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RESOURCES MANAGEMENT***

**EVALUATION OF THE EFFECTS OF BAMBOO ON UNDERSTORY PLANT  
SPECIES DIVERSITY AND RIVERBANK EROSION CONTROL ALONG  
NYABARONGO RIVER, NGORORERO DISTRICT, RWANDA**



A thesis submitted in partial fulfillment of  
the requirements for the degree of Master  
in Biodiversity Conservation and Natural  
Resources Management

By

Jean Pierre HATEGEKIMANA

(Reg. No:221027778)

**Supervisor (s):** Prof Beth A. Kaplin (PhD)

Jean de Dieu UWIZELIMANA (PhD)

**Kigali, October 2024**

**DECLARATION**

I Jean Pierre HATEGEKIMANA, declare that this dissertation is the result of my own work and has not been submitted for any other degree at the University of Rwanda or any other institution.

**Jean Pierre HATEGEKIMANA**

**APPROVAL**

I certify that this research project entitled "**EVALUATION OF THE EFFECTS OF BAMBOO ON UNDERSTORY PLANT SPECIES DIVERSITY AND RIVERBANK EROSION CONTROL ALONG NYABARONGO RIVER, NGORORERO DISTRICT, RWANDA**" was done under my supervision and has been submitted for examination with my approval.

**Prof Beth A. Kaplin (PhD)**

**On September 27<sup>th</sup>, 2024**

## DEDICATION

This work is dedicated to the All-Powerful God, who is also my inspiration, strong support system, and source of all knowledge, insight, and wisdom. He has been my source of strength throughout this academic program, and I have only succeeded under His wings.

This effort is also dedicated to my wife, Alphonsine UMUGWANEZA, whose unwavering support has enabled me to stay focused and finish the tasks I have started. To my children, who have been impacted by this quest in every manner imaginable: Benny Alan, Keza Anaella, Ian Ashel, and Mwiza Anaya.

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## TABLE OF CONTENTS

DECLARATION .....	i
APPROVAL .....	ii
DEDICATION .....	iii
ACKNOWLEDGMENTS .....	iv
TABLE OF CONTENTS .....	v
LIST OF FