. Contrary, there was no significant difference between >1300-1400 m and >1200-1300 m, >1400-1500 m, >1500-1600 m, >1700-1800 m, >1800-1900 m, >1900-2000 m, >2000-2100 m with p-value = 0.2821, p-value = 0.2475, p-value = 0.8725, p-value = 0.645, p-value = 0.1399, p-value = 0.1234 and p-value = 0.6625 respectively.

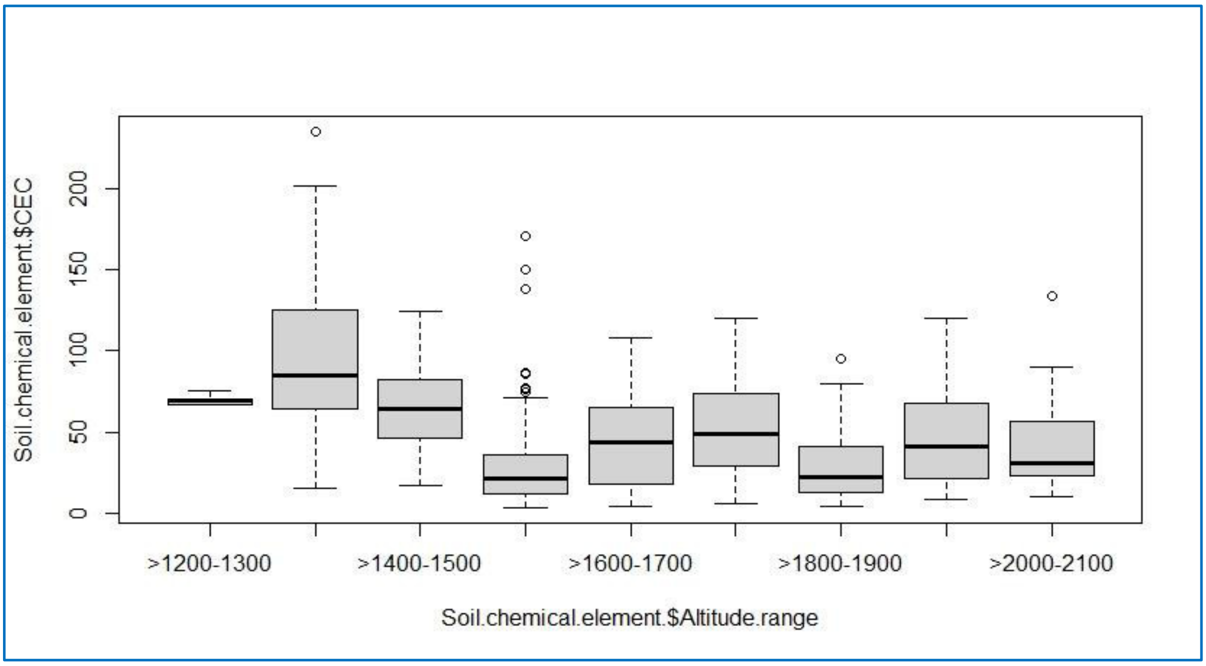


Figure 38. Soil CEC in various altitude ranges

Figure 39 shows the soil Al^{3+} in various altitude ranges. There was a significant difference with a p-value < 2.2e-16 and the averaged mean value was 6.94 mg/L. The highest and lowest averaged values were detected in >1900-2000 m asl with 11.14 mg/L >1200-1300 m asl with 0.72 mg/ L respectively. The Al^{3+} increased with the increase of altitude. With pairwise comparison, the altitude range with the highest mean value was compared with other altitude ranges and the findings show a significant difference between it with >1200-1300, >1300-1400, >1400-1500, >1600-1700, >1700-1800, >2000-2100 with p-value <0.05. Contrarily, there was no significant between the aforementioned highest mean value altitude with >1500-1600, >1900-2000, >1800-1900 and >2000-2100 with p-value >0.05. The Al^{3+} mean values are presented in Table 15.

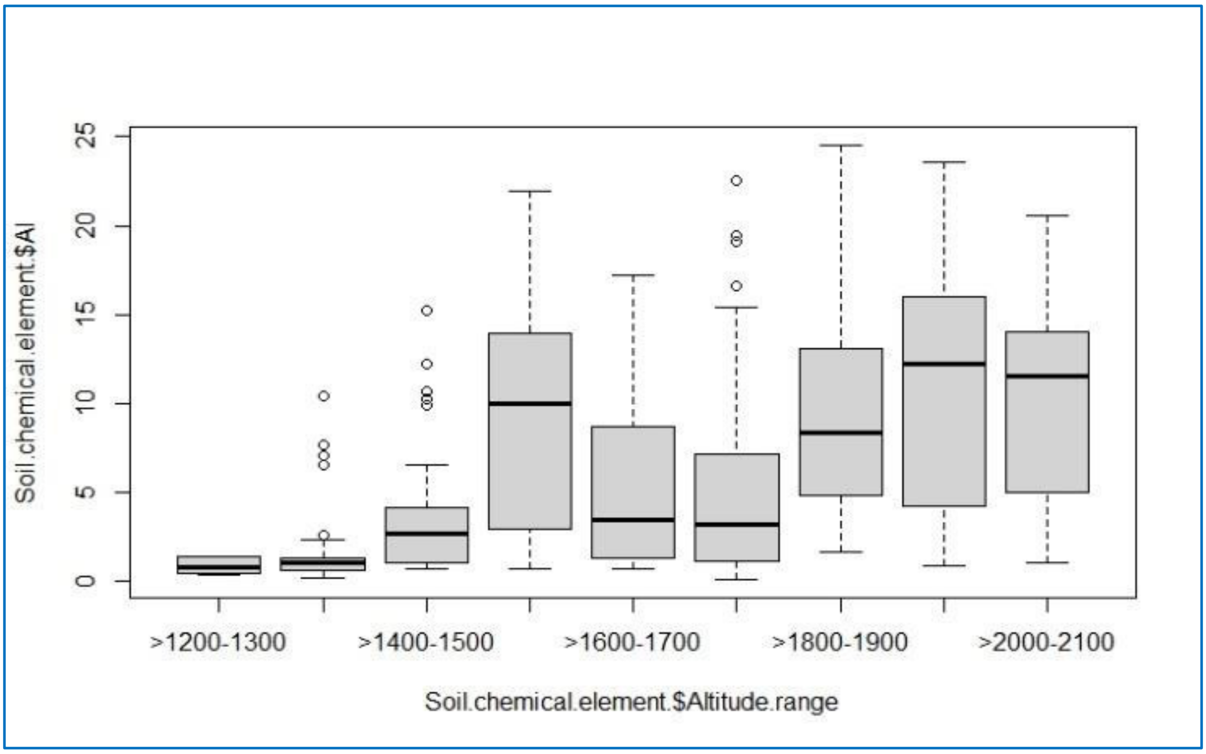


Figure 39. Soil Al^{3+} in various altitude ranges

Table 15. Averaged values, SD, Min, and Max of different chemical elements in various altitude ranges

Altitude in m asl		pH	N[%]	C[%]	C: N ratio	OM[%]	Na[mg/L]	K[mg/L]	Ca[mg/L]	Mg[mg/L]	Al[mg/L]	CEC[mg/L]	PO43[mg/L]	NH4[mg/L]	NO3 -NO2- [mg/L]
>1200-1300 m	Mean	4.97	0.12	1.36	11.1	2.34	0.71	4.97	52.65	11.51	1.32	69.83	0.97	0.54	7.36
	SD	0.08	0.02	0.19	0.4	0.33	0.33	0.73	3.81	0.73	0.19	3.10	0.68	0.31	4.38
	Min	4.86	0.10	1.13	10.5	1.95	0.33	3.85	49.27	10.72	1.10	67.27	0.40	0.20	2.00
	Max	5.07	0.14	1.58	11.6	2.72	1.09	5.68	58.54	12.73	1.43	75.36	1.84	1.01	12.00
>1300-1400 m	Mean	5.18	0.15	1.49	10.2	2.56	2.03	13.86	57.48	20.17	1.65	93.54	1.92	0.80	11.22
	SD	0.64	0.03	0.33	1.0	0.58	6.68	19.19	35.06	13.05	1.33	52.19	3.09	1.20	11.23
	Min	4.05	0.08	0.68	7.9	1.16	0.29	2.96	9.90	1.49	1.08	15.44	0.13	0.04	1.00
	Max	6.59	0.21	2.30	11.5	3.96	44.12	108.80	177.90	51.28	7.04	234.77	19.63	8.00	58.00
>1400-1500 m	Mean	4.52	0.16	1.62	10.1	2.79	0.99	7.37	47.24	11.29	2.78	66.88	1.86	0.75	8.29
	SD	0.42	0.03	0.50	1.3	0.86	0.52	3.60	22.11	7.41	2.23	28.72	3.03	0.71	7.50
	Min	3.76	0.11	0.93	7.2	1.60	0.32	2.53	4.89	2.29	1.10	16.96	0.14	0.01	0.00
	Max	5.56	0.31	3.67	13.4	6.33	2.95	18.85	103.70	32.24	10.66	124.38	17.46	4.22	33.00

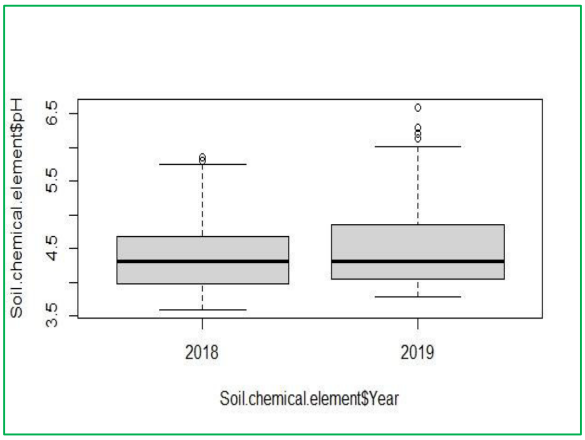
>1500-1600 m	Mean	4.21	0.21	2.74	12.6	4.73	0.69	4.70	20.88	4.75	8.53	31.02	1.88	1.34	16.09
	SD	0.40	0.07	1.20	1.8	2.06	0.40	3.09	21.25	6.43	6.00	29.72	2.53	0.80	12.65
	Min	3.60	0.07	0.72	9.3	1.23	0.04	1.05	0.01	0.67	1.06	3.77	0.16	0.05	0.00
	Max	5.49	0.46	6.93	16.7	11.94	2.15	16.69	124.20	30.02	21.99	170.77	15.93	4.85	68.00
>1600-1700 m	Mean	4.50	0.19	2.36	12.5	4.06	0.94	4.83	34.60	5.53	6.02	45.89	2.97	1.19	13.18
	SD	0.52	0.05	0.69	1.0	1.19	0.57	2.64	25.26	4.15	4.77	29.56	2.61	0.66	8.82
	Min	3.78	0.10	1.27	10.5	2.18	0.29	1.71	0.27	0.90	1.10	4.48	0.41	0.01	1.00
	Max	5.63	0.31	4.01	15.1	6.92	3.37	17.53	85.39	20.85	15.06	108.42	11.14	3.16	41.00
>1700-1800 m	Mean	4.45	0.24	2.97	12.2	5.11	1.13	5.20	41.28	6.18	3.01	53.79	2.47	2.47	17.21
	SD	0.46	0.10	1.48	1.5	2.55	0.69	4.20	27.75	4.07	2.46	29.81	3.34	3.39	13.54
	Min	3.30	0.05	0.35	7.7	0.60	0.19	1.51	1.70	1.25	1.10	6.31	0.20	0.24	1.00
	Max	5.36	0.48	6.93	14.7	11.94	4.47	16.85	108.90	18.51	7.18	120.44	17.39	16.94	57.00
>1800-1900	Mean	4.09	0.21	2.44	11.8	4.21	1.08	4.58	20.29	4.29	8.94	30.24	1.69	4.50	13.66
	SD	0.36	0.11	1.22	1.6	2.10	0.63	2.70	17.04	3.48	4.48	21.97	2.44	9.83	13.42
	Min	3.46	0.08	0.77	10.0	1.32	0.26	1.03	1.46	0.58	3.67	4.64	0.15	0.46	1.00
	Max	5.24	0.70	7.29	16.4	12.57	2.68	12.30	70.20	12.40	15.43	95.00	11.26	51.85	75.00

>1900-2000 m	Mean	4.18	0.27	3.11	11.7	5.37	1.26	6.63	31.84	6.99	10.52	46.71	1.58	5.64	19.71
	SD	0.55	0.09	1.06	1.1	1.82	0.67	2.85	24.92	5.16	6.28	31.51	1.95	7.31	22.73
	Min	3.20	0.16	1.83	9.3	3.15	0.35	2.72	2.28	1.72	2.67	9.09	0.10	0.76	0.00
	Max	5.43	0.51	6.15	13.4	10.60	2.92	14.18	90.82	17.56	17.87	119.77	6.80	29.21	114.00
>2000-2100 m	Mean	4.14	0.24	2.69	10.9	4.63	1.44	5.29	30.83	5.33	12.24	42.89	2.21	5.49	18.47
	SD	0.46	0.09	1.33	1.8	2.29	1.10	2.43	23.25	4.12	2.20	28.40	2.85	3.52	12.37
	Min	3.55	0.10	0.96	7.4	1.66	0.35	1.18	3.85	1.39	9.45	10.75	0.24	0.86	2.00
	Max	5.36	0.45	6.06	14.1	10.44	5.63	11.63	109.80	16.99	14.09	133.84	14.30	13.54	55.00
Total	Mean	4.42	0.20	2.40	11.7	4.15	1.08	6.21	34.26	7.68	6.08	49.24	2.11	2.14	14.29
	SD	0.56	0.08	1.14	1.7	1.97	2.24	7.34	27.21	8.10	5.35	37.09	2.75	4.15	12.76
	Min	3.20	0.05	0.35	7.2	0.60	0.04	1.03	0.01	0.58	1.06	3.77	0.10	0.01	0.00
	Max	6.59	0.70	7.29	16.7	12.57	44.12	108.80	177.90	51.28	21.99	234.77	19.63	51.85	114.00

3.3.3 Comparison of soil chemical variables in different years

The soil chemical variables were compared in different years (2018 and 2019) to determine their changes with time. No significant difference highlighted between different years with regard to pH, C, N and C: N ratio, OM, NO_3^- + NO_2^- and Al^{3+} with p-value = 0.4057, p-value = 0.2309, p-value = 0.1058, p-value = 0.513, p-value = 0.2309, p-value = 0.08668 and p-value = 0.1248 respectively. However, these tests revealed significant statistical differences as far as NH_4^+, PO_4^{3-} and CEC are concerned with p-value = 4.531e-08, p-value = 2.122e-05 and p-value = 4.452e-07 respectively. The mean values of different chemical elements for different times of data collection are presented in Table 16.

The pH, C, N, OM, and NO_3^-+NO_2^- mean values increased with time even though they were not statistically significant (Table 16). The soil C stock was higher in 2019 compared to 2018 with 17409.6 t ha^{-1} and 16216.2 t ha^{-1} respectively, which corresponds to the increase of 1193.4 t ha^{-1} in one year.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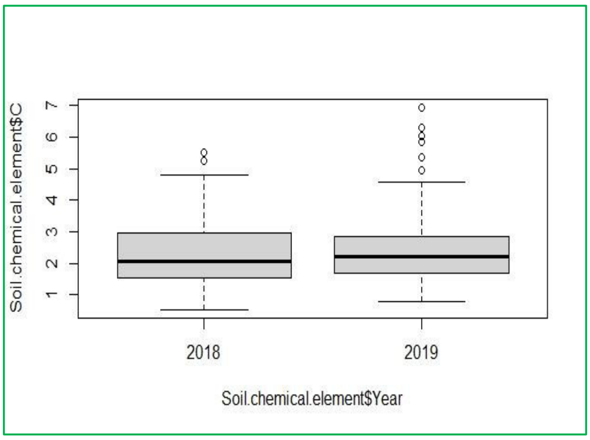
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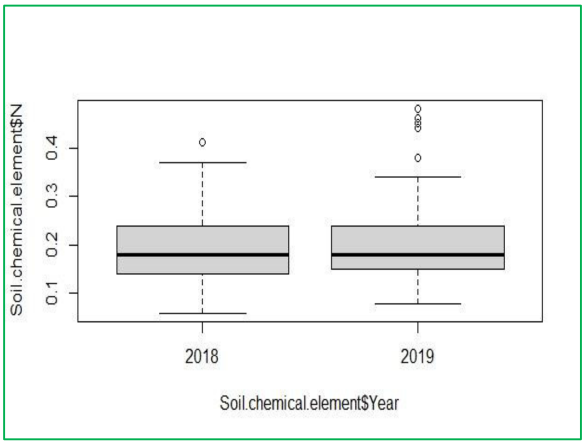
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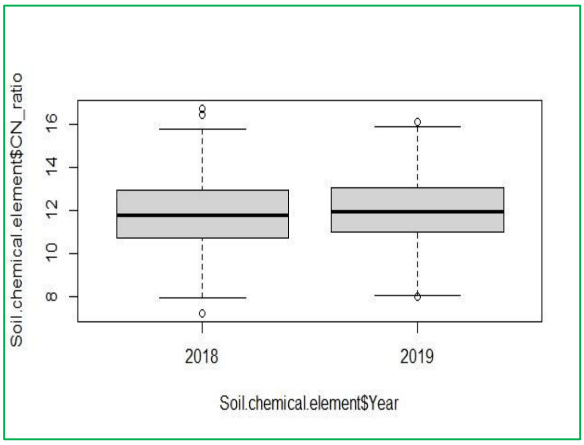
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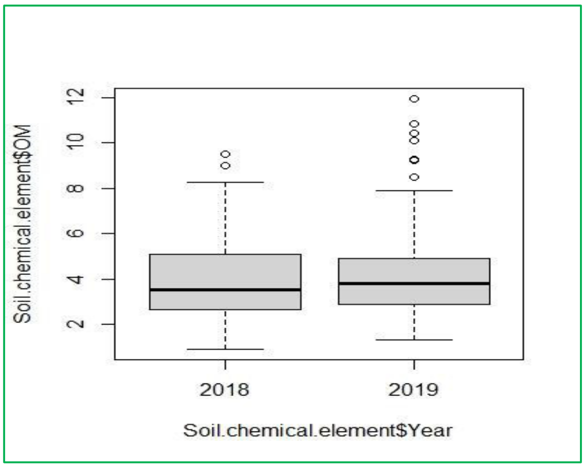
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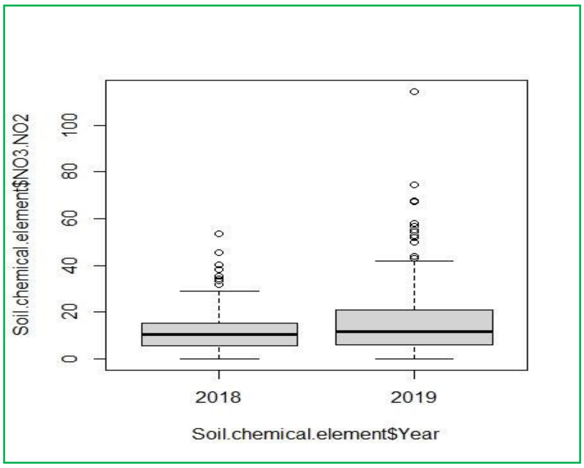
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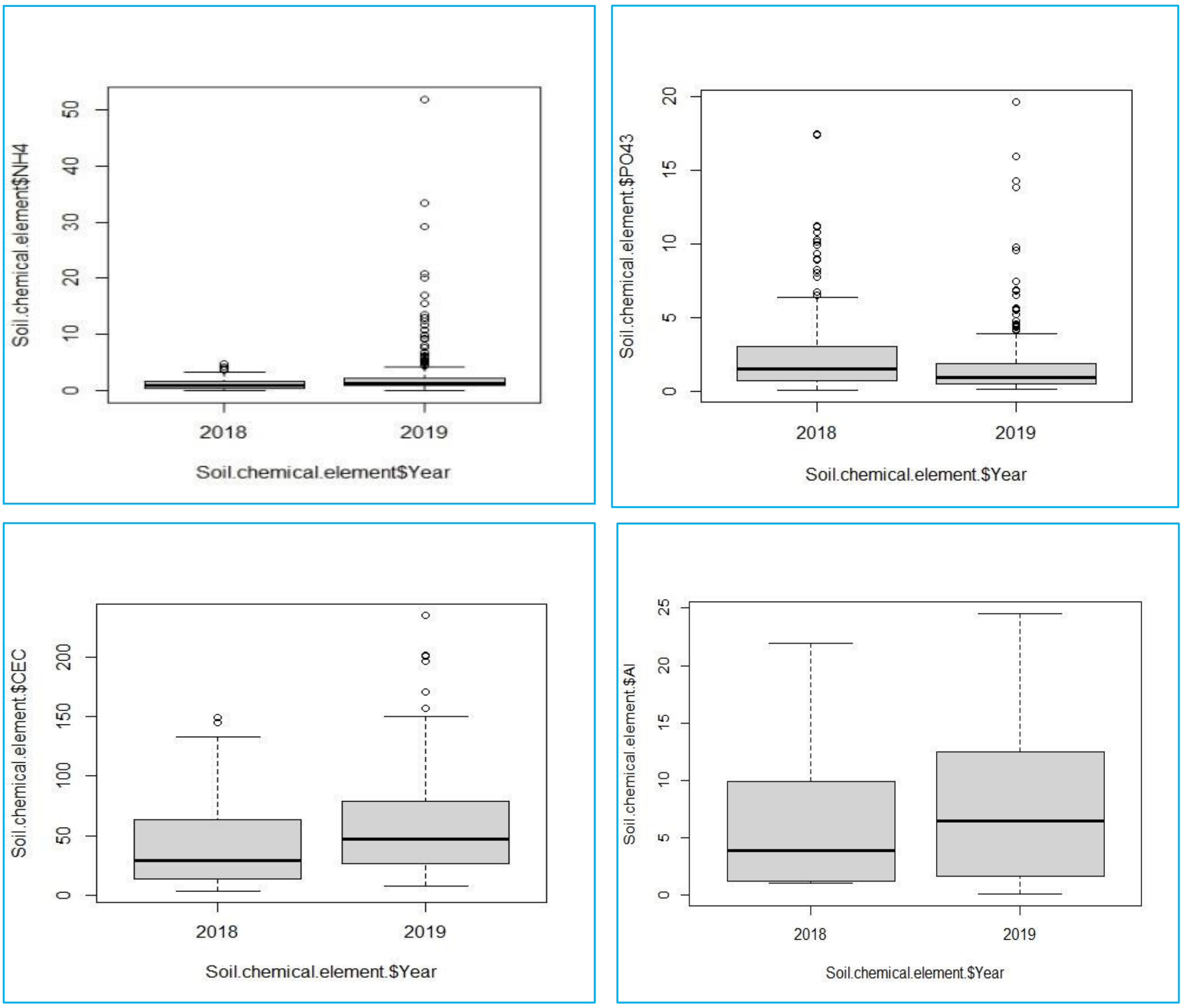


Figure 40. Comparison of pH, C, N, C: N ratio, OM, NO_3^-+NO_2^-, NH_4^+ PO_4^{3-}, CEC and Al $^{3+}$ in different times

Table 16. Averaged values, SD, Min, and Max of different chemical elements in different years

Year		pH	N[%]	C[%]	C: N ratio	OM[%]	Na[mg/L]	K[mg/L]	Ca[mg/L]	Mg[mg/L]	Al[mg/L]	CEC[mg/L]	PO43[mg/L]	NH4[mg/L]	NO3 -NO2- [mg/L]
2018	Mean	4.39	0.19	2.31	11.8	3.99	1.08	5.6	26.20	6.92	6.08	39.79	2.55	1.16	12.34
	SD	0.52	0.07	1.05	1.8	1.81	0.58	3.5	23.16	7.21	5.35	31.20	2.91	0.95	9.03
	Min	3.60	0.06	0.53	7.2	0.91	0.04	1.1	0.01	0.68	1.06	3.77	0.10	0.01	0.00
	Max	5.85	0.41	5.51	16.7	9.49	4.47	18.9	93.04	39.49	21.99	148.90	17.46	4.85	53.00
2019	Mean	4.44	0.21	2.48	11.7	4.28	1.07	6.7	41.00	8.32	7.67	57.13	1.74	2.96	15.93
	SD	0.59	0.09	1.22	1.7	2.09	3.00	9.4	28.53	8.75	6.55	39.74	2.55	5.42	15.03
	Min	3.20	0.05	0.35	7.4	0.60	0.24	1.0	5.75	0.58	0.1	7.64	0.14	0.08	0.00
	Max	6.59	0.70	7.29	16.1	12.57	44.12	108.8	177.90	51.28	24.56	234.77	19.63	51.85	114.00
Total	Mean	4.42	0.20	2.40	11.7	4.15	1.08	6.2	34.26	7.68	6.94	49.24	2.11	2.14	14.29
	SD	0.56	0.08	1.14	1.7	1.97	2.24	7.3	27.21	8.10	6.10	37.09	2.75	4.15	12.76
	Min	3.20	0.05	0.35	7.2	0.60	0.04	1.0	0.01	0.58	0.10	3.77	0.10	0.01	0.00
	Max	6.59	0.70	7.29	16.7	12.57	44.12	108.8	177.90	51.28	24.56	234.77	19.63	51.85	114.00

3.3.4 Comparison of soil chemical variables in different land uses

Figure 41 shows the comparison of pH, C, N, C: N ratio, OM, NO_3^- + NO_2^-, NH_4^+, PO_4^{3-} and CEC in various land uses. For soil pH, there was a significant difference with p-value = 1.736e-05 value for different land uses including AF (AF), cropland (CL), and natural forest (NF). The Wilcoxon rank-sum test with continuity correction was used to determine the significant level between different land uses. The recorded pH mean values are 4.47, 4.10, and 4.15 in AF, CL, and NF respectively.

Accordingly, with pairwise comparison, the pH value was compared between land uses to determine where is a change. As result, there was a significant difference between AF&CL and AF & NF with p-value = 0.0002318 and p-value = 0.001393 respectively. On the other hand, the difference between CL and NF with a p-value = 0.8327 was not significant. The pH value was higher in AF (with mean value=4.46), followed by NF (4.15) and CL (mean value=4.09). This clearly shows the positive impact of AF on soil pH comparing to the CL and NF. Inversely, there was no significant difference for C in various land uses with a p-value = 0.4228. The obtained C values (%) are 2.37, 2.47, and 2.7 in AF, CL, and NF respectively.

A significant difference (p-value = 0.01567) between land uses was detected as far as soil N is concerned. With pairwise comparison, the tests highlighted that the difference between AF and NF was significant (p-value = 0.00739) and none of these differences were statistically significant between AF & CL and CL& NF with p-value = 0.2156 and p-value = 0.2902 respectively. In addition, the result showed a significant difference between land uses in terms of the C: N ratio (p-value = 2.099e-08). The obtained N values (%) are 0.19, 0.21, and 0.26 in AF, CL, and NF respectively.

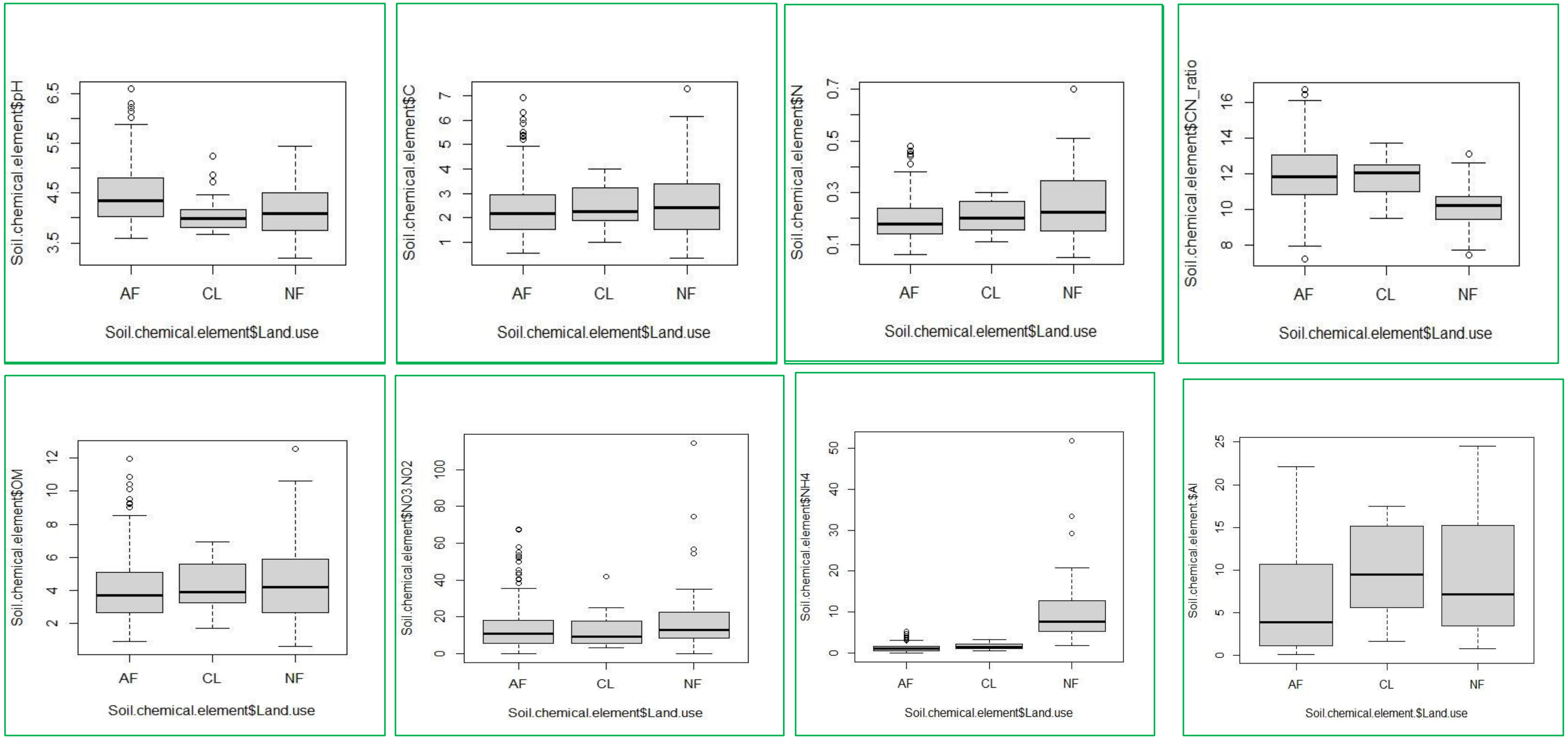
By comparing the C: N ratio between different land uses, the results show a significant difference between AF & NF and CL&NF with p-value = 5.306e-09 and p-value = 2.154e-06 respectively whereas there was no significant difference between AF and CL with p-value = 0.9904. The recorded C: N ratio average values are 11.9, 11.8, and 10.2 respectively.

By comparing OM in various land uses, there was no significant difference with p-value = 0.4228. The tests did not confirm any significant difference with regard to NO_3^- + NO_2^-, (p-value = 0.4364). The recorded OM values (%) are 4.1, 4.3, and 4.7 in AF, CL, and NF respectively. After testing the NH_4^+ level for different land uses, the result showed a significant difference with a p-value < 2.2e-16. Moreover, the comparison between land uses, there was a significant difference between AF and CL, AF and NF; and CL and NF with p-value = 0.001078, p-value < 2.2e-16 and p-value = 2.496e-15 respectively.

Besides, the results show a significant difference for both PO_4^{3-} and CEC with p-value = 2.674e-08 and p-value = 0.007262 respectively. In addition, the PO_4^{3-} was significant between AF and other land uses with p-value = 4.664e-07, p-value = 0.004376 in CL and NF respectively. Similarly, with CEC, there was a significant difference between CL and NF with p-value = 1.075e-08.

The PO_4^{3-} high mean value were recorded in NF (2.98 mg/L) followed by AF (2.12 mg/L) and CL (0.59 mg/L). By comparing CEC between land uses, the results show a significant difference between AF and CL with p-value = 0.002538 whereas none of these differences was significant between AF and NF (p-value = 0.7057). Besides, the test did show a significant change between CL and NF with a p-value = 0.001756. 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) (Table 17).

In addition, the statistical difference was significant for Al^{3+} with p-value = 5.255e-05. With pairwise comparison, there was a significant difference between AF and CL, and AF and NF with p-value <0.05 while the analysis did not identify a significant difference between CL and NF land uses. The averaged soil C stock in various land use were 18954 t ha^{-1}, 17339.4 t $ha^{-1,}$ and 16637.4 t ha^{-1} in NF, CL, and AF respectively. More soil C stock was observed in NF, which also contains more C concentration compared to the other land uses as a result of the progressively accumulated litter of the leaves, twigs, and other vegetation from the forest area.


Soil.chemical.element$pH
Soil.chemical.element$C
Soil.chemical.element$N
Soil.chemical.element$CN_ratio
Soil.chemical.element$OM
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Soil.chemical.element.$Al
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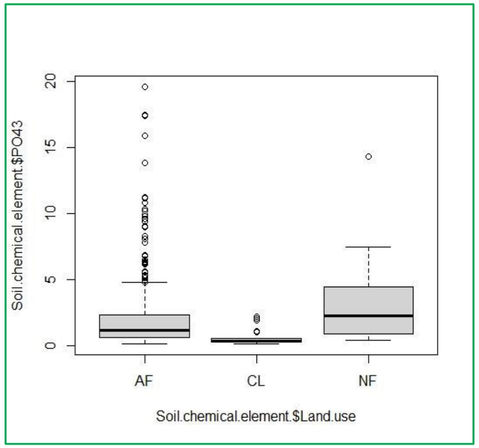
NF
Soil.chemical.element$Land.use



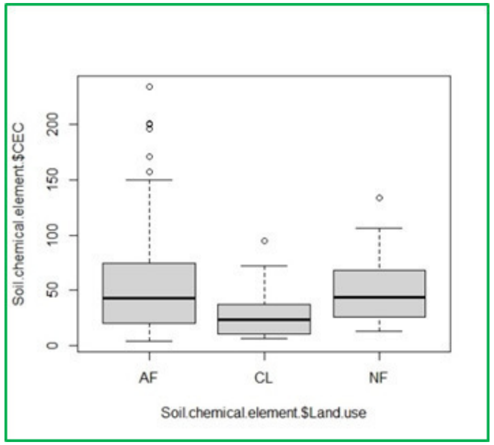


Figure 41. Comparison of pH, C, N, C: N ratio, OM, NO_3^-+NO_2^-, NH_4^+, PO_4^{3-}, CEC and Al^{3+} in different land uses

Table 17. Averaged values, SD, Min, and Max of different chemical elements in various land uses

Land use		pH	N[%]	C[%]	C: N ratio	OM[%]	Na[mg/L]	K[mg/L]	Ca[mg/L]	Mg[mg/L]	Al[mg/L]	CEC[mg/L]	PO43[mg/L]	NH4[mg/L]	NO3 -NO2- [mg/L]
AF	Mean	4.47	0.19	2.37	11.9	4.1	1.01	6.3	35.29	7.97	5.72	50.7	2.12	1.23	13.82
	SD	0.55	0.07	1.11	1.7	1.9	2.40	7.8	27.80	8.55	5.16	38.2	2.80	0.94	11.28
	Min	3.60	0.06	0.53	7.2	0.9	0.04	1.03	0.01	0.58	1.06	3.8	0.13	0.01	0.00
	Max	6.59	0.48	6.93	16.7	11.9	44.12	108.8	177.90	51.28	21.99	234.8	19.63	8.00	68.00

CL	Mean	4.10	0.21	2.47	11.8	4.3	1.06	4.80	18.33	4.68	11.33	28.9	0.59	1.72	12.10
	SD	0.39	0.06	0.83	1.0	1.4	0.57	2.38	17.41	3.81	5.53	22.7	0.61	0.78	9.28
	Min	3.68	0.11	1.00	9.5	1.7	0.35	2.49	0.63	0.84	3.67	6.0	0.10	0.63	3.00
	Max	5.24	0.30	4.01	13.7	6.9	2.68	10.39	70.20	12.40	17.49	95.0	2.20	3.39	42.00
NF	Mean	4.15	0.26	2.70	10.2	4.7	1.69	5.51	35.13	6.90	9.97	49.2	2.98	11.12	20.36
	SD	0.57	0.14	1.60	1.2	2.8	0.93	2.53	23.86	4.84	7.53	29.4	2.76	9.84	23.21
	Min	3.20	0.05	0.35	7.4	0.6	0.67	1.18	6.44	1.11	0.78	12.6	0.38	1.86	0.00
	Max	5.43	0.70	7.29	13.1	12.6	5.63	12.30	109.80	18.51	24.56	133.8	14.30	51.85	114.00
Total	Mean	4.42	0.20	2.40	11.7	4.1	1.08	6.21	34.26	7.68	6.08	49.2	2.11	2.14	14.29
	SD	0.56	0.08	1.14	1.7	2.0	2.24	7.34	27.21	8.10	5.35	37.1	2.75	4.15	12.76
	Min	3.20	0.05	0.35	7.2	0.6	0.04	1.03	0.01	0.58	1.06	3.8	0.10	0.01	0.00
	Max	6.59	0.70	7.29	16.7	12.6	44.12	108.8	177.90	51.28	21.99	234.8	19.63	51.85	114.00

3.3.5 Regression analysis of different soil chemical elements

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 influencing key soil processes. The test revealed that the recorded soil pH mean value across the study area is 4.2, which is very strongly acidic.

Figure 42 illustrates the association among various selected soil variables such as pH, CEC, and exchangeable cations in depths and land use 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 sol depths. The Al was negatively strongly correlated with pH in all soil depths. It meant that as the pH decreases, the AL increases.

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 (Table 18).

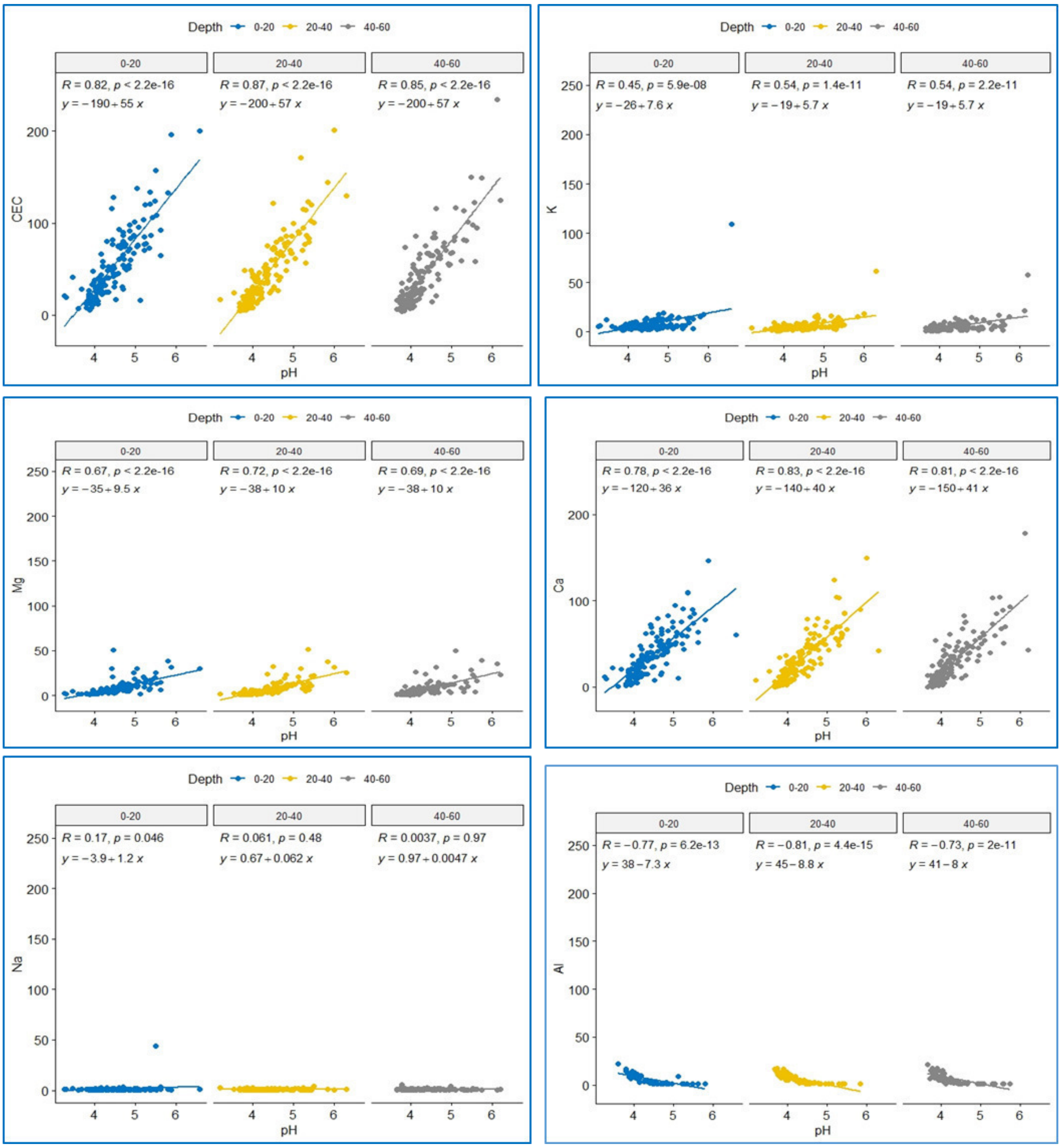


Figure 42. Relationship between soil pH, CEC, and exchangeable cations in different sampling depths

Table 18. The correlation coefficient and functional dependence for pH and basic cations in different soil depths

Soil Depth	Observed correlation	Linear regression	Cor. coefficient	Correlation intensity
0-20 cm	pH /CEC	$Y = -190 + 55\,X$	R = 0.82	Strong correlation
20-40 cm		$Y = -200 + 57\,X$	R=0.87	Strong correlation
40-60 cm		$Y = -200 + 55\,X$	R=0.85	Strong correlation
0-20 cm	pH /K	$Y = -26 + 7.6\,X$	R=0.45	Moderate correlation
20-40 cm		$Y = -19 + 5.7\,X$	R=0.54	Moderate correlation
40-60 cm		$Y = -19 + 5.7\,X$	R=0.54	Moderate correlation
0-20 cm	pH /Mg	$Y = -35 + 9.5\,X$	R=0.67	Moderate correlation
20-40 cm		$Y = -39 + 10\,X$	R=0.72	Strong correlation
40-60 cm		$Y = -38 + 38\,X$	R=0.69	Moderate correlation
0-20 cm	pH /Ca	$Y = -120 + 36\,X$	R=0.78	Strong correlation
20-40 cm		$Y = -140 + 41\,X$	R=0.83	Strong correlation
40-60 cm		$Y = -150 + 51\,X$	R=0.81	Strong correlation
0-20 cm	pH /Na	$Y = -3.9 + 1.2\,X$	R=0.17	Weak correlation
20-40 cm		$Y = 0.67 + 0.062X$	R=0.061	Negligible correlation
40-60 cm		$Y = 0.97 + 0.0047\,X$	R=0.0037	Negligible correlation
0-20 cm	pH /Al	$Y = 38 - 7.3\,X$	R = -0.77	Strong correlation
20-40 cm		$Y = 45 - 8.8\,X$	R=-0.81	Strong correlation
40-60 cm		$Y = 41 - 8\,X$	R=-0.73	Strong correlation

Figure 43 shows the relationship between pH, CEC, exchangeable cations, and Al in various altitude ranges. The difference between two successive altitude ranges is one hundred meters i.e. there are 900 meters from the lower altitude range to the upper altitude range (>1200 – 1300 m to >2000-2100 m). The substantial rainfall, high mountains, high slopes, land degradation are among serious features of the study area and all are found in the aforementioned altitude ranges. Besides, the soil of the study area is strongly acidic. Hence, there was a need to know at which intensity the soil pH and exchangeable cations are correlated with the altitudinal gradients. To respond to this, we selected chemical elements, which are highly affected by high precipitations through leaching.

By the use of Spearman correlation analysis, the soil pH was strongly correlated with CEC and basic cations in all altitude ranges except in the lowest altitude range where it was weak. Firstly, the pH was weakly correlated with CEC in the lowest altitude range while they were strongly correlated in all the remaining altitude ranges. The soil pH was moderately correlated with K in >1200-1300 m, >1400-1500 m, >1500-1600 m, >1800-1900 m, >1900-2000 m, >2000-2100 m while it was weakly correlated in the remaining ranges. Mg was strongly correlated above 1500 and weakly correlated in >1400-1500, moderately correlated in >1300-1400 m, and negligibly correlated in the >1200-1300 m considered as the lowest altitude range of our study area.

Ca was strongly correlated in all altitude ranges above 1400 m, moderate in >1300-1400, and weak in the lowest altitude. Na was found to be either negligible or weak across all altitude ranges. Al was very strongly correlated with pH in >1200-1300 m and >1900-200m, moderate in > 1300-1400 m, and strongly correlated in all other remaining altitudes.

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. 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.

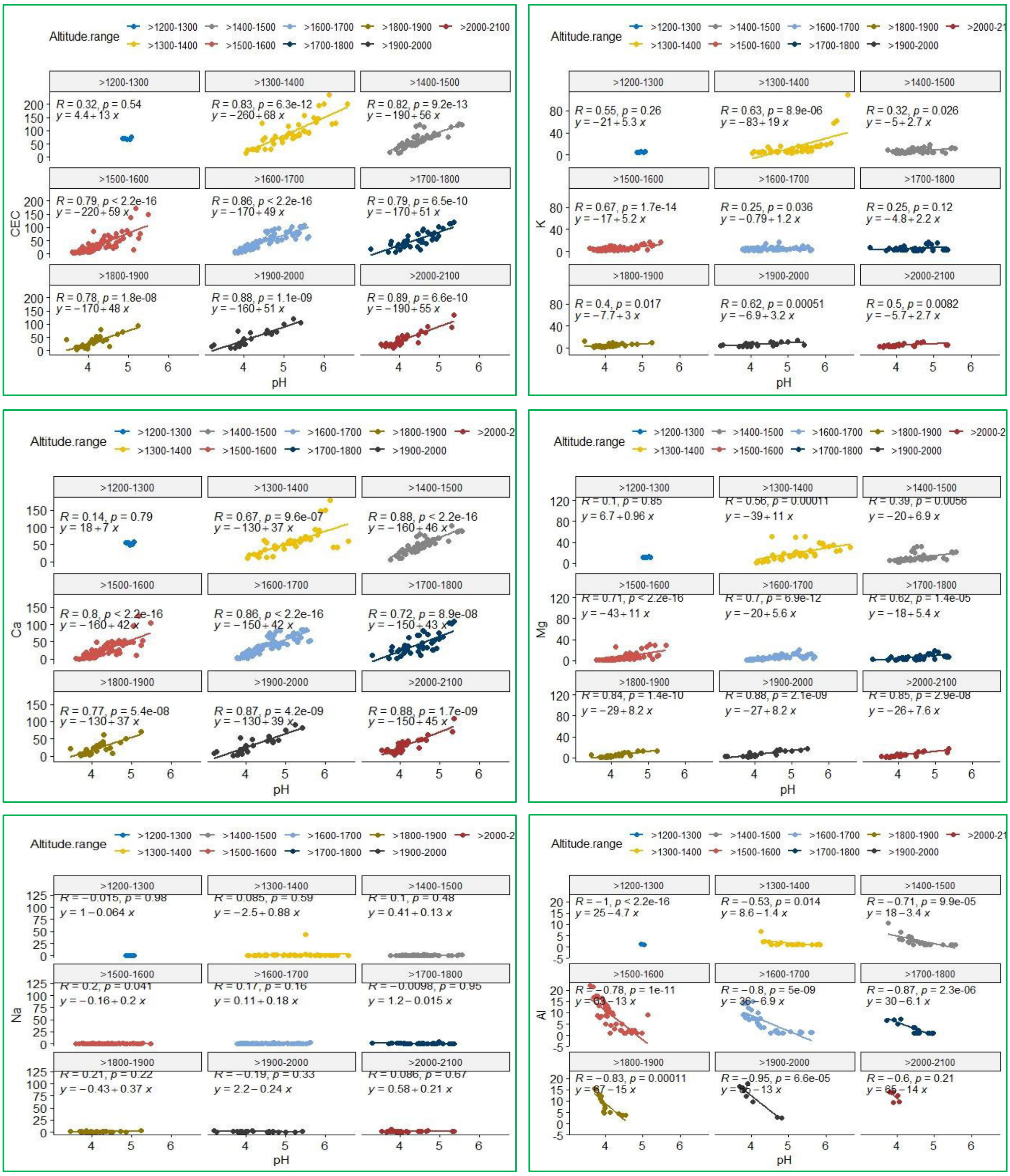


Figure 43. Relationship between soil pH, CEC, and exchangeable cations in different altitude ranges

Table 19. The correlation coefficient and functional dependence for pH and basic cations in different altitude ranges

>2000-2100	>1900-2000	>1800-1900	>1700-1800	>1600-1700	>1500-1600	>1400-1500	>1300-1400	>1200-1300
Y=-190+55 X	Y=−160+51	Y=−170+48	Y=−170+51 X	Y=−170+49 *X*	Y=−220+59	Y=−190+56 X	Y=−260+68	Y=44+13 X
0.89	0.88	0.78	0.79	0.86	0.79	0.82	0.83	0.32
Strong	Strong	Strong	Strong	Strong	Strong	Strong	Strong	Weak
Y=−5.7+2.7 *X*	Y=−6.9+3.2	Y=−7.7+3 *X*	Y=−4.8+2.2 *X*	Y=−0.79+1.2	Y=−17+5.2 *X*	Y=−5+2.7 *X*	Y=−21+5.3 *X*	Y=−21+5.3
0.5	0.62	0.4	0.25	0.25	0.67	0.32	0.63	0.55
Moderate	Moderate	Moderate	Weak	Weak	Moderate	Weak	Moderate	Moderate
Y=−26+7.6 *X*	Y=−27+8.2	Y=−29+8.2	Y=−18+5.4 *X*	Y=−20+5.6 *X*	Y=−43+11 *X*	Y=−20+6.9 *X*	Y=−39+11 *X*	Y=6.7+0.96
0.85	0.88	0.84	0.62	0.7	0.71	0.39	0.56	0.1
Strong	Strong	Strong	Strong	Strong	Strong	Weak	Moderate	Negligible
Y=−150+45 *X*	Y=−130+39	Y=−130+37	Y=−150+43 *X*	Y=−150+42 *X*	Y=−160+42	Y=−160+46 *X*	Y=−130+37 *X*	Y=18+7
0.88	0.87	0.77	0.72	0.86	0.8	0.88	0.67	0.14
Strong	Strong	Strong	Strong	Strong	Strong	Strong	Moderate	Weak
Y=0.58+0.21	Y=2.2−0.24	Y=−0.43+0.	Y=0.11+0.18	Y=0.11+0.18	Y=0.16+0.2	Y=0.41+0.13	Y=−2.5+0.88	Y=1−0.064
0.086	0.19	0.21	0.0098	0.17	0.2	0.1	0.085	0.015
Negligible	Weak	Weak	Negligible	Weak	Weak	Negligible	Negligible	Negligible
Y=65−14 *X*	Y=66−13 *X*	Y=6.−15 *X*	Y=30−6.1 *X*	Y=36−6.9 *X*	Y=63−13 *X*	Y=18−3.4 *X*	Y=8.6−1.4 *X*	Y=25−4.7 *X*
-0.87	-0.95	-0.83	-0.87	-0.8	-0.78	-0.71	-0.53	-1
Strong	Very strong	Strong	Strong	Strong	Strong	Strong	Moderate	Very strong

Functional dependency	Observ
Linear regression	pH /CEC
Correlation coefficient	
Correlation intensity	
Linear regression	pH /K
Correlation coefficient	
Correlation intensity	
Linear regression	pH /Mg
Correlation coefficient	
Correlation intensity	
Linear regression	pH /Ca
Correlation coefficient	
Correlation intensity	
Linear regression	pH /Na
Correlation coefficient	
Correlation intensity	
Linear regression	pH /Al
Correlation coefficient	
Correlation intensity	

Figure 44 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.

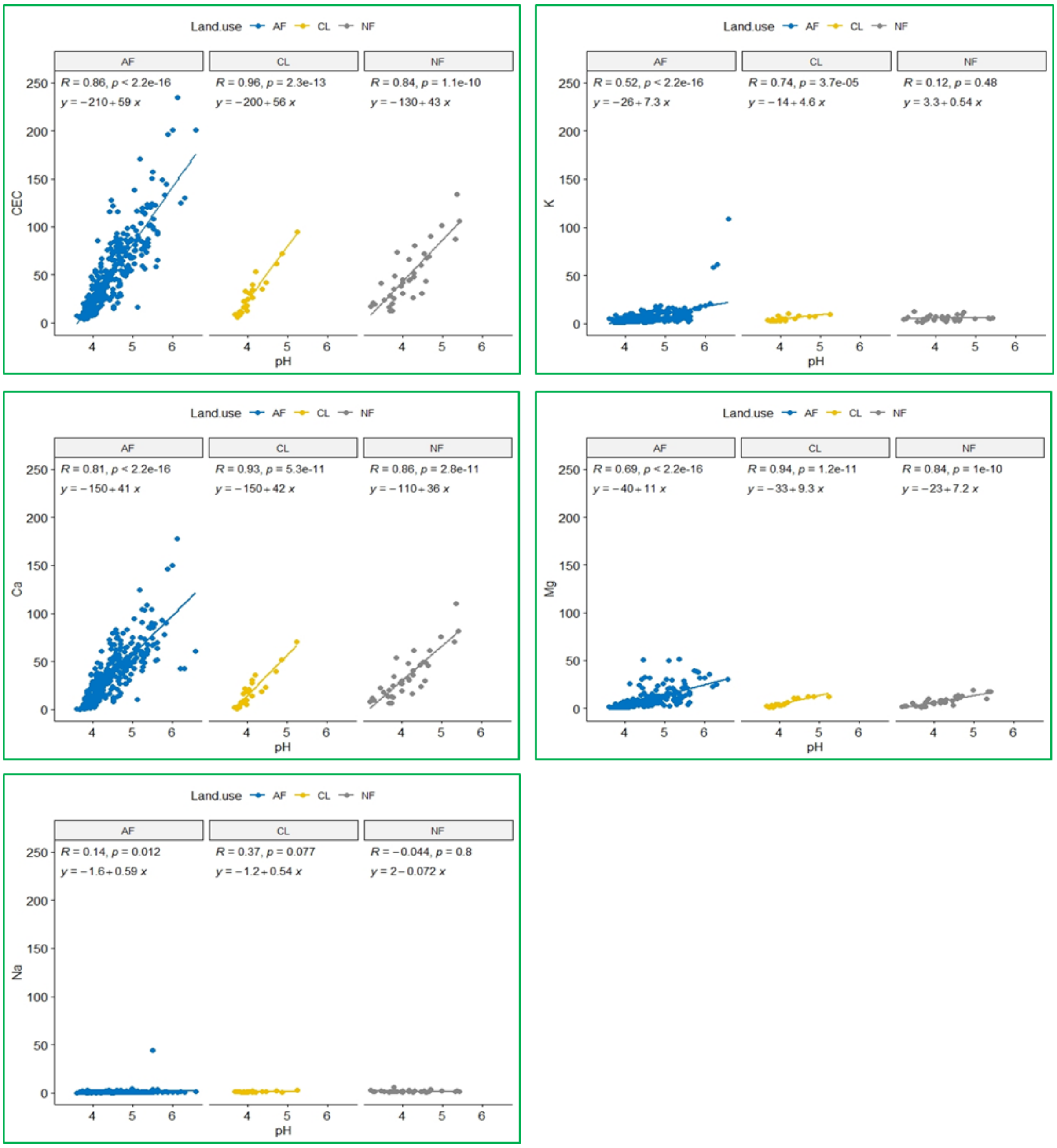


Figure 44. Relationship between soil pH, CEC, and alkaline-forming cations in different land uses

Table 20. The correlation coefficient and functional dependence for pH and basic cations in different land uses

Land use	Observed correlation	Linear regression	Correlation coefficient	Correlation intensity
AF	pH /CEC	Y=-210 +59 X	0.86	Strong correlation
CL		Y=-200+56 X	0.96	Very strong correlation
NF		Y=-130+43 X	0.84	Strong correlation
AF	pH /K	Y=-28 +7.3 X	0.52	Moderate correlation
CL		Y=-14+4.6 X	0.74	Strong correlation
NF		Y=3.3+0.54X	0.12	Weak correlation
AF	pH /Mg	Y= -40+11 X	0.69	Moderate correlation
CL		Y=-33+9.3 X	0.94	Very strong correlation
NF		Y=-23+7.2 X	0.84	Strong correlation
AF	pH /Ca	Y=-150+41 X	0.81	Strong correlation
CL		Y=-150+42 X	0.93	Very strong correlation
NF		Y=-110+36 X	0.86	Strong correlation
AF	pH /Na	Y=-1.6+0.59 X	0.14	Weak correlation
CL		Y=-1.2+0.54X	0.37	Weak correlation
NF		Y=2-0.072 X	0.044	Negligible correlation

3.3.6 Evaluation of soil physical properties in different altitude ranges and land uses

The soil of the study area was evaluated in terms of physical status with the main focus of the soil BD. Kruskal-Wallis rank sum test showed a significant difference between various altitude ranges (df = 8, p-value = 0.02209). The average mean value was 1.17 g cm^3 and a standard deviation of 0.25. The lowest mean value (0.91 g cm^3) was found in NF and corresponds to the highest altitude range across the study area whereas the highest value was obtained in the lowest altitude range recorded in the AF landscape around NF of Cyamudongo. The tests highlighted that the soil BD reduced with the augmentation either of the altitudes significantly at some extends or non-significantly for some ranges of the altitude.

With pairwise comparison, the Wilcoxon rank-sum exact test revealed a significant difference (p-value <0.05) between the altitude range with low minimum value (>2000-2100) and other altitude ranges including >1300-1400, >1400-1500, >1500-1600, and >1600-1700. The analysis did not confirm any significant differences (p-value >0.05) between >2000-2100 and >1200-1300, >1700-1800, and >1900-2000.

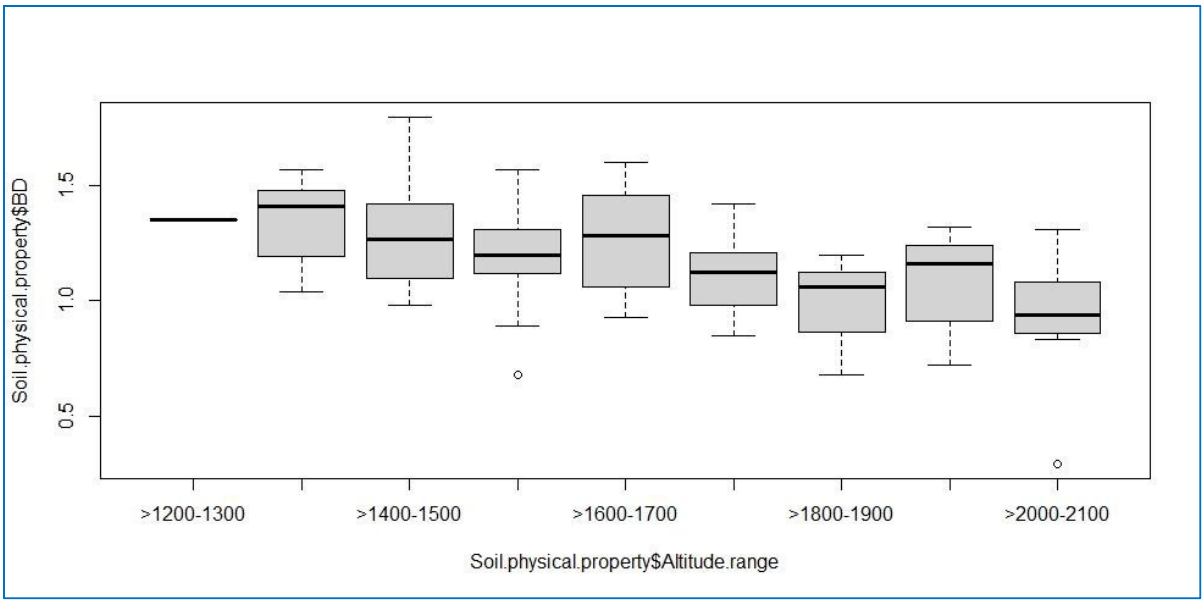


Figure 45. Soil BD in various altitude ranges

The BD was assessed in different land uses and the test highlighted a significant difference between them (df = 2, p-value = 0.002999). With pairwise comparison, the result was significant only between AF and NF (p-value = 0.001015). No significant difference identified between AF and CL (p-value = 0.3146); and CL and NF (p-value = 0.133). The soil texture was found to vary with both land use and the level of altitude. The lower altitude ranges were characterized by loamy clay and slightly sand clay in both AF and CL.

The high altitude ranges in AF and CL were characterized by very clayey silt, very silty clay, and pure silt. The NF of Cyamudongo is only located in high altitude ranging from 1700 to 2100 m asl and the observed soil texture in the highest altitude level was medium clayey silt, medium silty clay, pure silt, sandy silt, sandy silt, and slightly silty clay while it was loamy clay and very silt clay in the lowest level of the soil found in NF.

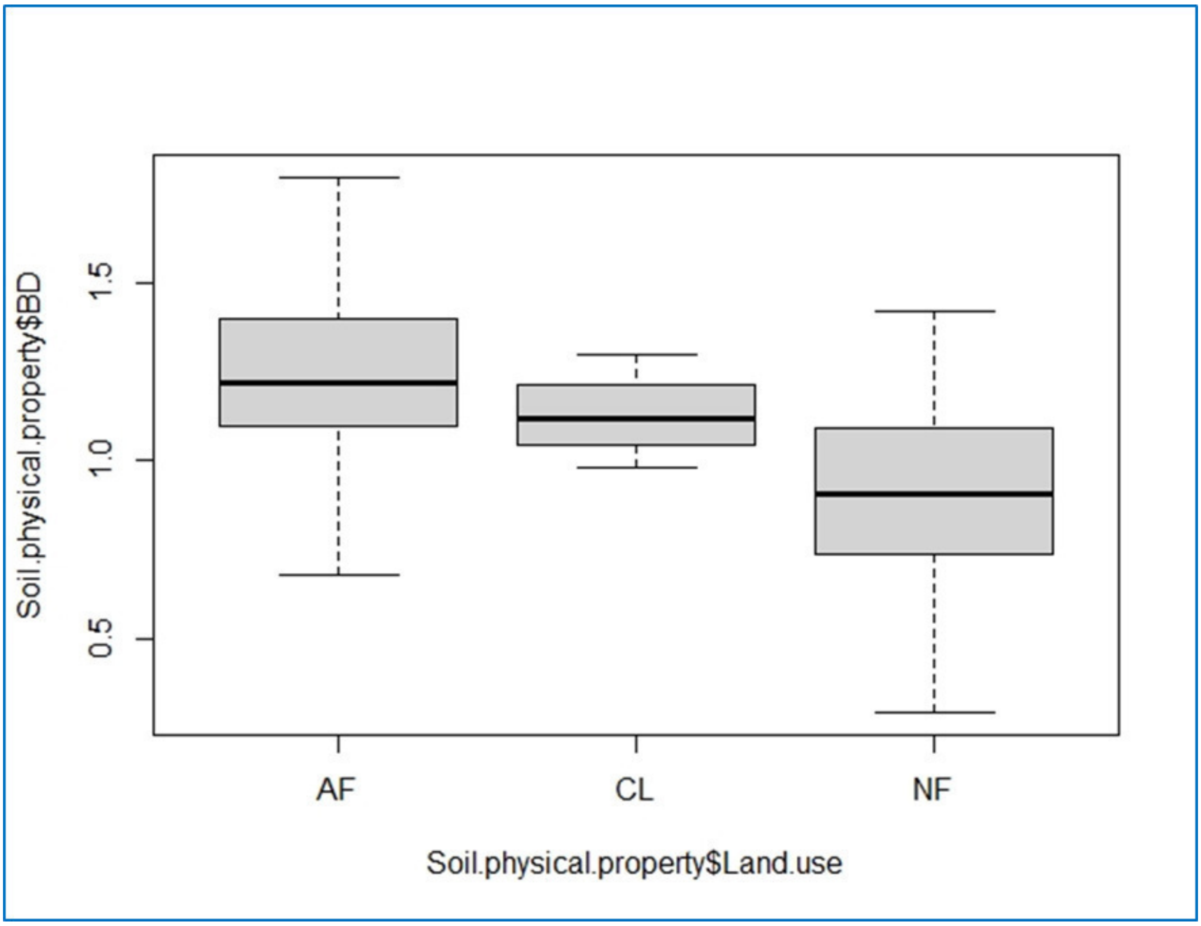


Figure 46. Soil BD in various land uses

It was found that the soil BD was affected by soil texture, land use, and altitude level. The tests highlighted that the soils of AF and NF were significantly different and their soil textures are different in various altitude ranges (Table 21). The soil of the highest density was recorded in AF (1.57 g cm^3) with medium silty clay soil texture whereas the soil of the lowest density was recorded in NF (0.29 g cm^3) with sandy silt soil texture. Different mean soil BD values per land use, altitude ranges, and soil texture are provided in Table 21.

Generally, the soil BD in AF ranged from 0.85 g cm^3 of silty loam soil to 1.57 g cm^3 medium silty clay soil with an altitude ranging from 1200-2100 m asl. The soil BD in CL ranged from 0.98 g cm^3 of very silty clay to 1.3 g cm^3 of loamy clay with an altitude between 1500-2000 m asl. The soil BD in NF varied between 0.29 g cm^3 of sandy silt soil to 1.42 g cm^3 of loamy clay, which was found at an altitude between 1700 -2100 m asl.

Table 21. Description of soil BD in various land uses, altitude ranges, and soil texture

Land use	Altitude range	Soil texture	N	Mean	Minimum	Maximum	Std. Deviation
AF	>1200-1300	Loamy clay	1	1.3500	1.35	1.35	
		Total	1	1.3500	1.35	1.35	
	>1300-1400	Loamy clay	3	1.2667	1.12	1.41	.14503
		Slightly sandy clay	3	1.5100	1.46	1.57	.05568
		Very silty clay	1	1.0400	1.04	1.04	
		Total	7	1.3386	1.04	1.57	.20045
	>1400-1500	Loamy clay	5	1.3500	.98	1.80	.30133
		Medium silty clay	1	1.1500	1.15	1.15	
		Silty loam	1	1.0500	1.05	1.05	
		Weak silty clay	1	1.4000	1.40	1.40	
		Total	8	1.2938	.98	1.80	.25923
	>1500-1600	Loamy clay	6	1.3100	1.12	1.57	.18751
		Medium silty clay	3	1.0433	.89	1.15	.13614
		Medium silty sand	1	1.2000	1.20	1.20	
		Silty loam	1	1.3100	1.31	1.31	
		Very loamy silt	1	.9600	.96	.96	
		Very silty clay	2	.9400	.68	1.20	.36770
		Weak silty clay	2	1.3950	1.37	1.42	.03536
		Total	16	1.1956	.68	1.57	.22748
	>1600-1700	Loamy clay	2	1.3550	1.22	1.49	.19092
		Medium silty clay	1	1.5700	1.57	1.57	
		Very silty clay	6	1.2800	1.01	1.60	.21100
		Weak silty clay	3	1.1267	.93	1.43	.26652
		Total	12	1.2783	.93	1.60	.22703

	>1700-1800	Pure silt	1	1.2000	1.20	1.20	
		Silty loam	1	.8500	.85	.85	
		Very silty clay	2	1.1250	1.10	1.15	.03536
		Weak silty clay	2	1.1400	1.06	1.22	.11314
		Total	6	1.0967	.85	1.22	.13486
	>1800-1900	Loamy clay	1	1.2000	1.20	1.20	
		Silty - loamy sand	1	1.0600	1.06	1.06	
		Weak silty clay	1	1.1200	1.12	1.12	
		Total	3	1.1267	1.06	1.20	.07024
	>1900-2000	Very clayey silt	2	1.2800	1.24	1.32	.05657
		Total	2	1.2800	1.24	1.32	.05657
	>2000-2100	Very clayey silt	1	.8900	.89	.89	
		Very silty clay	1	1.1900	1.19	1.19	
		Total	2	1.0400	.89	1.19	.21213
CL	>1500-1600	Loamy clay	1	1.3000	1.30	1.30	
		Total	1	1.3000	1.30	1.30	
	>1800-1900	Pure silt	1	1.1300	1.13	1.13	
		Very silty clay	1	.9800	.98	.98	
		Total	2	1.0550	.98	1.13	.10607
	>1900-2000	Very silty clay	1	1.1100	1.11	1.11	
		Total	1	1.1100	1.11	1.11	
NF	>1700-1800	Loamy clay	1	1.4200	1.42	1.42	
		Very silty clay	1	.9000	.90	.90	
		Total	2	1.1600	.90	1.42	.36770
	>1800-1900	Pure silt	1	.6800	.68	.68	
		Strong clayey silt	1	.7500	.75	.75	
		Total	2	.7150	.68	.75	.04950
	>1900-2000	Medium silty clay	1	1.2100	1.21	1.21	
		Pure silt	1	.9100	.91	.91	

	Very clayey silt	1	.7200	.72	.72	
	Total	3	.9467	.72	1.21	.24705
>2000-2100	Medium clayey silt	1	.9700	.97	.97	
	Medium silty clay	1	1.3100	1.31	1.31	
	Pure silt	1	.8300	.83	.83	
	Sandy silt	1	.2900	.29	.29	
	Slightly silty clay	1	.9400	.94	.94	
	Total	5	.8680	.29	1.31	.36962
Grand total		73	1.1725	.29	1.80	.25518

3.4 Discussion

The average means of pH, C, N, C: N ratio, OM, $NO_3^- + NO_2^-$, NH_4^+, PO_4^{3-}, CEC, and Al^{3+} in different soil depths and altitude ranges were obtained from the analysis. 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-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 affect 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 share 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 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) 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. Further, 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.

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 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. 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 recorded in the area outside Cyamudongo isolated rain forest (Chapter four).

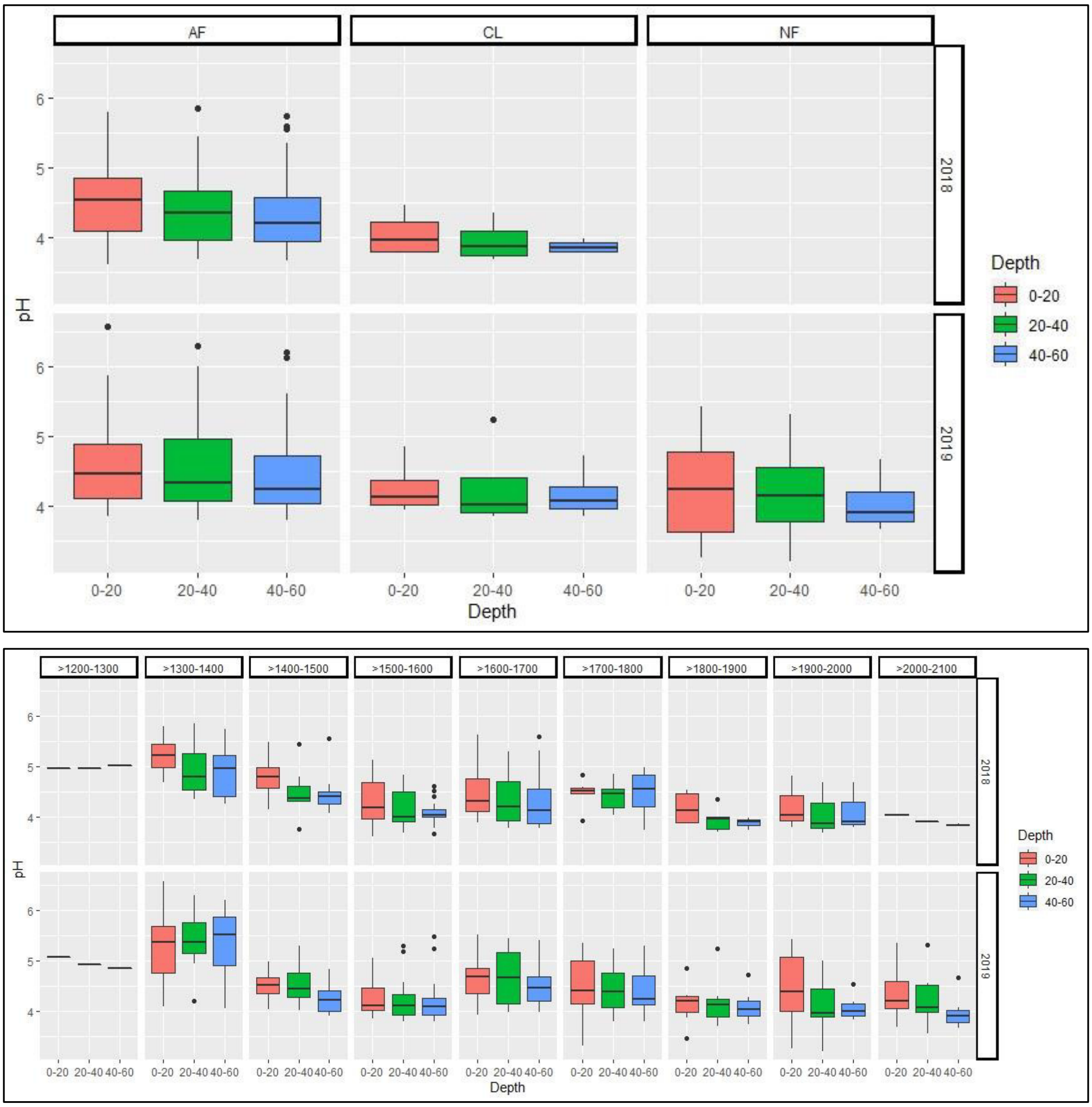


Figure 47. Comparison of soil pH in various sampling depths, land uses, and altitude ranges in different times

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 contributing 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. 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, Adugna 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). 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).

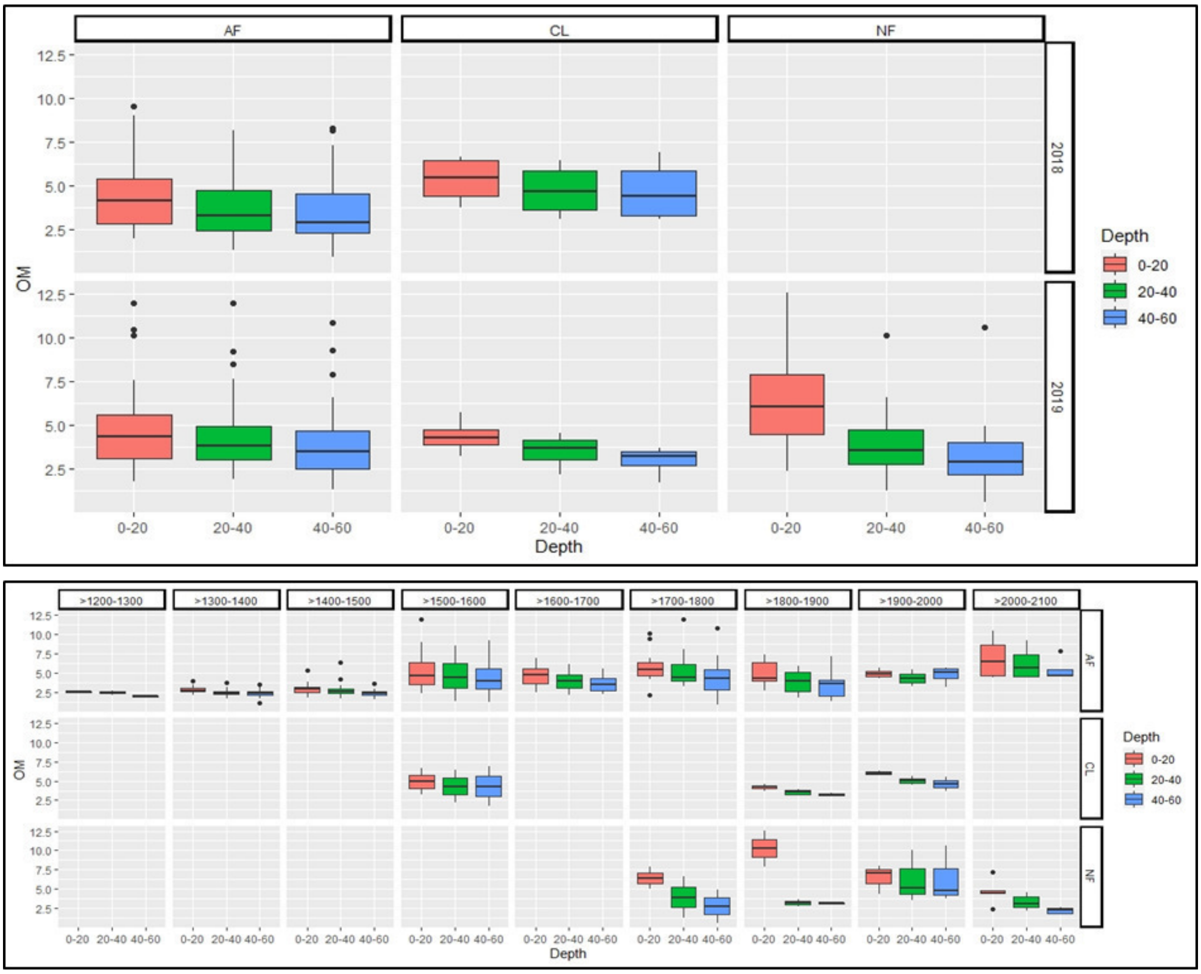


Figure 48. Comparison of soil SOM in various sampling depths, land uses, and altitude ranges in different times

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 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. 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 Yüksek 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 (Kumar et al., 2010).

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. Staring 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, Yüksek, 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.

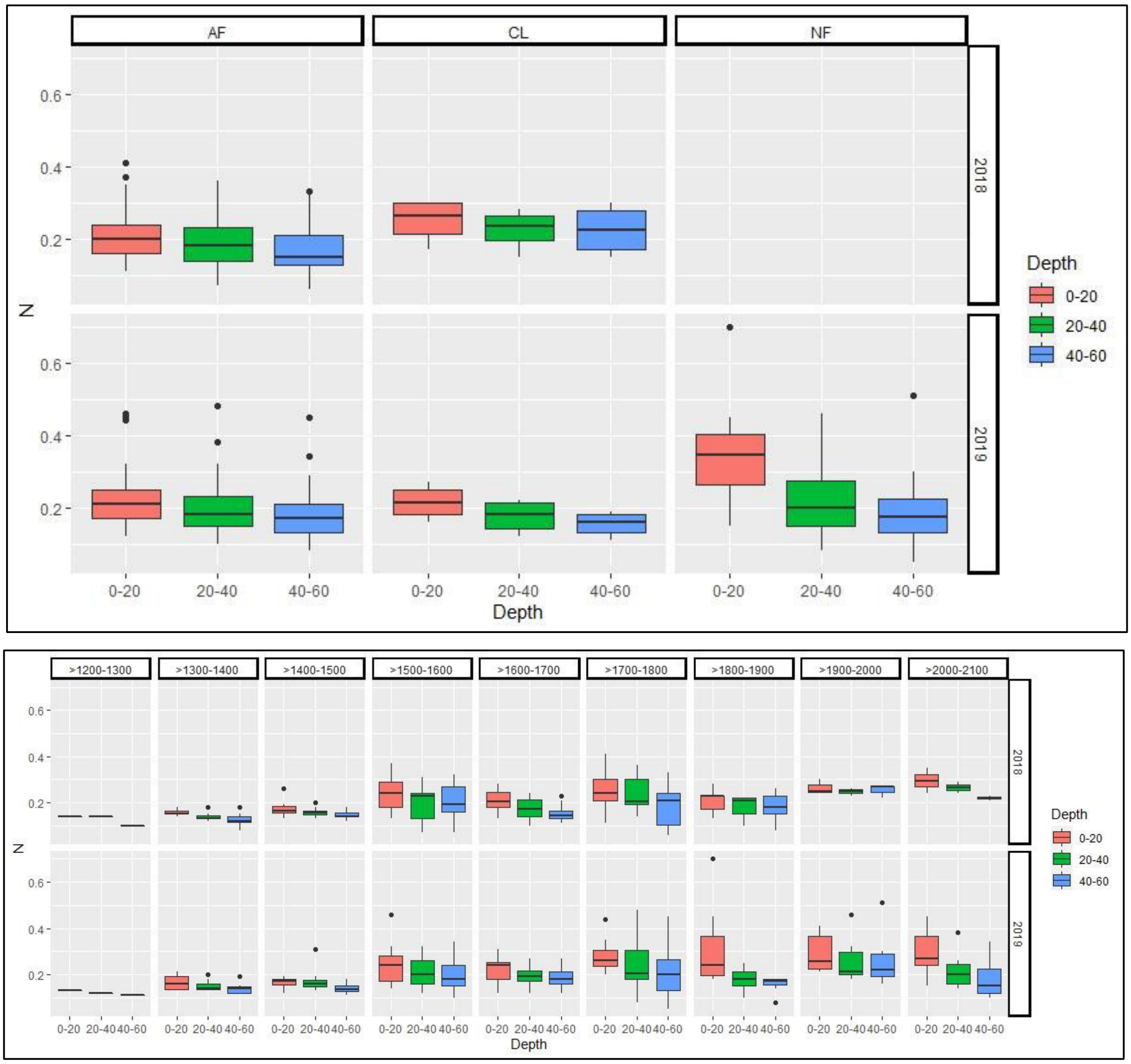


Figure 49. Comparison of soil total N in various sampling depths, land uses, and altitude ranges in different times

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. 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 Amera, (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 ($p \leq 0.05$).

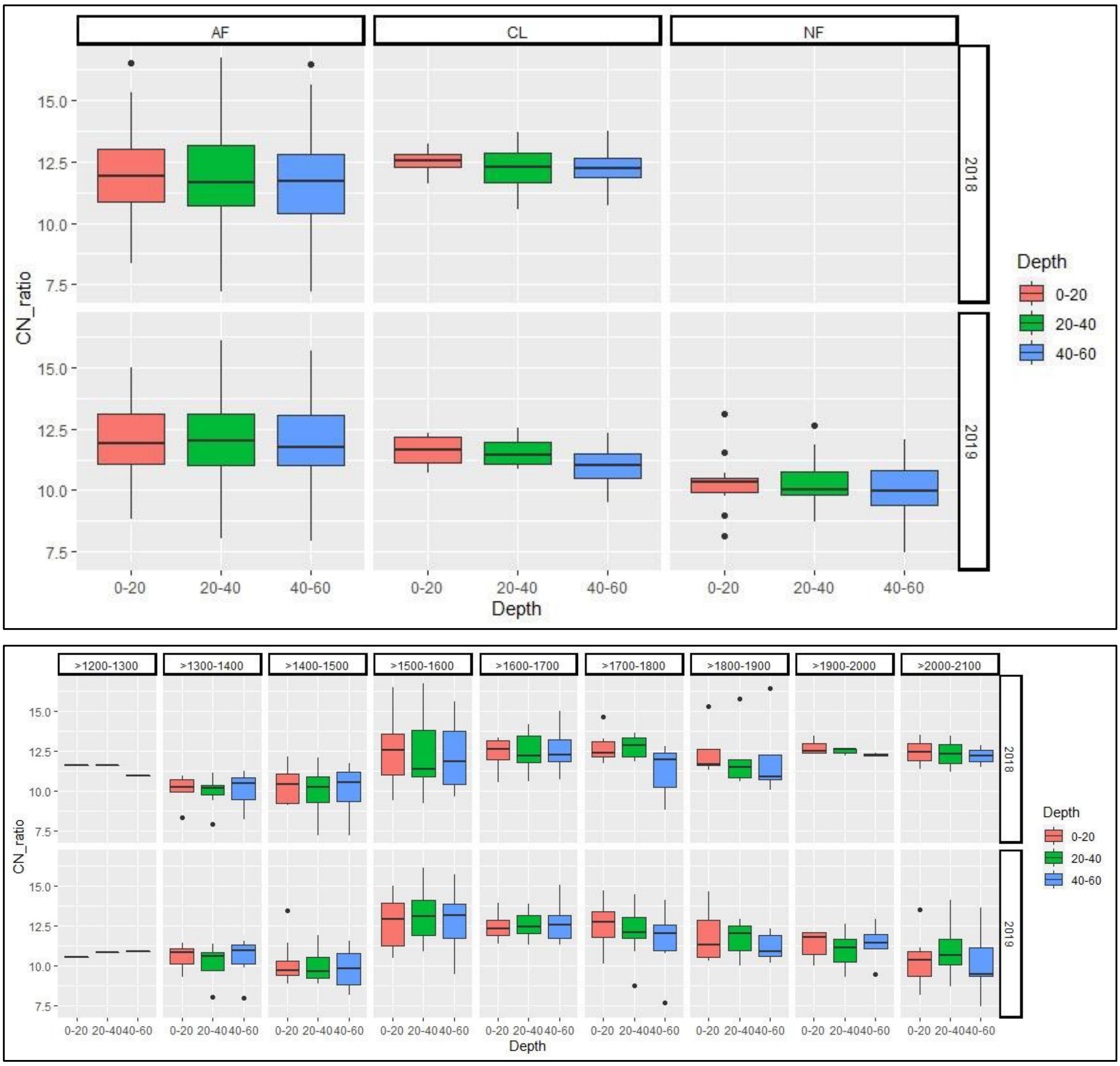


Figure 50. Evaluation of soil C: N ratio in soil depths, land use, and altitude range with time

It was found that the observed $NO_3^-+NO_2^-$ 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 $NO_3^-+NO_2^-$ 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 NO_3^-+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.

The NO_3^-+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 (4 0-60 cm). In CL, they were 15.07, 10.81, and 13.58. In NF, they were 21.24, 19.30, and 18.82. The NO_3^- + 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: NF >AF >CL.

This result concurs with Xue et al., (2013). In their study, significant effects were observed in the concentration of soil nitrate-nitrogen (NO_3−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 NO_3−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 NO_3-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).

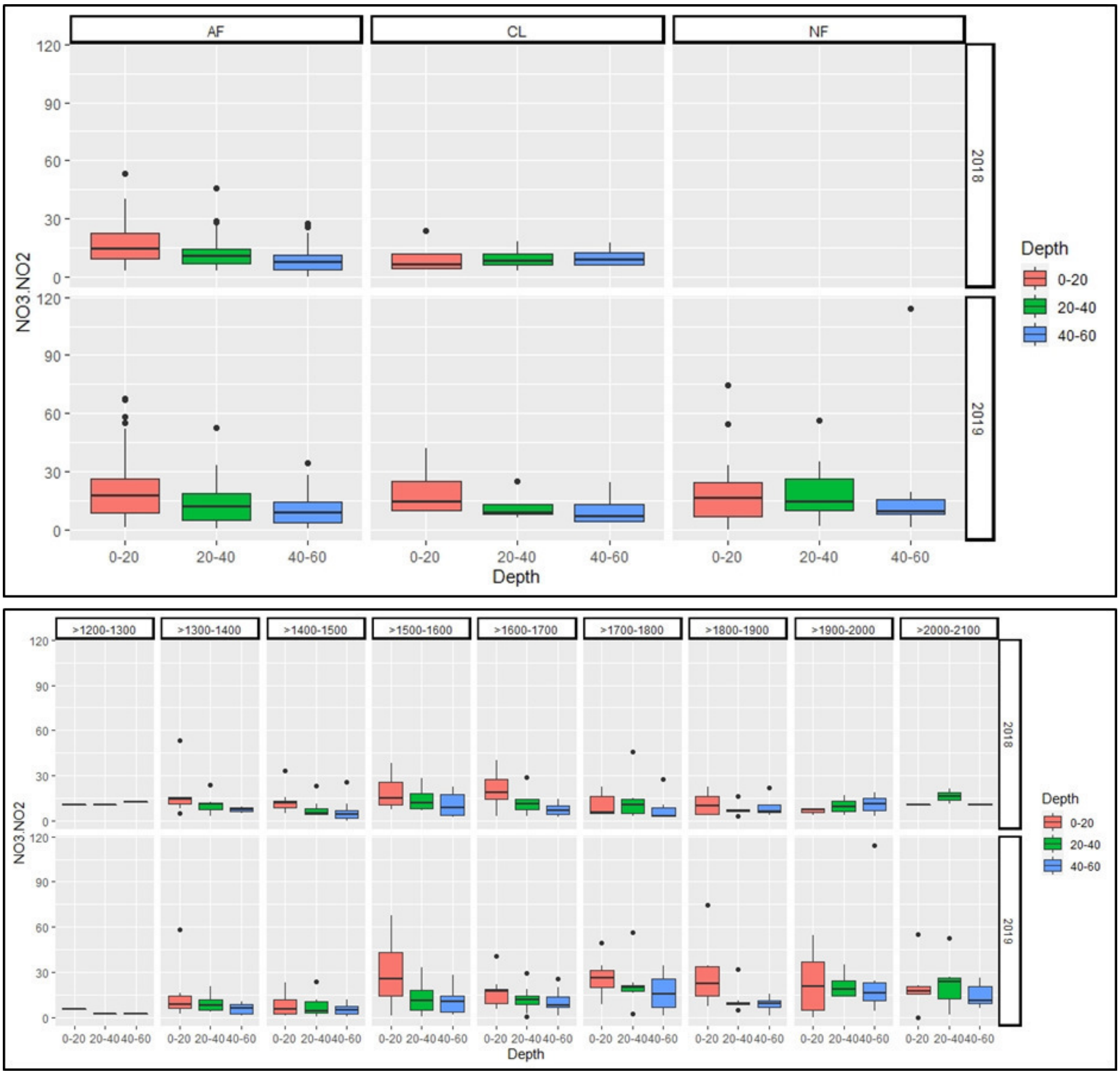


Figure 51. Comparison of soil NO_3^- + NO_2^- ratio in various sampling depths, land uses, and altitude ranges in different times

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 $NH4^+$ 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. 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 (NH_4^+-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 (NO_3−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).

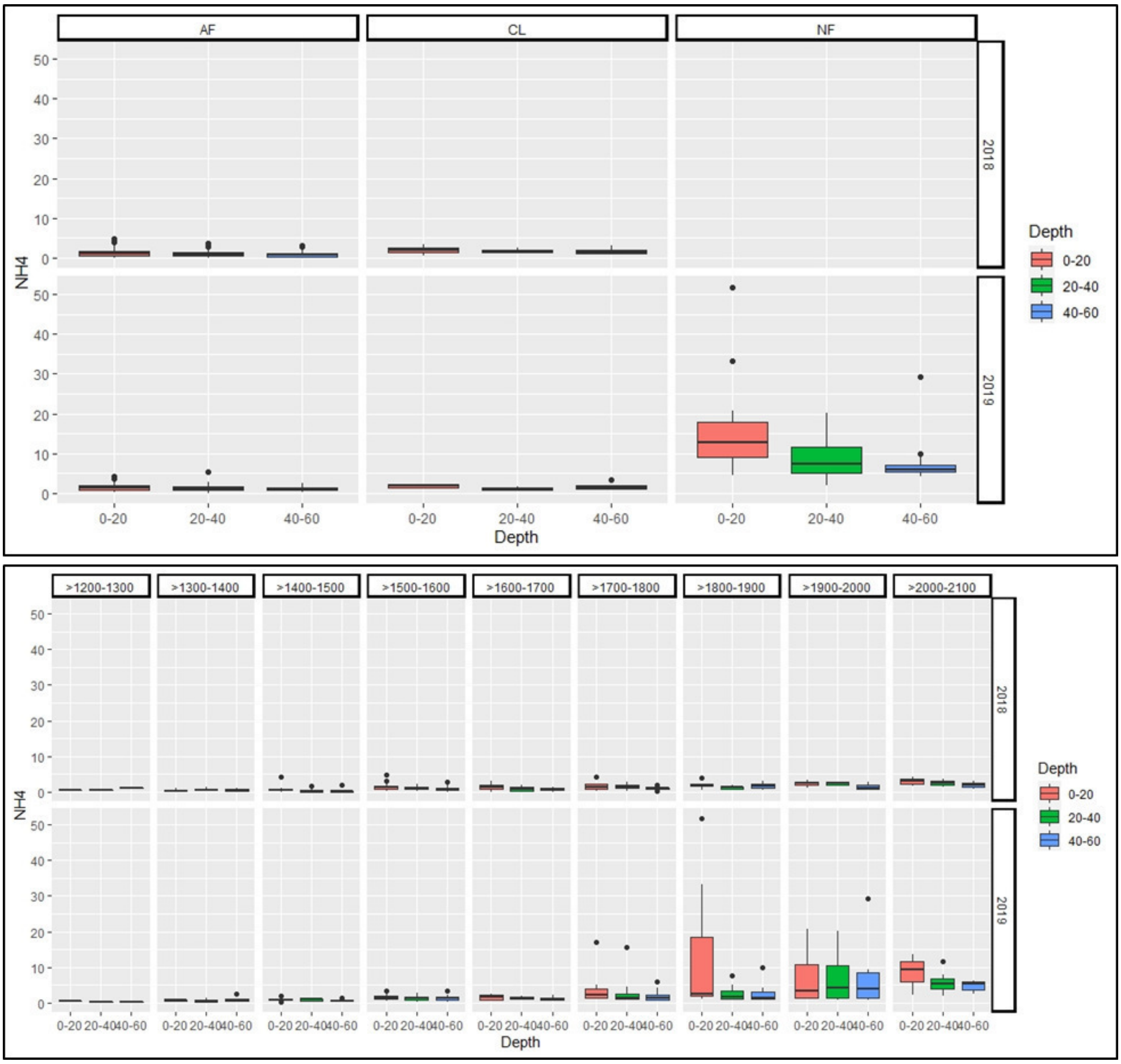


Figure 52. Assessment of soil NH_4^+ ratio in soil depths, land uses, and altitude ranges with time

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: 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 significant 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 (Inherent Factors Affecting Soil Phosphorus, 1994). 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.

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.

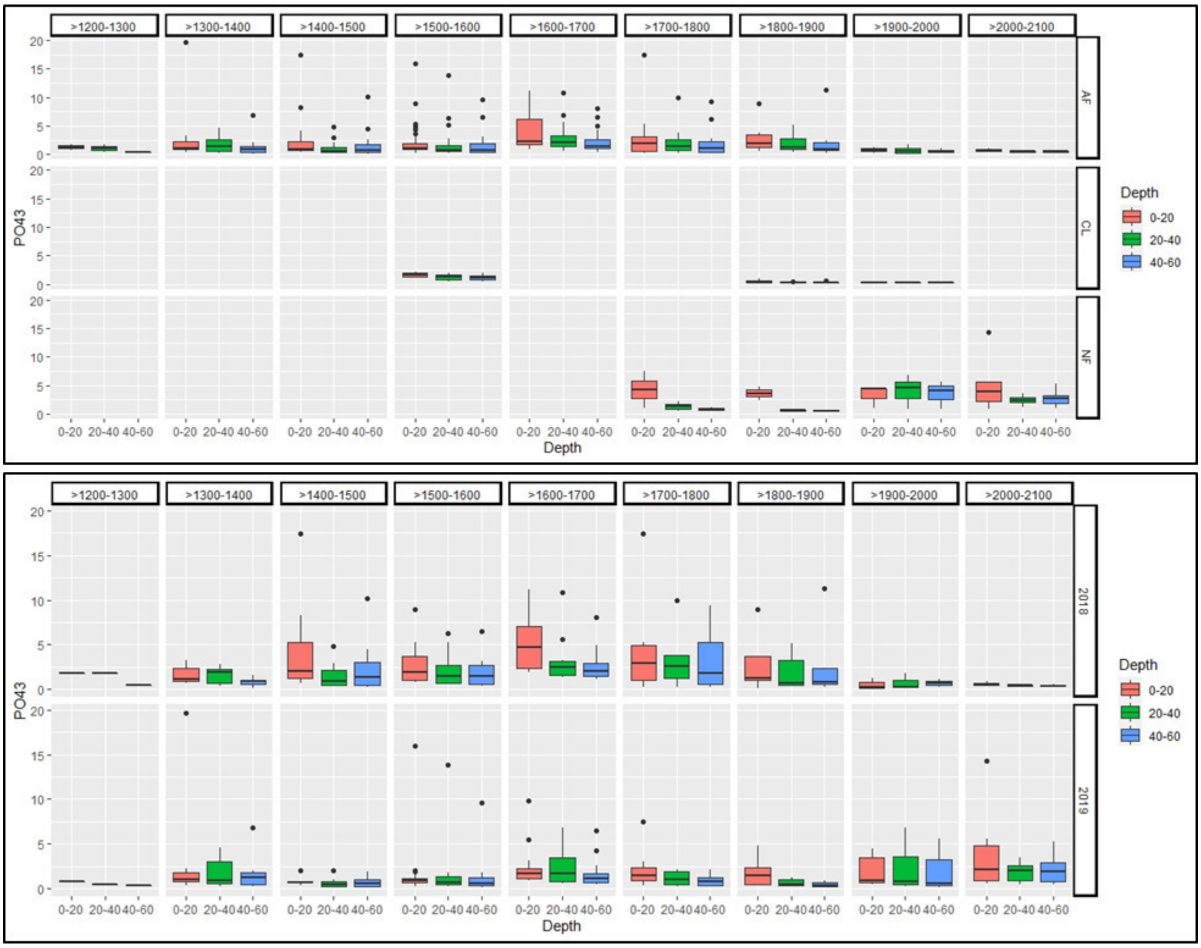


Figure 53. Comparison of soil PO43- ratio in various sampling depths, land uses, and altitude ranges in different times

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 $A1^{+3}$ and H^{+} (Robertson and Ellis, 1999).

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. 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 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.

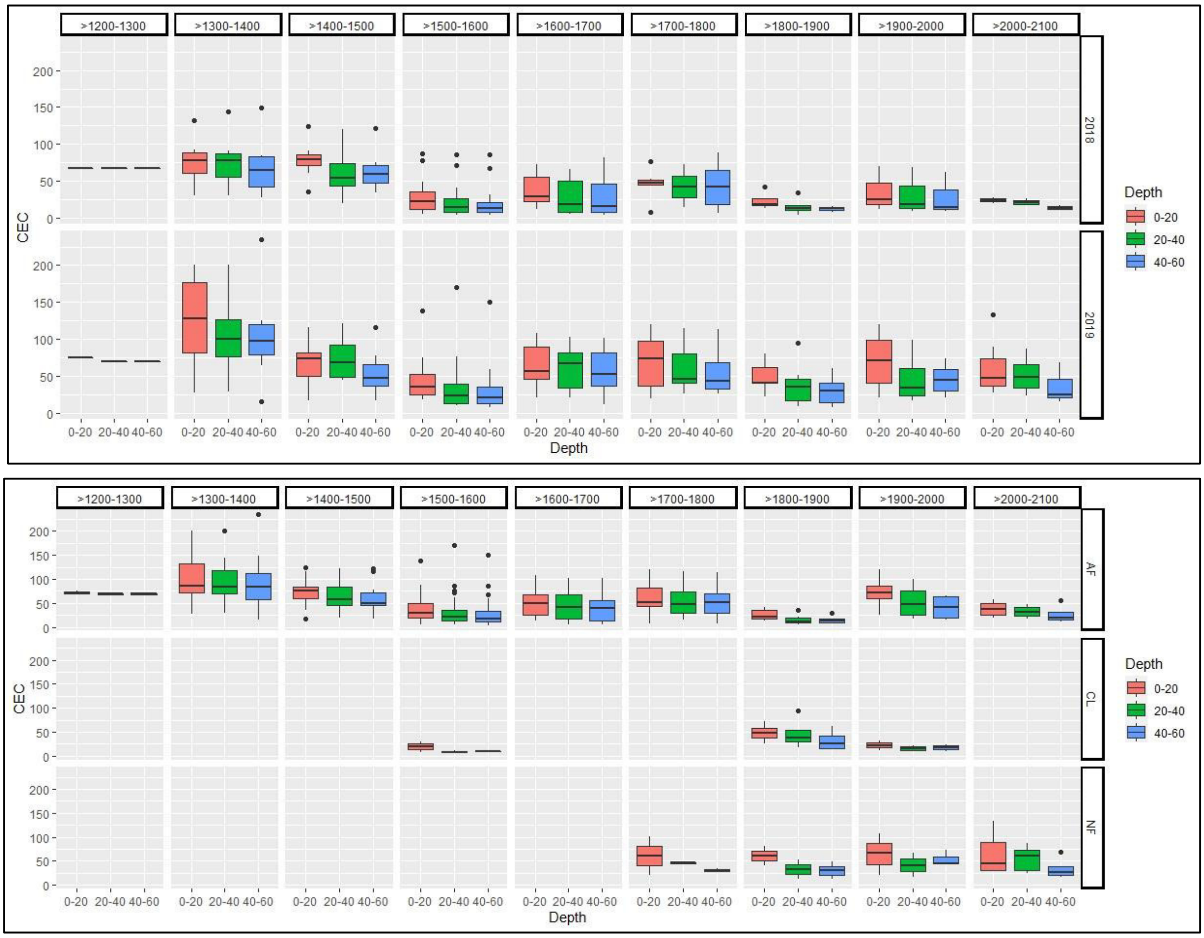


Figure 54. Evaluation of soil PO_4^{3-} in sampling depths, land uses, and altitude ranges with time

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 Al 3+ coupled with substantial rainfall were found to be the main source of soil acidity of the study area. The Al 3+ 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 ($Ca^{2+,}$ Mg^{2+}, K^{1+}). 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 Al^{3+} and to a lesser extent Mn^{2+}" (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.

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. 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.

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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(H2O)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.

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. 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 (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 reduction of altitude (Jiang et al., 2019).

Concerning the soil BD, it was found to be higher in AF, followed by CL and NF, and was significantly different among them and in various altitude ranges. The soil BD was higher in the lower level of altitude whereas it was lower (0.29 g/cm3) in the high altitude ranges, which correspond to the NF land use. The lower quantity of BD of the soil observed in NF is due to the unbroken supply of leaves, twigs and other plants that are accumulated and mixed with the surface soil and consequently affect the BD of NF soil compared to the other land uses such as CL and AF. This is in good agreement with Negasa et al., (2017), Chemeda et al., (2017), and (Arteaga et al., 2017) who reported the soil BD that was smaller in forested areas compared to the other land uses.

These results are also consistent with Tellen & Yerima, (2018) who reported a significant difference in different land uses and altitude levels with regards to soil BD and further support the lowest soil BD they recorded in NF compared to the other land uses. This is also in line with (Saeed et al., 2019) who reported the reduction of soil BD with the augmentation of the level of altitude.

In terms of soil texture, the soil in NF, which is located in the high altitude ranges of this study, was found to be mainly silty as also supported by the result of this study. The findings of this study also concur well with Tesfahunegn & Gebru, (2020) who reported a soil BD that was significantly different across land-use types where it was low in NF. The observed soil texture in the low altitude range, which is mainly loamy clay and slightly sandy clay, is due to the high erosion from the upper mountains of high slopes that collect the soil and plant materials in the way and deposit them in the low altitude level of the study area.

The high values of BD observed in AF and CL areas can be due to the intensive management practices applied together throughout the year during land preparation for cropping, and associated maintenance activities of the crops that result in the reduction of OM compared to the NF. This is in complete agreement with Fentie et al., (2020) who stated the high soil BD values in CL compared to the forest lands. Nevertheless, these results are in contradiction with Vashisht et al., (2020) who found more values of soil BD in forests (uncultivated land) compared to other land uses. It was found that the soil BD relies on the soil texture and the level of the altitude. This seems to confirm Charan et al., (2013) findings where on one hand the BD depended on soil texture while on the other hand, the BD did not show any change with the level of altitude that does not lend support to the observations made under this research with regards to the impact of altitude on BD of the soil.

The overall estimated soil C stock of the study area was 16848 t ha -1. The highest amount (18954 t ha-1) was observed in NF compared to the other land use management decisions and this, in turn, expresses the ability of the soil of NF to sequester more C compared to the other land uses of the study area. This is in good agreement with Kenye et al., (2019), Seyum et al., (2019), and Vesterdal & Leifeld, (2010) who reported more soil C stock in forest land compared to the other land uses. The smallest quantity (9547.2 t ha-1) was observed in the lowest altitude level (>1200-1300 m asl) of the study area and there was a trend to increase with the increase of altitude. This fits well with Huang et al., (2019) who recorded more soil C stock at higher altitude levels than in lower altitudes across their study areas. The low altitude level of the study area is characterized by intensive agriculture activities, which are performed in all seasons, which result in low C stocks that boost the breakage of organic compounds, supplied by crops and mixed AF tree species. This result corroborates with Abebe et al., (2020) who recorded a small quantity of soil C stock in cropland than other land use.

The tests revealed a high amount of C stock in 2019 (17409.6 t ha-1) compared to 2018 (16216.2 t ha-1) which is due to the continuous cultivation and growth of the plant and tree composition in the area of study that generated about 1193.4 t ha-1 in one year. The high-recorded amount of C stock in NF is due to the high C concentration compared to the other land uses because of the progressively accumulated litter of the leaves, twigs, and other vegetation covers from the forest area. This also caused the high quantity of C stock at the surface layer (0-20 cm) and consistently reduced with the increase of soil depths. This is in complete agreement with Montes-Pulido et al., (2017) and Amanuel et al., (2018) who reported more C stock under natural plant cover and surface layer contained high C quantity for various land use that was declined with the increase of soil depths.

CHAPTER FOUR

AGROFORESTRY FOR BIODIVERSITY CONSERVATION

4.1 Introduction

The severe rate of biological resource loss is accelerated by the increase of demographic pressure on natural resources and anthropogenic activities (Udawatta et al., 2019). Human illegal activities (e.g. poaching) especially conducted near protected areas cause instabilities to the resources inside protected areas (Joseph et al., 2014). Human activities especially those carried out by the indigenous people such as extraction of non-timber forest products from the forest, human settlement, and unsustainable agriculture activities applied near protected areas affect the biodiversity of the protected area, and the establishment of the buffer zone may be the best option to the reduction of the conflict between community and protected area (Ahmad et al., 2012). The human settlements to the surroundings of protected areas and searching the agricultural land result in the reduction of the size of the protected area and affects its biological resources. Any restriction to the use of protected areas affects the social-economic conditions of the people and creates conflict between protected areas and the surrounding community, and the creation of the buffer zone can minimize such conflict (Joseph et al., 2014).

Biodiversity is the foundation of several ecosystem services such as regulation of the climate, purification of the water and air among others and helps to sustain human health on the planet and there should be collaborative approaches between different people of all countries to prevent any challenge to the existing biological resources (Ramanatha, 2020).

In the last few years, much more information on the role of AF in biodiversity conservation has become available. The incorporation of AF tree species in the agricultural landscape can act as a habitat. The AF supports the conservation of biodiversity resources especially the leftovers from natural habitats (McNeely & Schroth, 2006). AF can enhance the biological resources of a given cropped area as it adds the wood components to the existing monoculture system (Zinov'ev & Sole, 2004). AF has the potential for providing habitats outside formally protected land, connecting nature reserves, and alleviating resource use pressure on conservation areas (Bhagwat et al., 2008). Integration of AF can improve biodiversity in agricultural lands (Udawatta et al., 2019). McNeely & Schroth, (2006) highlighted that AF systems can attract biodiversity species in the agricultural landscapes around the natural forest.

The AF local species can contribute more than pure agricultural land management systems but its contribution can be of less impact compared to the NF. Its contribution will depend on other management decisions such as preventing illegal activities. Zabin & Langley, (1976) mentioned that the biodiversity drop could be prevented by incorporation of AF into CL as they provide shelter on land. The appropriate management strategy that considers the ideas of farmers combined with research and follow-up activities can enhance the interaction between AF, NF, and biodiversity (McNeely & Schroth, 2006). It has been shown that AF can help to conserve biological resources, manage the environmental conditions between isolated forests and their surroundings, and can be used as a way of preparedness, mitigation, and adaptation against climate change-related issues (Montes-Londoño, 2017). Further, he suggested the implementation of AF systems in the buffer zones with the purpose of management of biological resources. Sagastuy & Krause, (2019) affirmed that AF could harbor a large number of animals compared to the pure agricultural landscapes in addition to the improvement of soil productivity. AF has been proved to attract more plants and animals while enhancing the functionality of ecosystem services.

The high rate of human growth should not compromise the sustainability of biological resources as they support the functionality of the planet's ecosystems (Leakey, 1998). Rwanda is covered by diversified ecosystems such as natural ecosystems comprising mountainous humid forests, gallery forests, savannahs, wetlands, planted forests, and agro-ecosystems which host several plants and animals (Ministry of Lands, 2005). It has been demonstrated that the favorable ecological conditions together with the geographic position of Rwanda donate the opportunity for having particular plant species especially in Nyungwe mountain rain forest and its patches (Fischer and Killmann, 2008). Human development activities, illegal practices, and the shortage of land were found to be the main factors, affecting the country’s biodiversity resources (REMA, 2010). Dehling, (2014) declared that the main challenge to the country’s biodiversity is due to the people who are searching for land for agriculture expansion.

NNP including its isolated part of Cyamudongo provides vital watershed protection for the country. It harbors a considerable number of animals and plants from which some are endemics. Therefore, NNP is facing several problems as a result of adjacent poor people with high density who need to survive by the resources collected from the forest (USAID and WCS, 2013). It has been proposed that conservation practices are strengthened by monitoring and assessment of biodiversity resources (Lindenmayer et al., 2012). The evaluation and monitoring of reptiles is an essential tool in environmental management (Edgar et al., 2010). The first studies of flowering plants considered some of them to be indicators species due to their association with soil and environmental factors where they create favorable conditions to host the animal resources (Ferris & Humphrey, 1999).

Not much is known about the impact of sustainable AF on biological indicator resources. The impact of sustainable AF on biodiversity indicator species around Cyamudongo fragmented rainforest has not been investigated. Therefore, biodiversity assessment of indicator species is urgently needed to provide a basis for conservation efforts. The aim of this study is to evaluate the impact of sustainable AF on four taxonomic groups of flowering plants, reptiles, amphibians, and ferns as indicator species outside Cyamudongo isolated rain forest while detecting their change with time. It is hypothesized that there is a significant difference with time in targeted biodiversity indicator species due to the implemented sustainable AF practices. In the line of the research aim, the following questions stated:

- What are the biodiversity indicator species for taxonomic groups of flowering plants, ferns, amphibians, and reptiles in the surroundings of Cyamudongo isolated rain forest?
- What is the frequency/relative frequency of flowering plants, ferns, amphibians, and reptiles of the study area?
- How sustainable AF contributes to the attractiveness and management of flowering plants, ferns, amphibians, and reptiles as biodiversity indicator species of the study area?
- What is the threat category based on the IUCN red list for amphibians and reptiles that are induced by sustainable AF implemented in the study area?
- How the flowering plants, ferns, amphibians, and reptiles change with time as far as sustainable AF is concerned?

4.2 Materials and methods

4.2.1 Study area description

The Rusizi district especially in the surroundings of Cyamudongo isolated natural forest has been selected to monitor the biodiversity indicator species including flowering plants, ferns, reptiles, and amphibians. Rusizi District is located in the Southeast of Rwanda and is one of seven districts of the Western Province. The Rusizi district has a total area of 959 km^2. 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-}. Most of the people (>89%) own < 2 ha which compromises the development of agriculture productivity. Several crops are mixed and grown on one ha (GOR-KD, 2019). The Rusizi district has both public and private forests which occupy a total area of 357 km^2. The private forest occupies the largest percentage with 64 % corresponding to 35% of the total district area and it is followed by state forest with 35% and the least is 1% (corresponding to 9.59 km^2) of total district area. High demographic pressure combined with a large number of people who rely on agriculture and intensive precipitation, resulted in land degradation, especially on high slopes. Therefore, land protection measures are needed for sustainable district land management (District, 2013).

Three sectors of the Rusizi District including Gitambi, Nkungu, and Nyakabuye located in the community around Cyamudongo isolated forest were selected because they were the main intervention area of the Cyamudongo Project. However, the increasing human population converted this forest into farmlands and tea plantations and was progressively reduced in size up to 300 ha and harbors a wide range of flora and fauna species (Mvunabandi et al., 2015). However, some wild flowering plants, ferns, reptiles, and amphibians are present in their surroundings, and there was no study conducted to assess these biodiversity indicator resources. 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). Historically, Cyamudongo forest (Figure 1) was connected to Nyungwe on its Northeastern side.

4.2.2 Sampling design

According to Heiskanen et al., 2013, the sampling design consists of the spatial layout of the sample plots, sample plot design, and determination of the sample size. 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. The four km corresponds to the radius of the buffer established by the Cyamudongo Project. The transects and plots of the entire study were consistent (Figure 54).

4.2.3 Biodiversity indicator species survey in AF landscape

The evaluation of biodiversity has been demonstrated to be the preliminary step to manage the habitat. Its purpose is to gather and assess the information required to make decisions and recommendations for the future (Graham et al.,2005). The assessment of biodiversity indicator species was made every 250 m along transect not exactly in plot center of the cultivated area but with focus on the edges or borders of the field. Concerning the biodiversity indicator species, the focus was the forest species known to readily colonize the cultural landscape if certain conditions are met. The first survey was done in the dry season (July and August 2018) and repeated during the rainy season (October and November 2018) to cover the major active periods of amphibians and reptiles. The activity of amphibians is highly dependent on weather, and comparisons between areas of collection under radically different weather conditions may not be valid (Martin et al., 1975).

Given the diversity of amphibian life histories, habitat preferences, and different means of locomotion, more than one sampling technique is needed to sample adequately all species of amphibians(Martin et al., 1975). For reptiles and amphibians, the assessment was done within the plot and opportunistically throughout the transect to maximize data collection. The survey was repeated in 2020 concerning the period the initial assessment was done to detect change throughout the time for biodiversity indicator species because of the establishment of sustainable AF systems in the community around Cyamudongo isolated rain forest.

Furthermore, a digging and search on wood debris, under stones were used to maximize the records. Besides, the local inhabitants were asked if they encounter/observe see some reptiles and amphibians' species on their farms. The instruments employed were a camera to capture photos of recorded species or signs of their presence and pictures to help the subsequent identification while GPS points were taken to record the distribution of collected items in the sampling area.

4.2.4 Statistical analysis

The collected data were analyzed with a focus on hypothesis testing, species richness, diversity, frequency, and endemism. All data were entered, organized in Microsoft excel, and analyzed using Multivariate Statistical Package (MVSP) 3.0. T-test was used to compare a significance level between the two recording times (2018 and 2020) in terms of frequencies.

Species richness was described as a total species list showing family, common and scientific names. The checklists of reptiles and amphibians were produced using data from the field and literature review and their threat category based on the IUCN red list was documented. The software application used to analyze spatial data for map production showing the spatial distribution of recorded items was ArcMap software 10.4.

4.3 Results

4.3.1 Reptiles and amphibians

Three species of reptiles were recorded including one snake (*Philothamnus ruandae)* and two chameleons *(Rhampholeon boulengeri and Bradypodion adolfifriderici* (Figure. 55). In terms of conservation importance, based on the IUCN Red list, one species (*Philothamnus rwandae*: Rwanda Emerald Green Snake) was identified as near threatened (NT) and endemic to the Albertine Rift region while others were of least concern (LC).

Table 22. Species of reptiles recorded in 2018 and 2020 and their IUCN conservation status

Scientific Name	Common name	Family	IUCN status	Endemism
Bradypodion adolfifriderici	Ituri chameleon	Chamaeleonidae	LC	
Philothamnus ruandae	Rwanda Emerald Green Snake	Colubridae	NT	AR
Rhampholeon boulengeri	Boulenger's pygmy chameleon	Chamaeleonidae	LC	

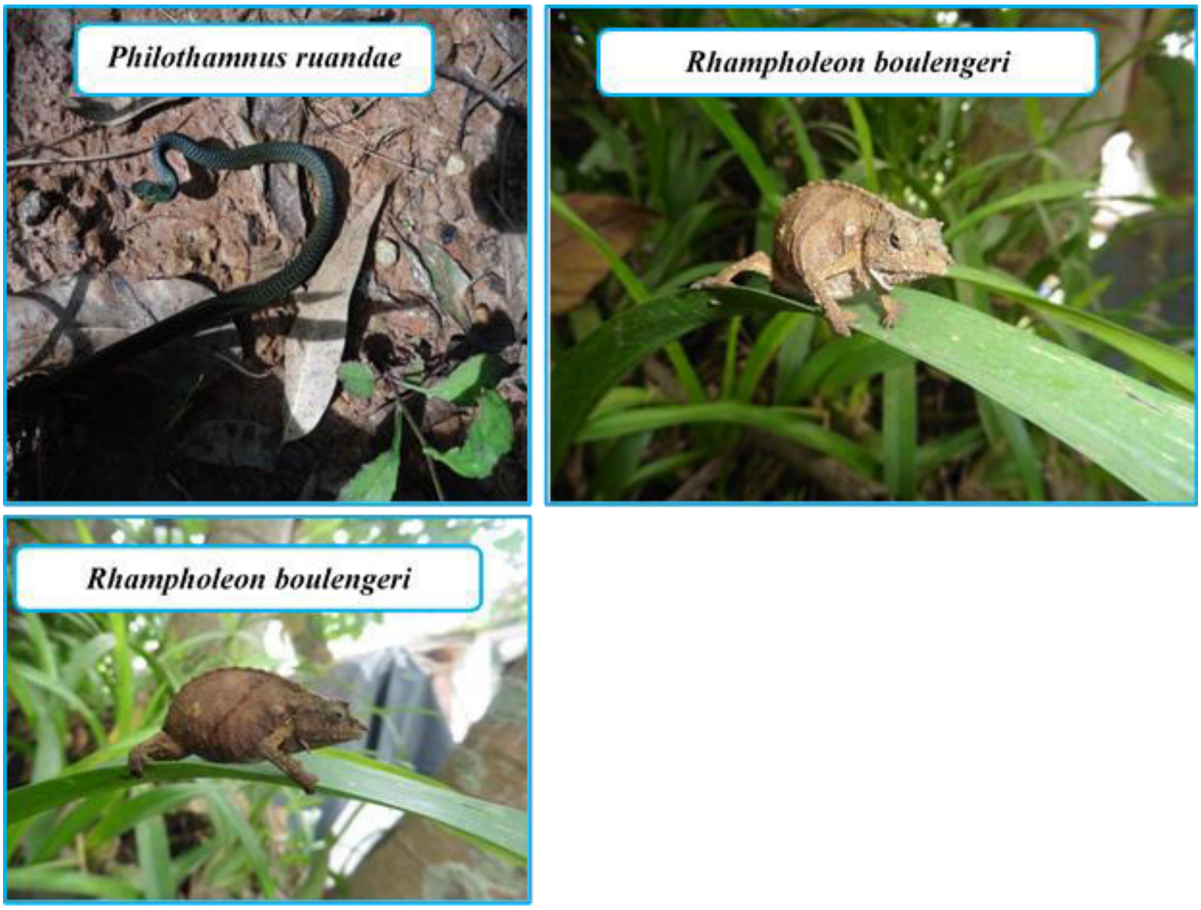


Figure 55.Photos of recorded biodiversity indicator species of reptiles

Four species of amphibians were recorded within plots and along transects including, *Afrixalus orophilus, Sclerophrys kisoloensis, Leptopelis kivuensis,* and *Hyperolius castaneus* while one species, *Boulengerula fischeri* was recorded opportunistically. According to IUCN Red List, two species were Vulnerable (VU) (*Afrixalus orophilus* and *Hyperolius castaneus*), one species (*Leptopelis kivuensis*) is NT, and one species as data deficient (DD) (*Boulengerula fischeri)* while *Sclerophrys kisoloensis* was LC.

Table 23: Species of amphibians recorded and their IUCN conservation status

Scientific name	Common name	Family	IUCN status	Endemism
Afrixalus orophilus	Banana frog	*Hyperoliidae*	VU	AR
Sclerophrys kisoloensis	Kisolo toad	*Bufonidae*	LC	
Boulengerula fischeri	Fischer's African caecilian	*Caecilidae*	DD	AR
Hyperolius castaneus	Montane reed frog	*Hyperoliidae*	VU	AR
Leptopelis kivuensis	Kivu tree frog	*Hyperoliidae*	NT	AR

The result showed that the frequency /relative frequency of the reptiles and amphibians between 2018 and 2020 was significantly changed (t= -2.553, df =7 and sig. (2-tailed) = 0.03).


Sclerophrys kisoloensis (Male)


Sclerophrys kisoloensis (Male)


Sclerophrys kisoloensis (Female)


Hyperolius castaneus


Hyperolius castaneus

Figure 56. Photos of recorded biodiversity species of amphibians

Table 24 summarizes the data on reptiles and amphibians between 2018 and 2020. Based on Shannon's diversity indices of 2020, it was found that the more diverse species among the reptiles were *Rhampholeon boulengeri* (2.565) followed by *Bradypodion adolfifriderici* (0.693) whereas the more diverse species among amphibians was *Afrixalus orophilus* (1.609) followed by *Sclerophrys kisoloensis* (1.386).

A few species were found to adapt well outside the natural forest. These are *Rhampholeon boulengeri* (46.43%) among the reptiles. Also, the two species of *Afrixalus orophilus* (17.86 %) and *Sclerophrys kisoloensis* (14.29%) were found to adapt well outside the natural forest. The other remaining species of reptiles and amphibians may tolerate the environmental conditions outside the forest but care should be taken as are not frequent.

Table 24. Shannon's diversity indices and relative abundance of reptiles and amphibian species recorded in 2018 and 2020

#	Species name	Item	2018			2020		
			Index	Frequency	Relative frequency (%)	Index	Frequency	Relative frequency (%)
1	*Bradypodion adolfifriderici*	Reptile	0	1	5.26	0.693	2	7.14
2	*Philothamnus ruandae*	Reptile	NA	0	0.00	0	1	3.57
3	*Rhampholeon boulengeri*	Reptile	2.197	9	47.37	2.565	13	46.43
4	*Afrixalus orophilus*	Amphibian	1.386	4	21.05	1.609	5	17.86
5	*Sclerophrys kisoloensis*	Amphibian	1.099	3	15.79	1.386	4	14.29
6	*Boulengerula fischeri*	Amphibian	NA	0	0.00	0	1	3.57
7	*Hyperolius castaneus*	Amphibian	0	1	5.26	0	1	3.57
8	*Leptopelis kivuensis*	Amphibian	0	1	5.26	0	1	3.57

Figure 57 compares the frequency of the amphibians and reptiles recorded in 2018 and 2020. It was found that there was a positive change and the frequency number of the recorded species in 2020 was higher than in 2018.

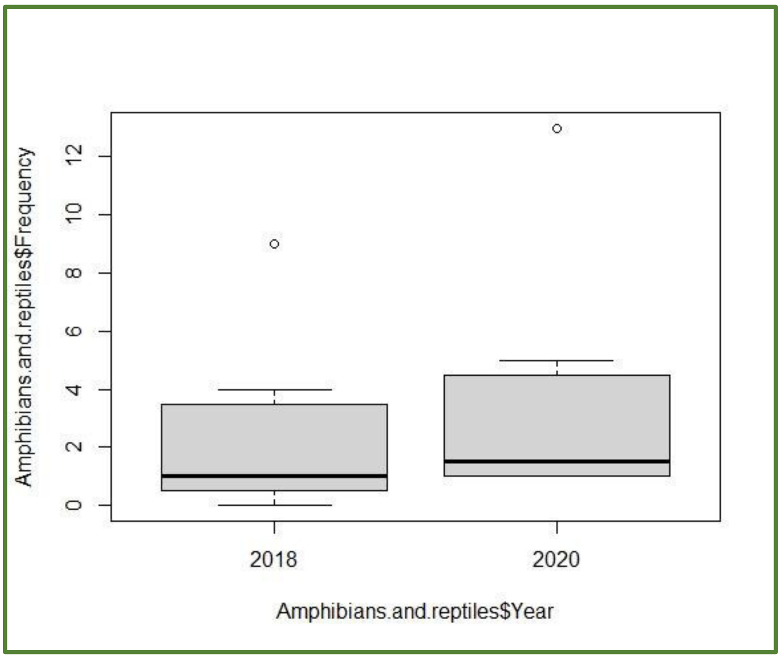


Figure 57. Comparison of recorded amphibians and reptiles in 2018 and 2020

4.3.2 Flowering plants and ferns

Sixteen species of flowering plants and 14 species of ferns were recorded in the plots designed along transects (Table 25). The focus was only on the species, which were in the agricultural landscape, which may also be found inside Cyamudongo isolated rain forest to investigate the impact of sustainable AF being implemented by the Cyamudongo Project to attract the plants and ferns as a result of created favorable environmental conditions outside the forest.

Some plants and ferns were recorded in the same plots while others were found in the independent plots along transects. The recorded plants and ferns were found at an altitude ranging from 1282 m asl to 2015 m asl and 4 km away from the main boundary of the Cyamudongo isolated rain forest. The flowering plant species (16) dominated the recorded ferns in terms of species richness (14).

Table 25. List of recorded flowering plants and ferns

#	Species name	Family	Item
1	*Aneilema aequinoctiale*	Commelinaceae	Flowering plant
2	*Bothriocline ruwenzoriensis*	Asteraceae	Flowering plant
3	*Crassocephalum paludum*	Asteraceae	Flowering plant
4	*Crassocephalum rubens*	Asteraceae	Flowering plant
5	*Cyanotis barbata*	Commelinaceae	Flowering plant
6	*Dioscorea alata*	Dioscoreaceae	Flowering plant
7	*Dracaena fragrans*	Dracaenaceae	Flowering plant
8	*Geranium arabicum*	Geraniaceae	Flowering plant
9	*Ipomoea involucrata*	Convolvulaceae	Flowering plant
10	*Isachne mauritiana*	Poaceae	Flowering plant
11	*Lindernia subracemosa*	Linderniaceae	Flowering plant
12	*Oplismenus hirtellus*	Poaceae	Flowering plant
13	*Ranunculus rugegensis*	Ranunculaceae	Flowering plant
14	*Setaria megaphylla*	Poaceae	Flowering plant
15	*Spermacoce princeae*	Rubiaceae	Flowering plant
16	*Virectaria major*	Rubiaceae	Flowering plant
17	*Arthropteris anniana*	Oleandraceae	Ferns
18	*Asplenium friesiorum*	Aspleniaceae	Ferns
19	*Asplenium aethiopicum*	Aspleniaceae	Ferns
20	*Asplenium mildbraedii*	Aspleniaceae	Ferns
21	*Asplenium normale*	Aspleniaceae	Ferns
22	*Drynaria volkensii*	Polypodiaceae	Ferns
23	*Dryopteris pentheri*	Dryopteridaceae	Ferns
24	*Elaphoglossum acrostichoides*	Lomariopsidaceae	Ferns
25	*Elaphoglossum kivuense*	Lomariopsidaceae	Ferns
26	*Oleandra distenta*	Oleandraceae	Ferns
27	*Pleopeltis macrocarpa*	Polypodiaceae	Ferns
28	*Pteris auquieri*	Pteridaceae	Ferns
29	*Pteris pteridioides*	Pteridaceae	Ferns

30	*Trichomanes rigidum*	Hymenophyllaceae	Ferns

Table 26 summarizes the data on flowering plants recorded in 2018 and 2020. The tests showed that the flowering plants with high Shannon diversity indices (2020) were *Spermacoce princeae* followed by *Dracaena fragrans* and *Virectaria major* with 2.485, 1.946, and 0.693, respectively. The relative frequencies of the aforementioned species were 17.39%, 10.14%, and 2.9%, respectively. The species of *Impatiens burtonii*, *Oplismenus hirtellus,* and *Ranunculus rugegensis* did not show any Shannon diversity index (0) and their relative frequencies were the least (1.45%). Generally, the tests revealed statistical significance for the species recorded in 2018 and 2020 [t=-3.01, df =15 and Sig. (2-tailed) =0.009].

Table 26. Shannon's diversity indices and relative frequencies of flowering plant species recorded in 2018 and 2020

#	Species name	2018			2020		
		Index	Frequency	Relative frequency (%)	Index	Frequency	Relative frequency (%)
1	*Aneilema aequinoctiale*	1.609	2	2.78	1.792	6	5.31
2	*Bothriocline ruwenzoriensis*	2.303	9	12.5	2.708	15	13.27
3	*Crassocephalum paludum*	0.693	2	2.78	0.693	2	1.77
4	*Crassocephalum rubens*	2.079	7	9.72	2.197	9	7.96
5	*Cyanotis barbata*	3.135	21	29.17	3.526	34	30.09
6	*Dioscorea alata*	1.792	5	6.94	1.792	6	5.31
7	*Dracaena fragrans*	1.792	6	8.33	1.946	7	6.19
8	*Geranium arabicum*	NA	0	0	0	1	0.88

9	*Ipomoea involucrata*	0	1	1.39	0.693	2	1.77
10	*Isachne mauritiana*	0.693	2	2.78	1.609	5	4.42
11	*Lindernia subracemosa*	0	1	1.39	0	1	0.88
12	*Oplismenus hirtellus*	0	1	1.39	0	1	0.88
13	*Ranunculus rugegensis*	0	1	1.39	0	1	0.88
14	*Setaria megaphylla*	2.079	7	9.72	2.398	11	9.73
15	*Spermacoce princeae*	1.792	5	6.94	2.303	10	8.85
16	*Virectaria major*	0.693	2	2.78	0.693	2	1.77

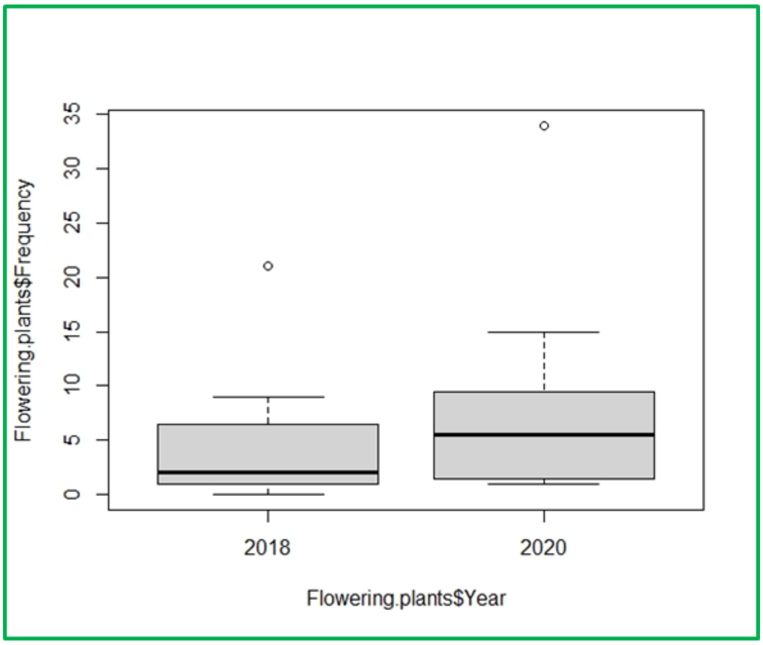


Figure 58. Comparison of recorded flowering plants in 2018 and 2020

Figure 58 compares the frequency of the flowering plants recorded in 2018 and 2020. The results show that the flowering plants recorded in 2020 are higher than the flowering plants recorded in 2018 in terms of their frequencies.

The ferns with high diversity indices were *Asplenium friesiorum* and *Asplenium abyssinicum* with 3.258 and 1.792 respectively, and *Arthropteris anniana*, *Dryopteris pentheri,* and *Elaphoglossum acrostichoides* with similar index (0.693). The relative frequency of the ferns with high diversity indices were 37.68%, 8.7%, and 2.9% respectively. The other remaining ferns (Table 27) did not show any diversity index (0) with a relative frequency of 1.45%. The tests did not reveal any statistical significance for the species of ferns recorded in 2018 and 2020 [t=-1.992, df =13 and Sig. (2-tailed) = 0.068].

Table 27. Shannon's diversity indices and relative frequencies of ferns species recorded in 2018 and 2020

#	Species name	2018			2020		
		Index	Frequency	Relative frequency (%)	Index	Frequency	Relative frequency (%)
1	*Arthropteris anniana*	0.693	2	5	1.099	3	5.77
2	*Asplenium friesiorum*	2.996	20	50	3.258	26	50
3	*Asplenium aethiopicum*	1.386	4	10	1.792	6	11.54
4	*Asplenium mildbraedii*	0	1	2.5	0	1	1.92
5	*Asplenium normale*	0	1	2.5	0	1	1.92
6	*Drynaria volkensii*	0	1	2.5	0.693	2	3.85
7	*Pteris pteridioides*	1.099	3	7.5	1.099	3	5.77
8	*Dryopteris pentheri*	0.693	2	5	1.099	3	5.77
9	*Elaphoglossum acrostichoides*	0.693	2	5	0.693	2	3.85
10	*Elaphoglossum kivuense*	0	1	2.5	0	1	1.92
11	*Oleandra distenta*	NA	0	0	0	1	1.92
12	*Pleopeltis macrocarpa*	0	1	2.5	0	1	1.92
13	*Pteris auquieri*	0	1	2.5	0	1	1.92

14	*Trichomanes rigidum*	0	1	2.5	0	1	1.92

Figure 59 compares the frequencies of ferns recorded in 2018 and 2020 in the sustainable AF systems established around Cyamudongo isolated rain forest. It was found that the frequencies of the ferns recorded in 2020 are higher than in 2018.

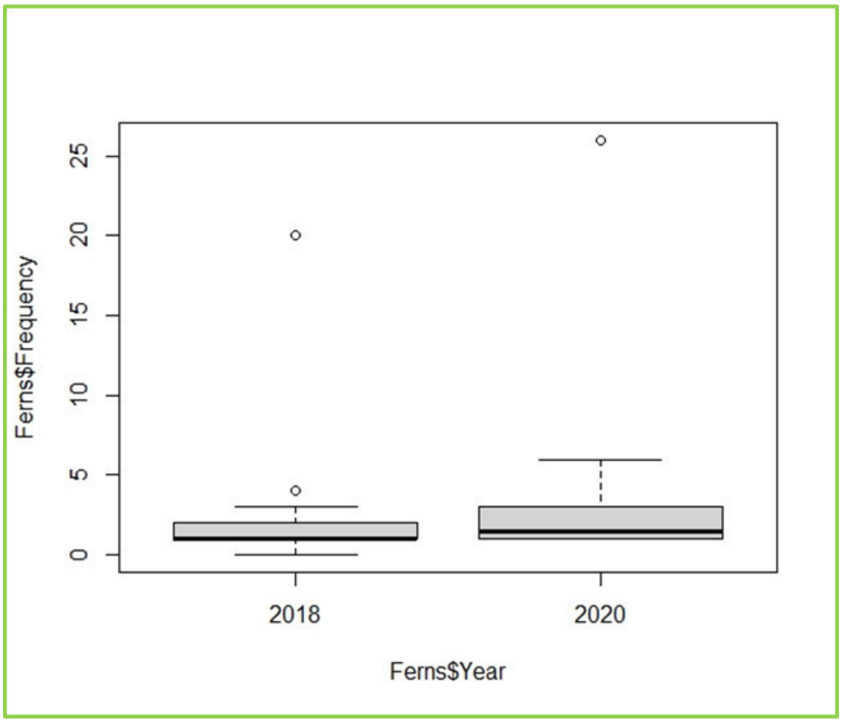


Figure 59. Comparison of recorded ferns in 2018 and 2020

Figure 60 demonstrates the relationship between different flowering plants recorded in the AF systems established around Cyamudongo isolated rain forest. The recorded indicator species were found to familiarize with the environmental conditions but at different scales based on how various species are presented on the Euclidean distance. The species were either joined together to illustrate how they are related together while others were individually branched with already established clusters made by several species.

The flowering species that qualified to be most related are *Virectaria major* and *Geranium arabicum*, which formed cluster 1 according to the Euclidean distance. *Ranunculus rugegensis* together with *Oplismenus hirtellus* and *Lindernia subracemosa* formed cluster 2 as the second related species of flowering plants in the study area. Further, clusters 1 and 2 were grouped to form cluster 3. Cluster 3 was branched with *Crassocephalum paludum34* to make cluster 4, which was further grouped with *Ipomea involucrata* to make cluster 5. Cluster 5 united with *Isachne mauritiana* to form cluster 6, which was further combined with *Aneilema aequinoctiale* to generate cluster 7. Cluster 7 was branched with *Dioscorea spec* to form cluster 8 that was further joined with *Dracaena fragrans* to make cluster 9, which was united with *Spermacose princeae* to produce cluster 10. Cluster 10 was combined with *Crassocephalum rubens* to make cluster 11 that was added to *Setaria megaphilla* to form cluster 12 that was added to *Bothriocline rwenzoriensis* to make cluster 13. Ultimately, cluster 13, which resulted from various clusters, was unified with *Cyanotis barbata* to make cluster 14. The *Cyanotis barbata* was grouped with other several species and it shows high adaptability to accommodate the environmental conditions compared to the other flowering plant species.

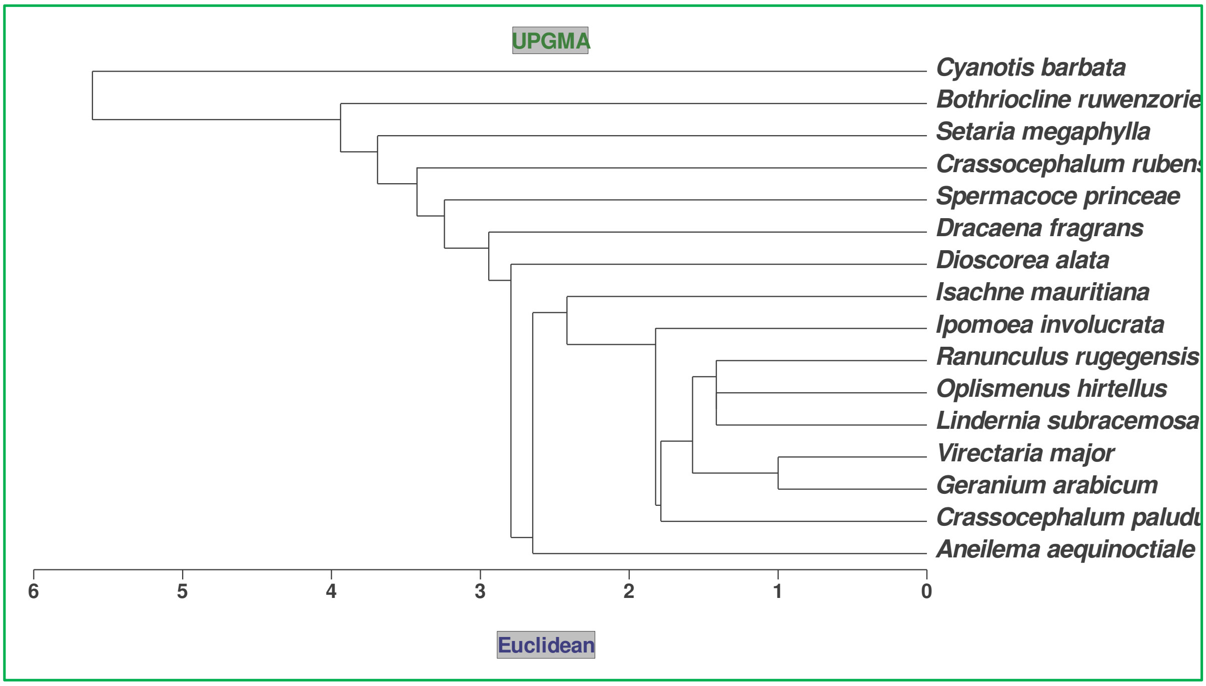


Figure 60. Dendrogram showing the similarity of recorded flowering plants around Cyamudongo isolated rain forest

Figure 61 shows the relationship between various species of ferns recorded in the AF systems around Cyamudongo isolated rain forest. The species of *Asplenium mildibraedii* and *Oleandra distenta* were found to be the most related ferns species, which were grouped with *Elaphogrosum acrostichoides* to form cluster 1 following the Euclidean distance. The species of *Drynaria volkensii* and *Asplenium normale* were grouped to form a second cluster. The species of *Pteris auquerii*, *Pleopertis macrocarpa,* and *Elaphrogrosum kivuens* were grouped to form a cluster 3. *Thrichomane rigidum* and *Dryopteris pentheri* were grouped to form cluster 4. Then clusters 1 and 3 were grouped to form cluster 5, which further grouped with cluster 2 to form cluster 6. Cluster 6 was grouped with cluster 4 to form cluster 7 to further grouped with *Pteris pteridioides* to make a cluster 8. The previous clusters were grouped with *Arthropteris anniana* to form cluster 9. All previous clusters were further grouped with *Asplenium aethiopicum* to form cluster 10 that was finally grouped with *Asplenium frisiorum* to form cluster 11.

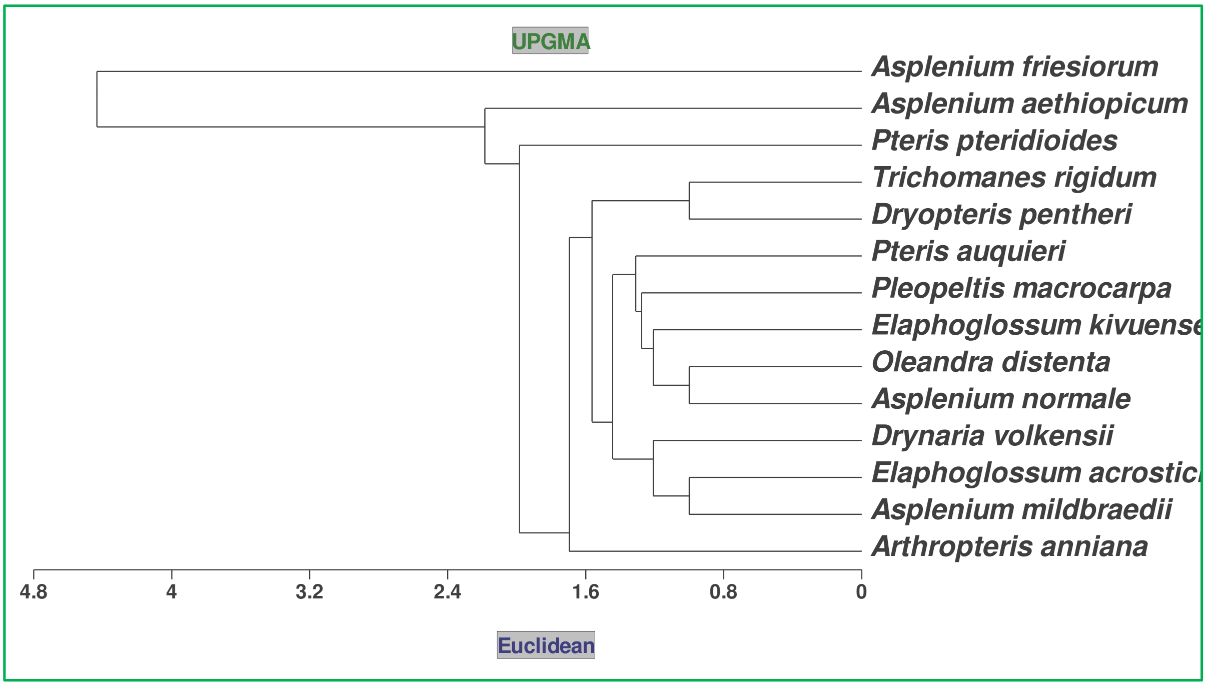


Figure 61. Dendrogram showing the similarity of recorded ferns species around Cyamudongo isolated rain forest

Some of the fern species are grouped along with other many species to form a cluster. In this respect, *Asplenium friosiorum* was grouped with other many species, which previously, formed clusters in different groups by different species. All recorded species were shown how they are related among them and their adaptability to the outside forest conditions compared to many other species of ferns.

The dominant families from which the recorded flowering plants are found are Asteraceae (3 *sp*) and Poaceae (3 *sp*) while the dominant family for ferns is Aspleniacea (4 *sp*) followed by Lomariopsidaceae, Oleandraceae, Polypodiaceae, and Pteridiaceae with an equal number of species (2 sp). The test showed a significant difference for data recorded in 2018 and 2020 in terms of frequencies of both flowering plants and ferns species. The most diverse genera among ferns were Asplenium with four species including *Asplenium friesiorum, Asplenium abyssinicum, Asplenium mildbraedii,* and *Asplenium normale.* Besides, the most diverse genera in recorded flowering plants were Crassocephalum with two species including *Crassocephalum paludum* and *Crassocephalum rubens*.

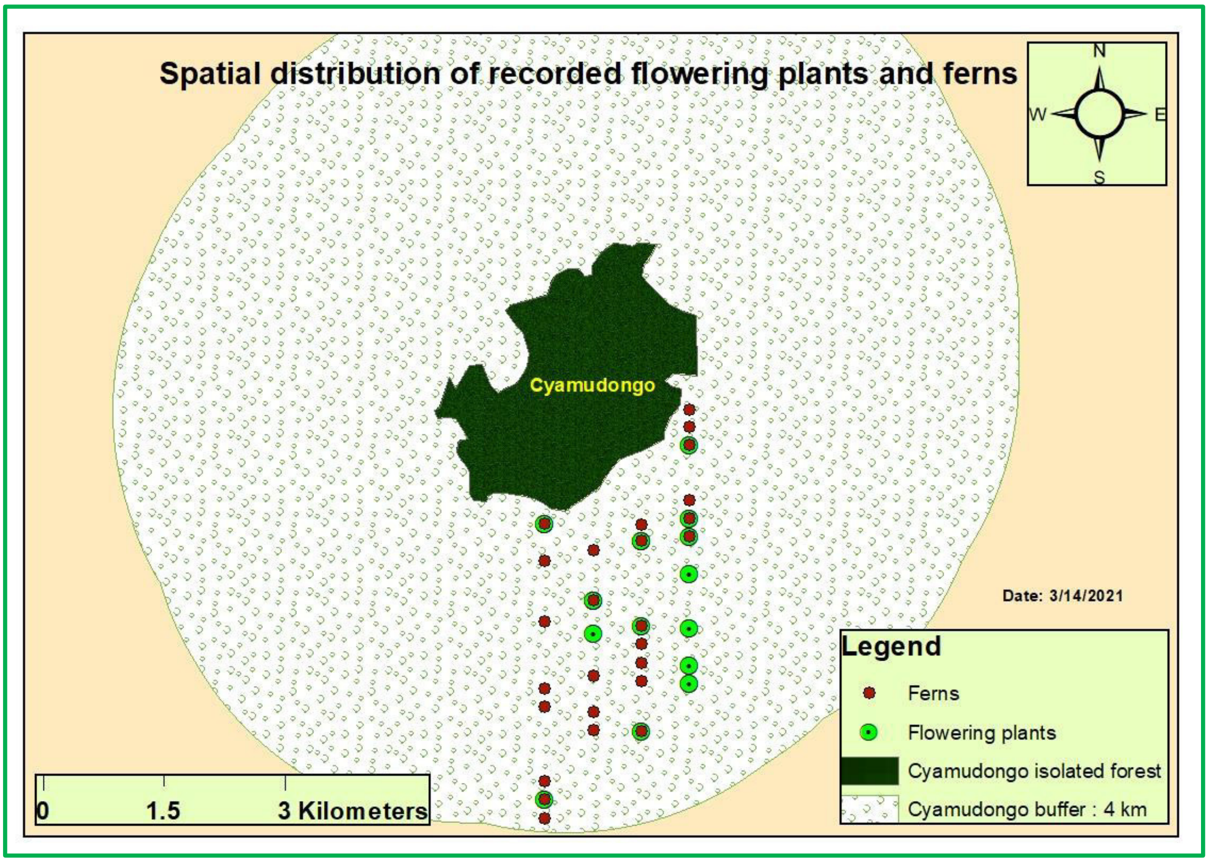
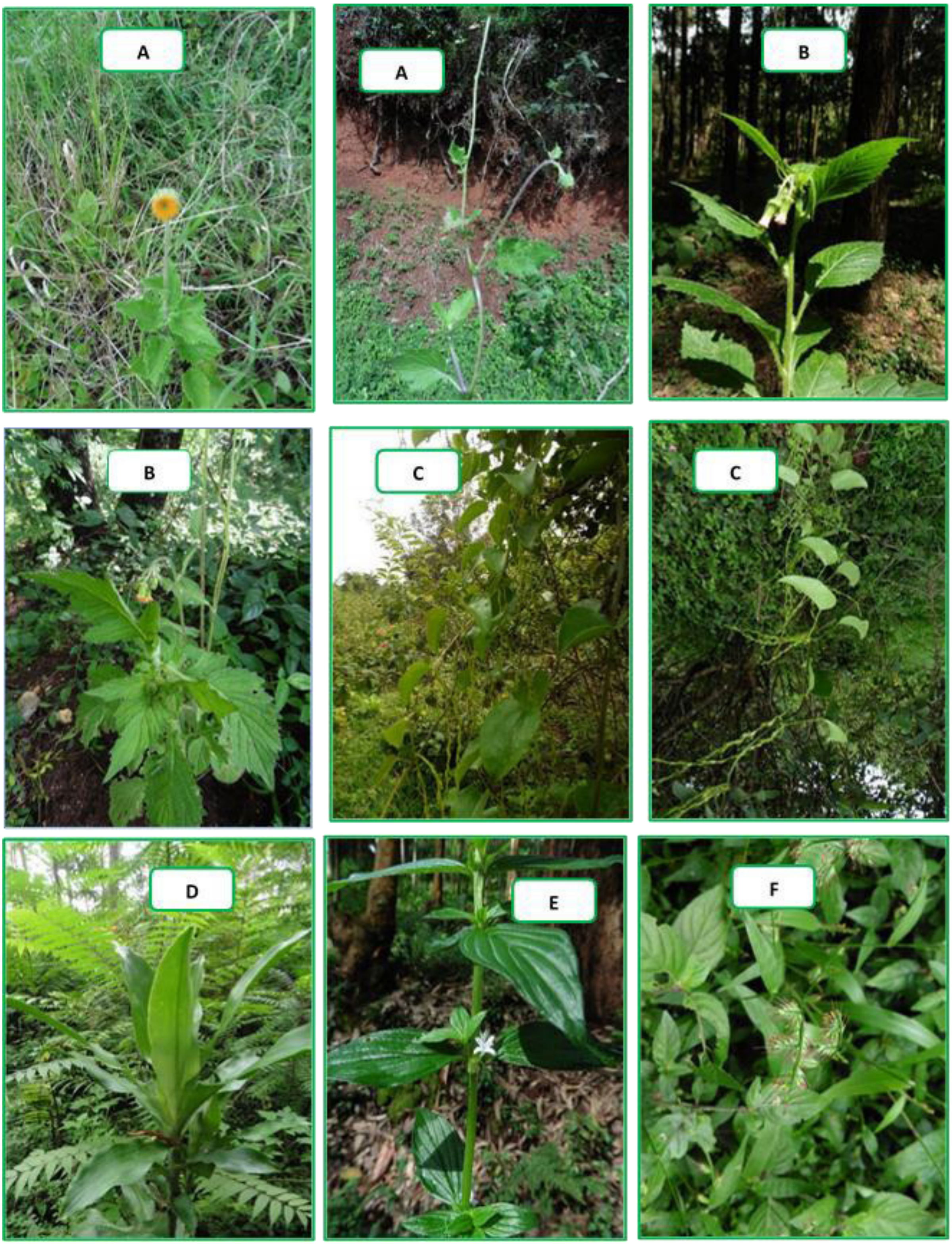


Figure 62. Spatial distribution of recorded flowering plants and ferns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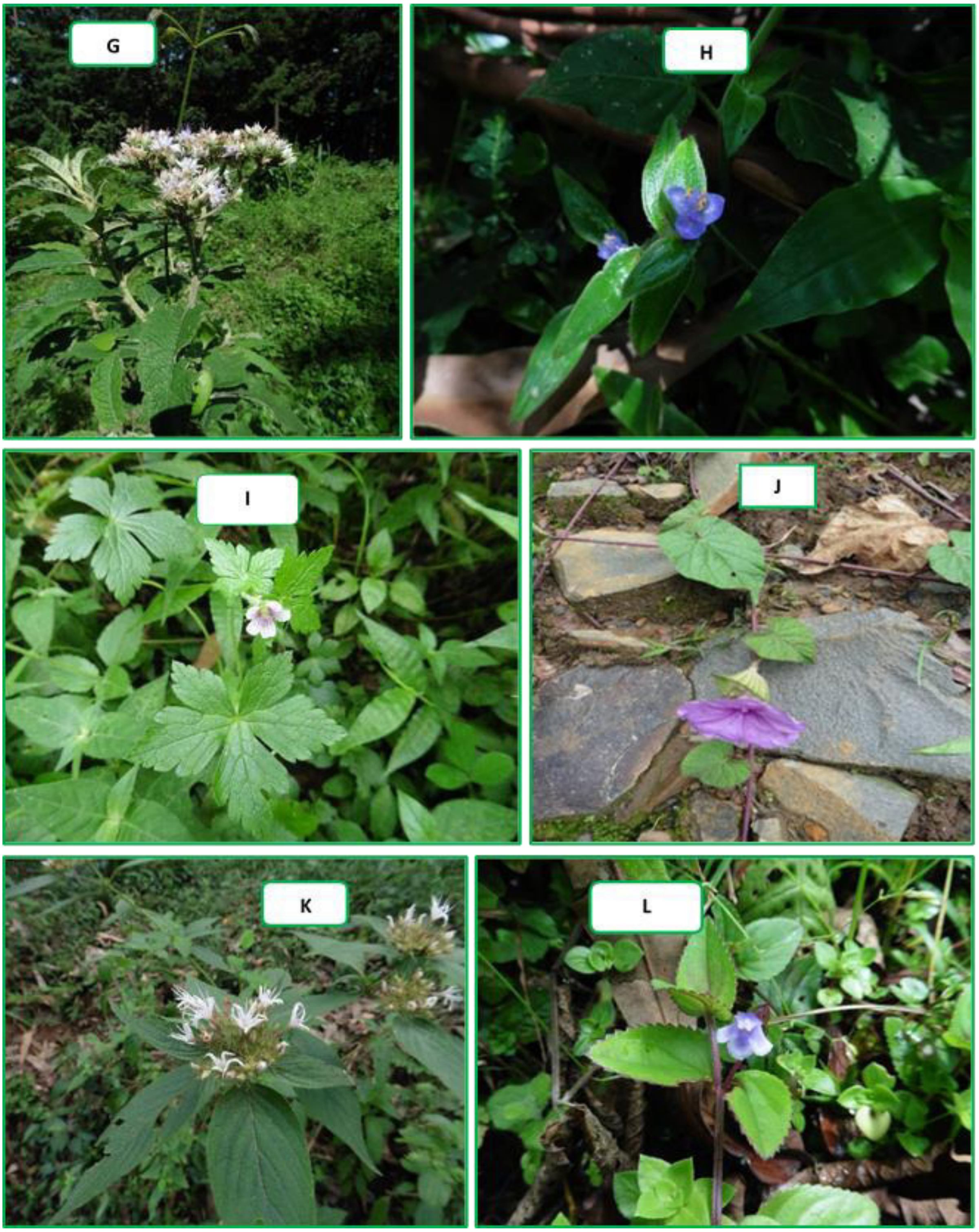
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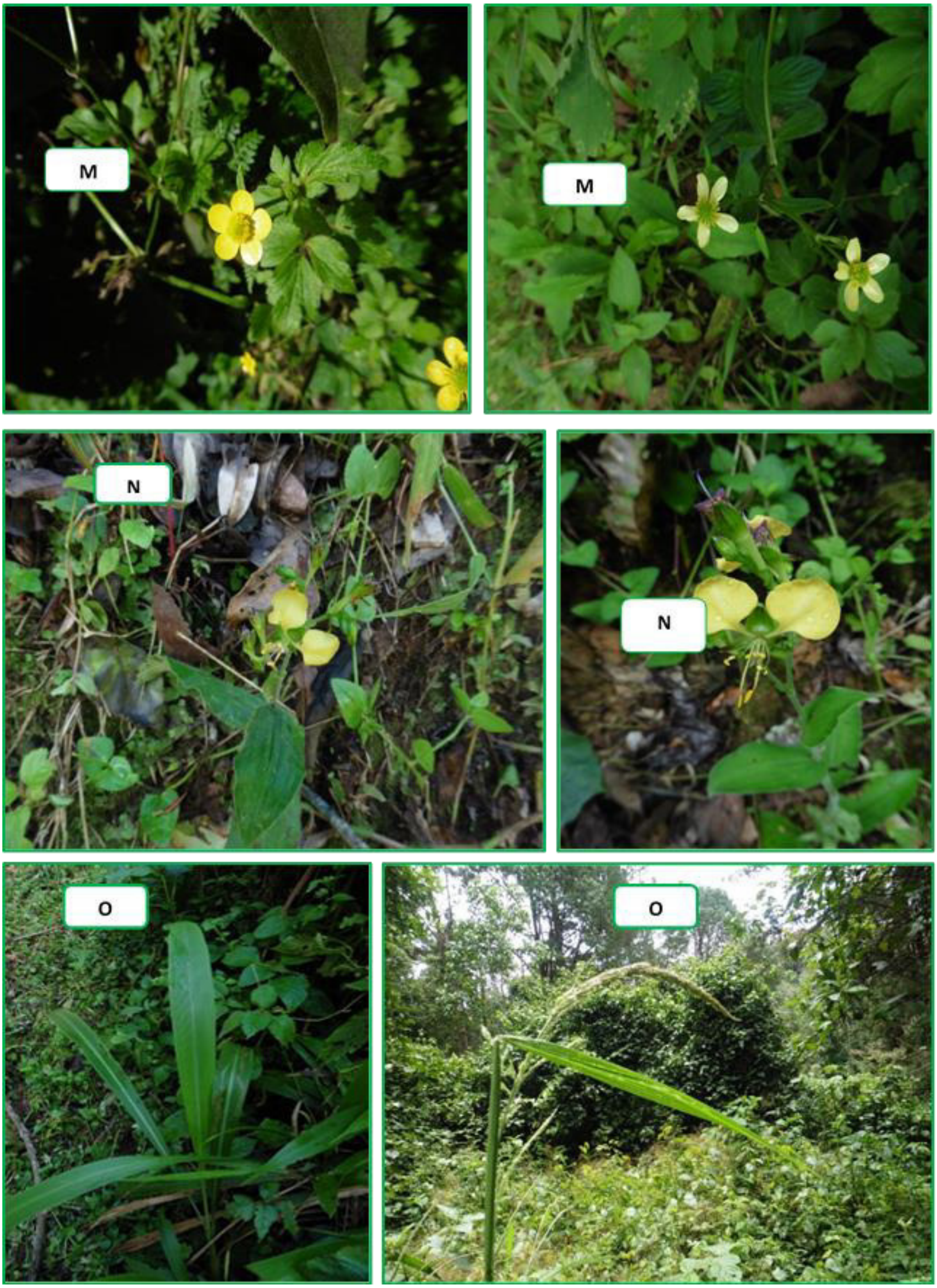
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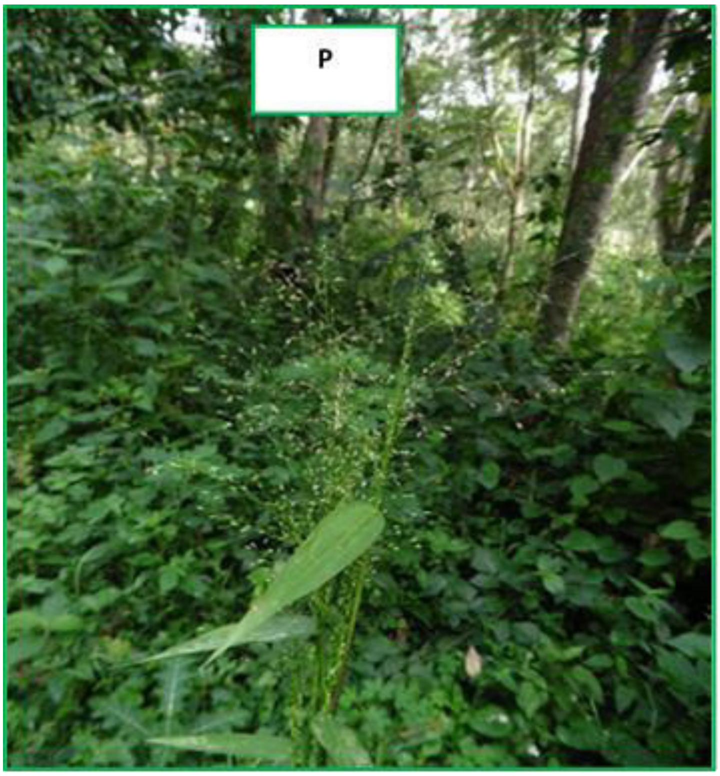

Figure 63. Photos of recorded biodiversity indicator species of flowering plants

A: *Crassocephalum paludum*, ***B***: *Crassocephalum rubens*, ***C***: *Dioscorea alata*, ***D:*** *Dracaena fragrans*, ***E***: *Spermacoce princeae*, ***F***: *Oplismenus hirtellus*, ***G***: *Bothriocline ruwenzorensis*, ***H***: *Cyanotis barbata*, ***I***: *Geranium arabicum*, ***J***: *Ipomoea involucrata*, ***K***: *Virectaria major*, ***L***: *Lindernia subracemosa*, ***M***: *Ranunculus rugegensis*, ***N***: *Aneilema aequinoctiale*, ***O***: *Setaria megaphyilla*, ***P***: *Isachne mauritiana*


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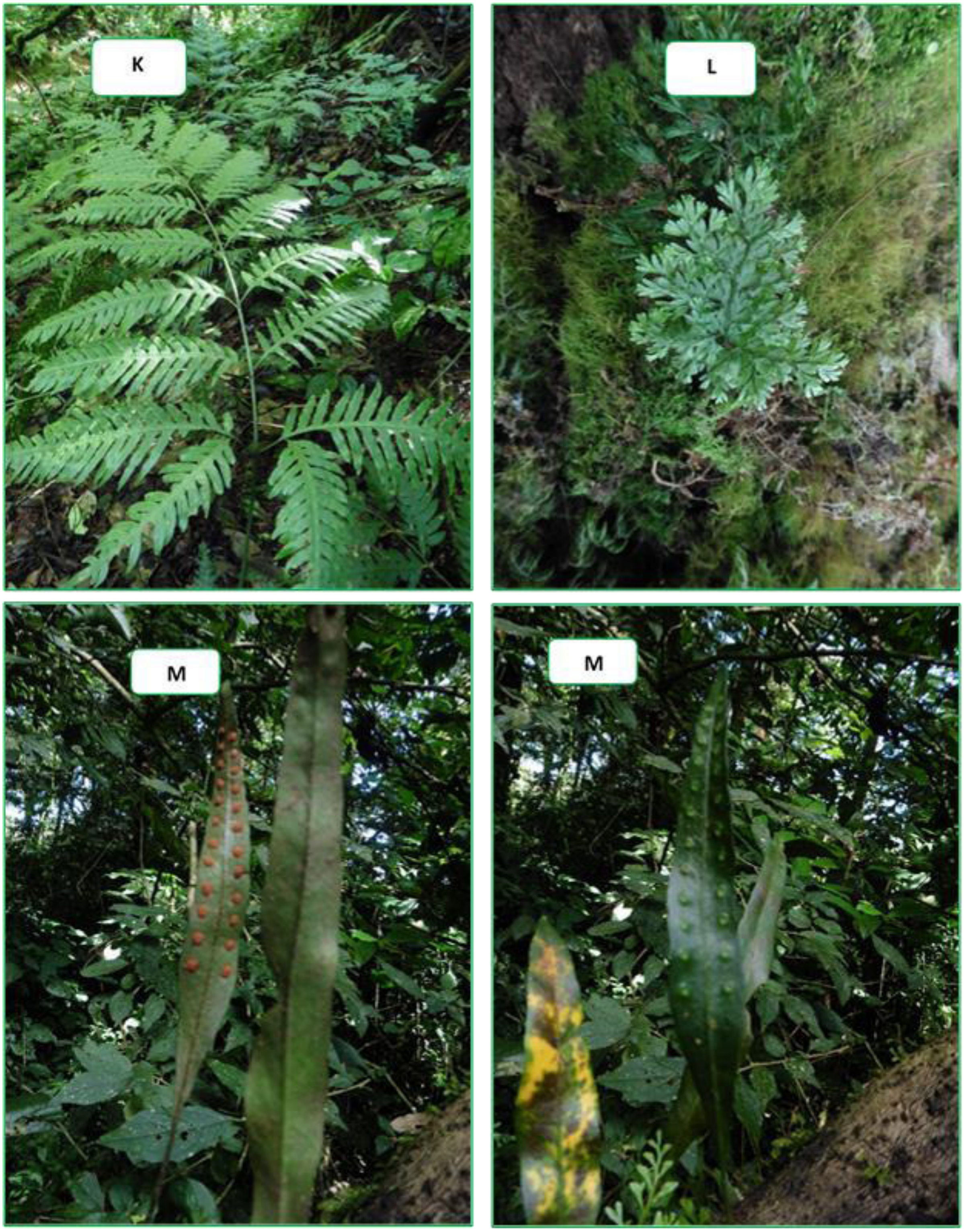
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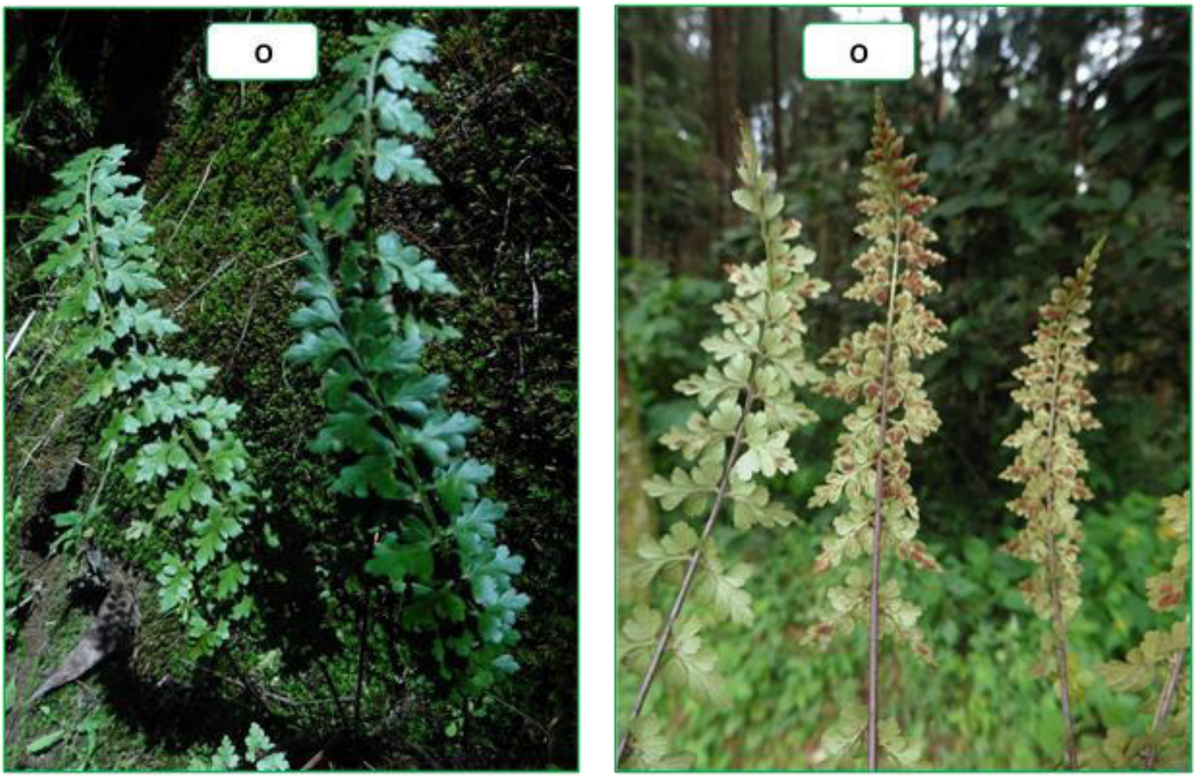

Figure 64. Photos of recorded biodiversity indicator species of ferns

***A**: Pteris pterioides, **B**: Asplenium frisiorum (kivuensis), **C**: Oleandra distenta, **D**: Arthropteris anniana, **E**: Asplenium aethiopicum, **F**: Drynaria volkensii, **G**: Dryopteris pentheri, **H**: Elaphoglosum acrostichoides, **I**: Asplenium normale, **J**: Elaphoglossum kivuense, **K**: Pteris auquieri, **L**: Trichomanes rigidum, **M**: Pleopeltis macrocarpa, **O**: Asplenium mildbraedii.*

Table 26. Detected changes by comparison of biodiversity indicators species in 2018 and 2020

Paired Samples Test for Ferns								
Frequency 2018 - Frequency 2020	Paired Differences					t	df	Sig. (2-tailed)
	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
				Lower	Upper			
	-.857	1.610	.430	-1.787	.073	-1.992	13	.068
Paired Samples Test for flowering plants								
Frequency 2018 - Frequency 2020	Paired Differences					t	df	Sig. (2-tailed)
	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
				Lower	Upper			
	-2.563	3.405	.851	-4.377	-.748	-3.010	15	.009
Paired Samples Test for amphibians and reptiles								
Frequency 2018 - Frequency 2020	Paired Differences					t	df	Sig. (2-tailed)
	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
				Lower	Upper			
	-1.125	1.246	.441	-2.167	-.083	-2.553	7	.038

4.4 Discussion

The sustainable AF practices changed the frequency of reptiles, and amphibians in the AF system implemented in the agriculture landscape located in the surroundings of Cyamudongo isolated rain forest. The comparison of the assessment results of 2018 and 2020 was made with regards to the frequencies and the tests revealed that the reptiles and amphibians were significantly changed (Sig. (2-tailed) and p-value= 0.038).

Besides, their change could be attributed to the cover of most of the planted trees, which could keep the humidity on the ground and make suit microhabitats to the survival of amphibians and reptiles. This result is supported by Udawatta et al., (2019) who stated that the importance of the AF system on biodiversity includes preserving germplasm of sensitive species, connecting remnants micro-habitats and support their integrity and their conservation, erosion control, water recharge, and increase of the moisture in the soil.

The amphibian species (5) are more dominant compared to the reptiles (3) concerning species richness of the study area. The tests showed that reptiles' and amphibians' species richness and relative frequencies in the surroundings of Cyamudongo isolated forest were significantly affected by sustainable AF practices coupled with best agronomic practices, which have improved the habitat of the reptiles and amphibians between 2018 and 2020. According to IUCN conservation status, one species of reptile is NT while two species are LC. Besides, two species of amphibians were found to be VU, one species is recorded as LC, one species is NT, and one species is DD.

As the results of this study show, the impact of AF on amphibians is more pronounced compared with reptiles as indicated by species richness, diversity index, frequency, and relative frequency. This significant change is attributed to sustainable AF practices including scattered trees on CL, boundary planting, home garden, and plantation on contour lines; and agronomic practices introduced, facilitated, and applied by the farmers, which have reduced the degradation of microhabitat of the reptiles and improved their habitats.

The combined effect of various AF trees species introduced and existing native mature species together with agriculture best practices such as erosion control, use of organic manure, and crop rotation among others created the multistage layers with a favorable environment, which contributed to the attractiveness of reptiles and amphibians in the agricultural land surrounding the Cyamudongo isolated forest while improving the agriculture production. This is in good agreement with Angarita et al., (2015) who reported the impact of AF in the modification of area conditions which favor the occurrence and dispersal of a few numbers of the leftover species of reptiles and amphibians after changing the natural forest into agricultural land uses.

Mostly, the amphibians were found in the plots with or bordering the water streams or ponds. Even though their change was significant, but still few species of reptiles and amphibians were identified. This last evidence shows how much the identified species should be given conservation priority. These results concur with the finding of Jonathan et al., (2004) in which he reported that the amphibians' declines and extinctions are a worldwide concern and their conservation priorities should target threatened taxonomic targets and regions with high levels of species endemism.

The species of *Boulengerula fischeri* with DD belonging to the Caecilian group of Herpelidae family that lives hidden in the ground and was found under banana plants of Rwihene village, Kingwa cell of Gitambi sector and in Nyaruhondo village, Mataba cell in Nkungu sector. This result conforms with the finding of Measey et al., (2011) who found it living in soil under banana plants after digging or by moving a fallen banana stems in the surroundings of Cyamudongo isolated forest.

Results of other studies showed similar responses of amphibians and reptiles in AF. Several long-term studies have examined how reptile species richness depends on land management. The study of Wanger et al., (2010) assessed the effects of land-use change on community composition of tropical amphibians and reptiles in Sulawesi, Indonesia, and found that reptile species richness was highest in natural-shade cacao AF and was only marginally different in the other habitats. Further, he found that the natural-shade cacao AF might enhance the resilience of both amphibians and reptiles against extensive species loss. For reptiles, natural-shade cacao AF may provide a valuable habitat on its own. Michael et al., (2018) studied the revegetation, restoration, and reptiles in rural landscapes as the insights from long-term monitoring programs in the temperate eucalypt woodlands of southeastern Australia and found significantly more reptile species on farms with higher amounts of native vegetation compared to farms with lower amounts of native vegetation. Baillie et al., (2004) reported that the chytrid fungus affects highly many of the Bufonidae species.

Comparing disturbed areas, teak AF presented the highest diversity for both taxa relative to non-natural environments, by factors such as big leaf size, generating conditions to the sustenance of some species. The introduction of AF resulted in alterations of the spatial distribution of species, restricting them to small remnants of native forests (Reklaitis et al., 1992). Transforming CL sites into structurally rich plantations can therefore be a valuable strategy for enhancing biodiversity in these AF systems, particularly if these sites are close to more natural source habitats (Brüning et al., 2018). Once the trees have matured to the degree that they are shading out the crop, that habitat becomes important for amphibians, which must travel from one activity area to another but must stay moist.

The number of recorded indicator species of flowering plants (16) was higher than the number of ferns (14) which shows the higher adaptability and species diversity of flowering plants compared to the ferns, especially in the conditions under the study area. In the context of agricultural productivity, some of the identified species were found to be invasive species as they can highly compete with associated crops. In addition to the observation made in the field and the farmers' feedback, this assumption was also based on their relative frequencies and Shannon diversity indices, which were very higher than other species.

These species are *Cyanotis barbata* and *Bothriocline ruwenzoriensis* among flowering plants and *Asplenium friesiorum* and *Asplenium aethiopicum* among ferns. This result shares a number of similarities with Silva et al., (2018) who recorded the families of Polypodiaceae and Pteridiaceae among others, and Asplenium as the most diverse genera among ferns recorded outside forests. On the other hand, the recorded species of *Ranunculus rugegensis* was found to be threatened and endemic to the Albertine Rift Region and it is restricted to Eastern D.R.Congo, Western Uganda, and Western Rwanda (Fischer, 2011).

AF attracts and helps to manage more biodiversity resources compared to any other land-use system with no tree integration while enhancing soil productivity (Sasal et al., 2015). They further confirmed that the plants change with time is pigeonholed by the augmentation of the number of species. Results so far have been very promising and it is expected that once the various AF tree species are grown mature, they will attract more species than how it does today. The mature and dead trees contribute more to the attraction of the forest biodiversity species including plants and animals than young species (World Conservation Monitoring Centre, 2013)

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Our work has led us to the conclusion that sustainable AF can contribute to the improvement of the C stock pools of AF and soil, change of soil properties, and biodiversity conservation especially in the area connected to the protected isolated rain forests.

In this study, various AF tree species (Table 1) were documented in terms of their contribution to the C stock and sequestration in different agro-ecological conditions of Rwanda including the surrounding areas of Cyamudongo isolated rain forest located in Rusizi District and Arboretum of Ruhande in Huye District. In all study areas, it was found that various AF tree species contribute differently to C stock and C sequestration and the amount of C stored and removed from the atmosphere depends on different factors such as tree species, plantation density, growth stage, or the age of establishment, applied management practices, WSD, wood C concentration, and climatic conditions in terms of rainfall and temperature.

The tests revealed that the sustainable AF practices implemented in the area around Cyamudongo isolated rain forest contribute more to C stock compared to the AF system of Ruhande Arboretum. In terms of C sequestration, it was found that the young AF tree species of Cyamudongo study area sequester more C than the mature AF tree species of Ruhande Arboretum. The t of CO_2 ha^{-1} yr^{-1} of young AF tree species was higher than the t of CO_2 ha^{-1} yr^{-1} of mature AF tree species which indicates the potential of young species in climate change mitigation and adaptation. The *Grevillea robusta* was found to store more C in all study areas and this showed its importance in the areas of Rwanda as a strategy to mitigate against climate change-related issues through C sequestration in addition to its contribution to the improvement of farmers wellbeing through the provision of multi-products and services such as fuelwood, stakes, timber and erosion control.

Returning to the hypothesis posed at the beginning of this study, it is now possible to state that there is a significant difference between the amount of the fixed C in the biomass of AF trees species established by the project and the existing AF trees species of the study areas.

The results highlighted differences in terms of WSD for various AF tree species from different study areas. Surprisingly, one of the AF tree species of the Cyamudongo study area was qualified to have more WSD value than other mature tree species. A 2-year-old *Croton megalocarpus* was found to have a high value of WSD followed by a mature species of *Grevillea robusta* and mature *Cedrela serrata.* In Ruhande, *Grevillea robusta* was found to have more WSD value followed by *Cedrella serrata*, *Maesopsis eminii,* and *Polyscias fulva*.

The tests revealed differences in terms of nutrient contents for various AF tree species of Cyamudongo and Ruhande study areas. Generally, this result did not show any significant difference for seven AF tree species of the Cyamudongo study area as far as the C: N ratio is concerned. Inversely, the tests revealed significant differences for four AF tree species established in the Ruhande AF plot. The tree content in terms of K was significantly different among AF tree species and tree components and the highest amount was recorded in leaves compared to the other components. Similarly, for the Mg and Ca content, the leaves had significantly the highest amount compared to the other components and among tree species while the highest amount of Na was recorded in the stem. This result has further strengthened our hypothesis that there is a significant difference between nutrient contents of AF trees established by the Cyamudongo Project and the existing AF trees species of the study areas especially for K, Mg, Ca, and Na. Despite this, it is clear to reject this assumption as far as the C: N ratio of different AF tree species is concerned.

The correlation between various tree variables was ranged from strong to very strong for AF mature tree species whereas it was found to be negligible to very strong for young AF tree species of the Cyamudongo study area. For Ruhande AF mature tree species, the correlation varied from moderate to very strong. The differences in terms of correlation for various AF tree species in different study areas varied with tree species, age, stage of growth, and tree shape.

By comparing the correlation coefficients for various tree variables for young and mature AF tree species, the results showed a high correlation variability for young species than mature or old species recorded in different environmental conditions of Cyamudongo and Ruhande study areas. The young tree species have a high growth rate, which affects rapidly some of the tree variables such as tree height and diameter, and these variables together with the WSD affect the overall tree biomass and C stock. For mature trees, the change in terms of height and diameter is not remarkable. These were found to be the main reasons for the low variability of correlation for mature tree species compared to young tree species. The correlation coefficients of mature AF tree species of the Cyamudongo study area ranged from medium to very strong whereas the mature AF tree species of Ruhande Arboretum ranged from strong to very strong as far as different tree variables are concerned. The correlation coefficients for 2 years established AF tree species by Cyamudongo Project varied from negligible to very strong that depended on correlated tree variables and species.

The tests revealed that the soil pH, C, C: N ratio, OM, NH_4^+, NO_3^-+NO_2^-, PO_4^{3-}, and CEC were significant in different soil depths whereas the N was not statistically significant. 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 NO_3^-+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. The BD of soil was statistically different across land uses and altitude ranges.

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 NO_3^-+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 NO_3^-+NO_2^-. The hypothesis is also supported and accepted for BD of the soil in various land uses and altitude ranges.

The sustainable AF practices changed significantly the frequency of reptiles, amphibians, and flowering plants in the surrounding area of Cyamudongo isolated rain forest while there was no statistical change observed on ferns with time as far as the frequency is concerned. There is evidence to support the hypothesis that sustainable AF affects significantly the biodiversity indicator species with time especially for flowering plants, reptiles, and amphibians.

These findings add to a growing body of literature on the impact of AF on the C stock, soil improvement, and biodiversity conservation. Transforming traditional agriculture into sustainable AF systems with various practices containing native tree species established in different times can therefore be a valuable strategy for attracting biodiversity including flowering plants, ferns, reptiles, and amphibians in the areas close to the natural source habitat of Cyamudongo isolated forest. I am confident that this research will serve as a base for future studies on the contribution of AF to C stock, soil properties, and biodiversity conservation, especially around protected areas. The current study was not specifically designed to monitor only the biodiversity indicator species rather targeted also various aspects of the wood biomass, nutrients content, and soil parameters. Despite this, I believe my work on the contribution of sustainable AF to the conservation of biodiversity indicator species could be a springboard for further studies.

5.2 Recommendations

- **For researchers**

It is proposed and recommended that further researches should be undertaken in the following areas:

- Contribution of other AF tree species to the C sequestration and C stock found in the agricultural landscape around all protected areas of Rwanda and the remnant natural forests such as Busaga natural forest and Ibanda-makera.
- The impact of micro-climate and an altitudinal gradient on the biodiversity indicator species around protected areas to facilitate land-use planning.

- **For policy and decision-makers, and land use planners**

- This research suggests that the policy and decision-makers and land use planners should take into consideration the biodiversity resources in the environmental policy and implementation plans. The evidence from this study intimates that there is a need for an integrated long-term monitoring plan for the biodiversity indicator species found in the area around Cyamudongo isolated rain forest.

- **For investors**

- The investors are recommended to invest in the community development projects and activities that can contribute to the improvement of the livelihood of the people especially around protected areas that mainly rely on the forest resources especially in Cyamudongo.

- **For partners and stakeholders**

- The partners and stakeholders in agriculture, forest and conservation activities should work collaboratively for the best practices of sustainable AF especially around protected areas as it is long term solution to the current changes related to climate change, land degradation, and biodiversity as the main driver of the environmental ecosystem services.

- **District and sector's agronomists and forest extensionists**

- The agronomists and forest extensionists at district and sector levels should engage the farmers in the agriculture development best practices and environmental education activities to make the farmers aware of the role of biodiversity in the sustainability of the human being on the earth so that there will be the improvement of the current biodiversity through applied best agriculture and forest activities.

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- My gratitude extends to the management of the Cyamudongo Project and staff for the endless support and encouragement from the beginning to the end of my Ph.D. studies: Mr. Siegmar Seidel, Prof. Dr. Eberhard Fischer, Mrs. Chantal Broccard, Mrs. Petra, Dr. Iris

Elisabeth Dröscher, Mrs. Katharina Rösch, and Ms. Ricah Wedegärtner, Dr. Marco Harbusch, Ms. Sarah Marie Müller and Mr. Aimable NSANZURWIMO among others.

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- I am indebted grateful to Mr. Ulli Bange and his team for the laboratory work including Ms. Annika Böhmer among others especially for their cherished time with many hours per day spent in the lab.
- I owe so much thanks to my wife, Marie Chantal ZANINKA, and my sons (Zidane HIRWA and Lucky HIRWA) for their love, moral support, encouragement, and patience during my absence from home. I cannot thank them enough.
- Thanks are also due to Mr. Jean De La Paix MURAGIJIMANA for English correction in this thesis and his day-to-day encouragement.
- Thanks are also due to Dr. Marie Laure RURANGWA who gave me much valuable advice and encouragement during my studies.
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- I am indebted grateful to the academic staff of IPRC Kitabi and more specifically Head of Forestry Department Mrs. Adeliphine MUDASHAMAGIRA and her team for their flexibility on the teaching timetable and encouragement during my studies.

- Probably I forgot to acknowledge someone who contributed to the completion and success of my Ph. D studies, if so, please forgive me, as I am always thankful.

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PERSONAL SUMMARY

I am a Ph.D. candidate in **Agroforestry** from the University of Koblenz-Landau /Germany, a holder of a Master of Science in **Environmental Management** from Kampala International University, and a Bachelor's degree with Honor in **Agroforestry** from UR former ISAE-BUSOGO and Secondary Level certificate in **Forestry** A2. I am a higher learning institution and university experienced lecturer with over 7 years in the field of education.

I am currently **Deputy Principal in charge of Academics and Training** of IPRC Kitabi. I **headed the department of Forestry Resources Management** of IPRC Kitabi for 3 years. I am skilled in working with projects. I worked with PAREF BTC, RIFFEAC, and GIZ as well as a very competent consultant in forestry and environmental management-related disciplines. I consulted in All Africa Golf East Africa Construction Ltd, SINGITA Kwitonda Rwanda, New Forest Company, BIOCOOP, etc.

I have very remarkable and reputable competencies in capacity building where I organized and coordinated several pieces of training such as ToT in GIS and RS, Knowledge Transfer, Harvesting Techniques, Forestry Inventory, Silviculture among others. I participated in summer schools and different international pieces of training and workshops in various countries such as Germany, Italy, Netherlands, Cameroon, etc. I have experience in research and academic writings. I can analyze data with data using various software such as ArcGIS, R, PAST, MVSP, and SPSS among others. I am a good communicator, Fluent in Both English and French.

I have paramount achievements in the academic sector where I proposed, designed, and participated in developing the curriculum of Forestry Engineering and Wood Technology of IPRC Kitabi; and proposed and Developed the Wood Innovation Center/ Center of Excellence in Nyamagabe District. Moreover, I have got significant memberships and appointments (RIFFEAC as a focal point at IPRC KITABI, Member of General Assembly and Administrative Council, Scientific facilitator in MoU between the University of Koblenz-Landau and IPRC Kitabi).

AREAS OF EXPERTISE

1. Forestry
2. Agroforestry
3. Agriculture
4. Landscaping
5. Environmental Management
6. Curriculum design and development

WORK EXPERIENCE

April 2021-Present: Rwanda Polytechnic-IPRC Kitabi

Deputy Principal in Charge of Academics and Training

July 2018 –Present: Rwanda Polytechnic-IPRC Kitabi

Senior Lecturer in Forest Resources Management Department

December 2015-June, 2018: IPRC Kitabi former Kitabi College of Conservation and Environmental Management (KCCEM).

Lecturer and Head of Department of Forest Resources Management

January 2014-December, 2016: Muhabura Integrated Polytechnic College.

Part-time Lecturer in MIPC

January, 2013-December: Community Integrated Polytechnic,

Assistant Lecturer and Head of Agriculture Department

2014-2015: University of Rwanda-CAVM/ Busogo campus

Assistant Coordinator of PAREF Be.2 and GIS Lab Assistant

2014-2015: IPRC Kitabi former Kitabi College of Conservation and Environmental Management (KCCEM).

Part-time Lecturer in Forest Resources Management Department

2010-2013: MINAGRI

Supervisor of crop assessment in GAKENKE District

September 19/2012-October 10/2012: BUMBOGO sector of GASABO District

Enumerator Post Enumeration Survey

January 18/ January to February 28/2011: CIAT/Harvest Plus/NYAMAGABE, NYARUGURU, NYAMASHEKE, and RUSIZI Districts

Supervisor in the Farmers Choice of Bean Varieties Study Survey

2007: EAVFO/GISOVU SECONDARY SCHOOL

Teacher in Forestry Department

CAPACITY BUILDING AND TRAINING

- **January-February 2020: Rwanda Wood Value Chain Association (RWVCA)**

  Propose, organize, develop and implement the workshop on wood seasoning and timber drying techniques, and industrial based training on wood processing for RWVCA members under the support of the Private Sector Federation (PSF)

- **April 2019: Italy**

  Participant in Wood Value Chain of the key Rwandan Forestry Sector Actors under the support of GIZ Rwanda

- **March 2018:** MoU between The University of Koblenz-Landau and IPRC Kitabi

  Scientific Facilitator of its implementation

- **June -July 2018:** KCCEM & RIFFEAC

  Organizer and coordinator of the workshops of Application of GIS&RS in Biodiversity Conservation and Adapted teaching methods for Lecturers of Rwanda and Protected area managers under the support of GIZ Rwanda

- **March, 2018:** Koblenz-Landau- University & IPRC KITABI

  Facilitator of Entrepreneurial design-thinking-workshop in Rwanda

- **January 2017**: RIFFEAC at Cameroun-Douala

  Participant in Technical workshop

- **Sep-Nov, 2016**: Frunk Fort University, Germany under GIZ & RIFFEAC project

  Summer school participant

- **Aug 29-Sep 19, 2015**: UR-CAVM/ BUSOGO campus

  Trainer on the application of GIS&RS in forest management

- **July10-24, 2015**: UR-CAVM/ BUSOGO campus

  Trainer of forest inventory module

- **Aug 24-28, 2015**: **DFS- Deutsche Forest service GmbH, held on UR-CAVM**

  Participant in the training of trainers of application of GIS&RS in forest management

- **July 6-10,2015**: **DFS- Deutsche Forest service GmbH under the support of BTC-PAREF Be.2**

  Trainer of trainers of forest inventory held at UR-CAVM/ BUSOGO campus

- **12-16/01/2015**: **DFS- Deutsche Forest service GmbH under the support of BTC-PAREF Be.2 Project**

  Training Harvesting techniques in Buffer Zone of NNP using a chainsaw

- **2-5/03/2015**: **DFS- Deutsche Forest service GmbH under the support of BTC-PAREF Be.2 Project**

  Training on the Module of Agroforestry systems and fruit trees

- **24-28/11/2014**: **DFS- Deutsche Forest service GmbH under the support of BTC-PAREF Be.2 Project**

  Training on sylviculture management

- **Nov 2014**: **DFS- Deutsche Forest service GmbH under the support of BTC-PAREF Be.2 Project**

  Training on the Module of Agroforestry

- **Oct 2010: MINAGRI**

  Training in Crop Assessment organized from **2010 to 2012.**

- **Sept, 14/2012-17/2012: National Institute of Statistic of Rwanda**

Training on Post Enumeration Survey

- **Jan, 11-18 2011: Harvest Plus and IFPRI**

  Training about farmers' choice of bean varieties study survey and using PDA and GPS devices for household-level data collection

- **April 2011**: RDB

  Training on wild animal behaviors' and visiting Volcano National Park

- **Dec, 17-21, 2007 MINEDUC**

  Pedagogic training

EDUCATION

2018- Present: **University of Koblenz-Landau, Germany**

Ph.D. Candidate in AGROFORESTRY

2014-2015 **Kampala International University, Uganda**

Master of Science in Environmental Management

2011-2012 **University of Rwanda, former ISAE**

Bachelor of Science in Agroforestry

2008-2010 **University of Rwanda the former ISAE-BUSOGO**

Advanced Diploma in Agroforestry

2000-2006 **GISOVO Secondary School**

Secondary Level certificate in Forestry

RESEARCH WORKS

- **January 2021**: Data on vegetation sampling in areas dominated by *Pteridium aquilinum* in Nyungwe forest, Western Province of Rwanda. J M V Senyanzobe, Josephine M Mulei , Elias Bizuru , **Concorde Nsengumuremyi.**
- **September 2020**: Impact of *Pteridium aquilinum* on vegetation in Nyungwe Forest, Rwanda. J.M.V. Senyanzobe, Josephine M. Mulei, Elias Bizuru and **Concorde Nsengumuremyi.**
- **August 2018**: Contribution of Ecotourism to the Conservation of Nyungwe National Park in Rwanda. Imanishimwe, A., Nsengimana, V., & **Nsengumuremyi, C**., 2018.
- **June 2012**: Application of Geographic Information System (GIS) for land use mapping in Busogo Sector, Musanze District (Alphonse Nahayo, **Concorde Nsengumuremyi**, and Isaac Ekise, 2012).

LANGUAGES

Kinyarwanda: Native speaker **English:** Fluent **French:** Fluent

REFERENCES

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5. **Prof. Donat NSABIMANA**

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I declare that the above information is true and only concerns me.

Table 27: The corrected radius of the 0.1 ha (1000 m^2) sample plot for different slopes

Appendix 1. The corrected radius of the 0.1 ha (1000 m^2) sample plot for different slopes

Slope(°)	Radius(m)	Slope(°)	Radius(m)	Slope(°)	Radius(m)
1	17.84	21	18.46	41	20.54
2	17.85	22	18.53	42	20.70
3	17.85	23	18.60	43	20.86
4	17.86	24	18.67	44	21.04
5	17.88	25	18.74	45	21.22
6	17.89	26	18.82	46	21.41
7	17.91	27	18.90	47	21.60
8	17.93	28	18.99	48	21.81
9	17.95	29	19.08	49	22.03
10	17.98	30	19.17	50	22.25
11	18.01	31	19.27	51	22.49
12	18.04	32	19.37	52	22.74
13	18.07	33	19.48	53	23.00
14	18.11	34	19.59	54	23.27
15	18.15	35	19.71	55	23.56
16	18.20	36	19.84	56	23.86
17	18.24	37	19.96	57	24.18
18	18.29	38	20.10	58	24.51
19	18.35	39	20.24	59	24.86
20	18.40	40	20.38	60	25.23

Appendix 2. Location of plots in transects and Random samples around the forest

Table 28: Location of plots in transects and Random samples around the forest

Location of plots						
No	Transect no	Plot no	Latitude	Longitude	Altitude	Comment
1	1	1	720510	9716065	1718	SS
2	1	2	720510	9715843	1658	SS
3	1	3	720510	9715601	1613	SS
4	1	4	720510	9715371	1570	SS
5	1	6	720510	9714846	1531	SS
6	1	7	720510	9714622	1463	SS
7	1	9	720510	9714024	1318	SS
8	1	10	720510	9713794	1335	SS
9	1	11	720510	9713570	1320	SS
10	1	12	720510	9713320	1335	SS
11	1	13	720510	9713090	1282	SS
12	1	14	720510	9712869	1345	SS
13	1	15	720510	9712639	1433	SS
14	1	16	720510	9712401	1448	SS
15	2	3	721110	9715737	1800	SS
16	2	6	721110	9714931	1595	SS
17	2	5	721110	9715121	1646	SS
18	2	7	721110	9714712	1566	SS
19	2	8	721110	9714366	1517	SS
20	2	9	721110	9714183	1484	SS
21	2	10	721110	9713928	1492	SS
22	2	11	721110	9713734	1481	SS
23	2	12	721110	9713505	1463	SS
24	2	13	721110	9713293	1458	SS
25	2	15	721110	9712829	1361	SS
26	2	16	721110	9712620	1330	SS
27	3	4	721710	9716345	1766	SS
28	3	5	721710	9716063	1798	SS

29	3	6	721710	9715858	1806	SS
30	3	7	721710	9750638	1783	SS
31	3	11	721710	9714799	1674	SS
32	3	12	721710	9714570	1633	SS
33	3	13	721710	9714335	1634	SS
34	3	14	721710	9714107	1653	SS
35	3	16	721710	9713646	1600	SS
36	3	17	721710	9713484	1579	SS
37	4	2	722310	9717490	1596	SS
38	4	3	722310	9717278	1635	SS
39	4	4	722310	9717047	1667	SS
40	4	7	722310	9716361	1662	SS
41	4	8	722310	9716139	1585	SS
42	4	9	722310	9715915	1535	SS
43	4	10	722310	9715694	1520	SS
44	4	11	722310	9715449	1527	SS
45	4	13	722310	9715003	1549	SS
46	4	14	722310	9714778	1521	SS
47	4	15	722310	9714543	1533	SS
48	4	16	722310	9714311	1509	SS
49	4	17	722310	9714083	1548	SS
50	NA	1	719458	9718269	1837	RS
51	NA	2	719458	9718269	1837	RS
52	NA	3	722256	9719034	1669	RS
53	NA	4	719673	9717933	2002	RS
54	NA	5	719194	9717209	2015	RS
55	NA	6	719152	9716934	1980	RS
56	NA	7	719003	9716722	1985	RS
57	NA	8	718889	9717354	1972	RS
58	NA	9	718555	9717261	1921	RS
59	NA	10	718053	9716949	1884	RS
60	NA	11	717666	9716894	1756	RS

61	NA	12	717544	9716675	1754	RS

RS: Random sample plot

SS: Systematic Sample plot

Appendix 3. Position of transects towards Bugarama downhills

Table 29: Position of transects along slope gradient towards Bugarama downhills

Position of transect	**Transect 1**	**Transect 2**	**Transect 3**	**Transect 4**
Shape *	Polyline	Polyline	Polyline	Polyline
Shape_Length	7065.562139	7231.553041	7675.300231	8516.885287
Latitude_start	720510.1314	721110.1314	721710.1314	722310.1314
Longitude_start	9709237.194	9709241.372	9709297.259	9709406.125
Latitude_End	720510.1314	721110.1314	721710.1314	722310.1314
Longitude_End	9716302.756	9716472.925	9716972.559	9717923.011
Latitude_Midle	720510.1314	721110.1314	721710.1314	722310.1314
Longitude_Midle	9712769.975	9712857.148	9713134.909	9713664.568

The Figures of appendix 4&5 show a graphical representation (using box plots) of nutrients contained in terms of C, N, C: N ratio, K, N, Na, and Mg for seven AF tree species of sustainable AF of surroundings of Cyamudongo isolated rain forest and four AF plot of Arboretum of Ruhande. The figures focus on the averaged values for different tree components or parts including branches, leaves, and stems.

Appendix 4. Comparison of averaged nutrients content in different tree components (stems, branches & leaves) of Cyamudongo AF tree species

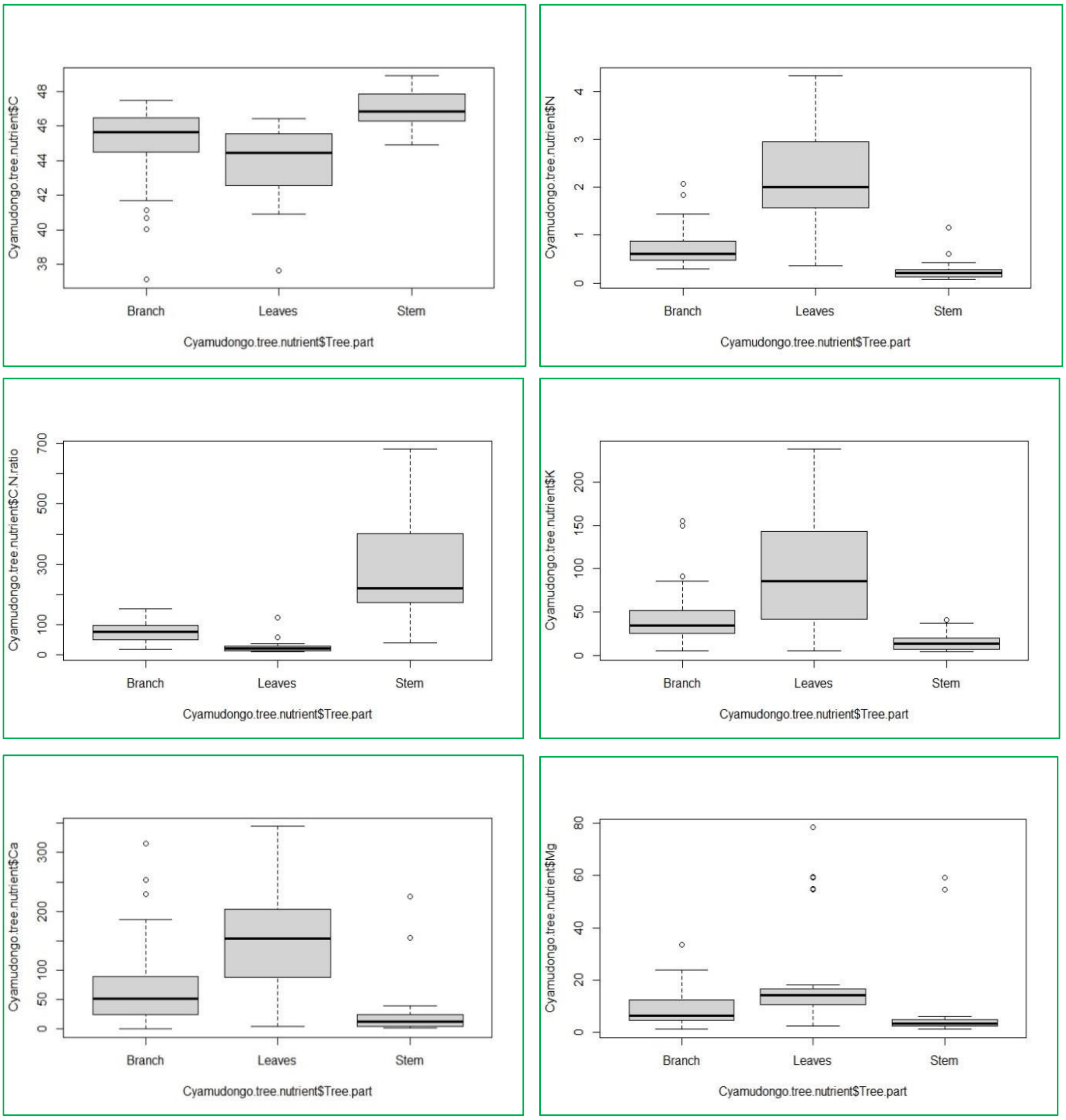

Figure 65: Comparison of averaged nutrients content in different tree components (stems, branches & leaves) of Cyamudongo AF tree species

Appendix 5. Comparison of averaged nutrients content in different tree components (stems, branches & leaves) of Ruhande AF tree species

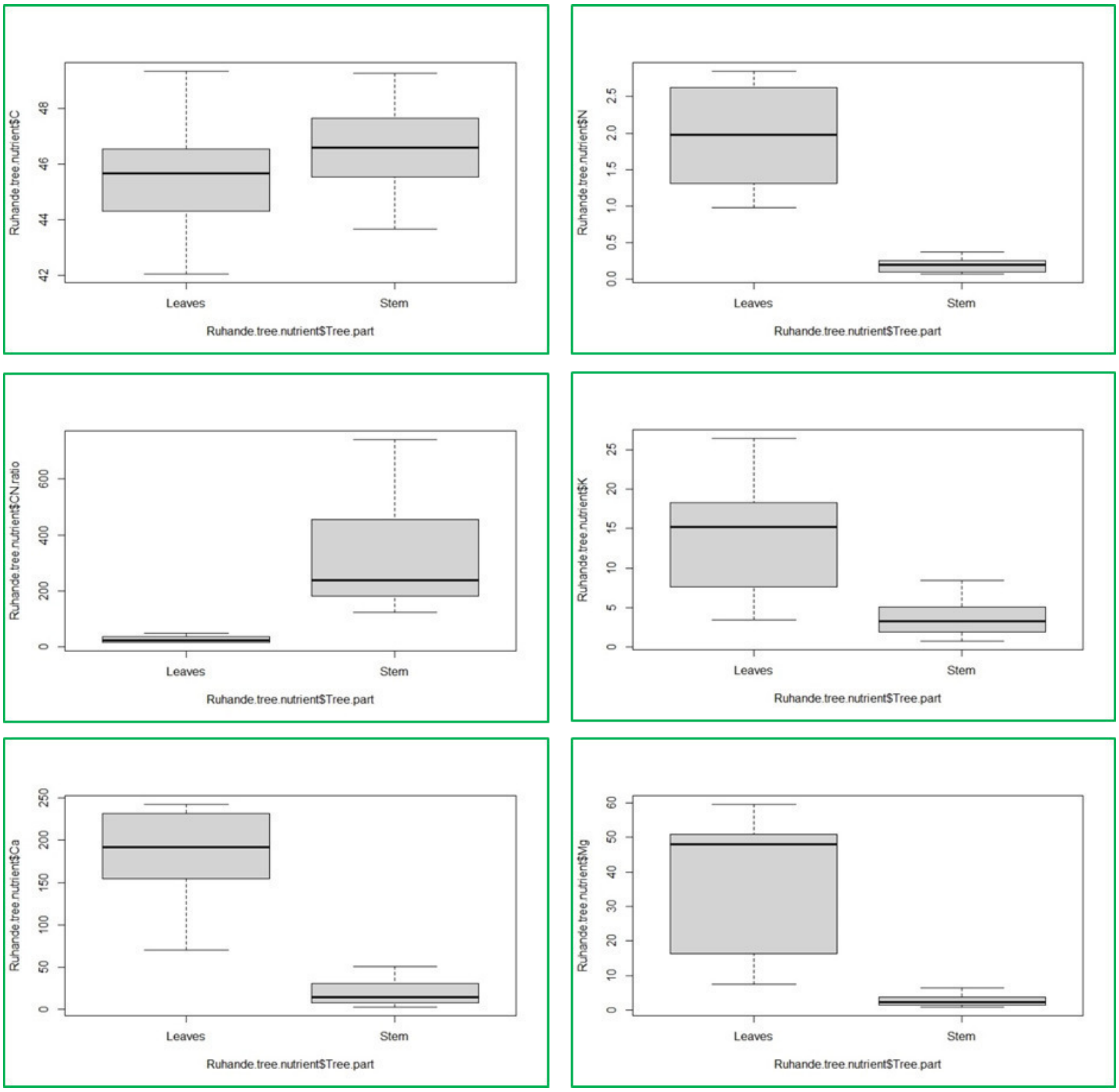

Figure 66. Comparison of averaged nutrients content in different tree components (stems & leaves) of Ruhande AF tree species

DECLARATION

I, Concorde NSENGUMUREMYI, declare that this thesis has been composed only by myself and presents the results of my work, and has not been submitted for any previous application for a degree or any other professional qualification at any other university. Moreover, except where states otherwise by references or acknowledgments, the work presented is wholly my own.

Date and signature: August 25, 2021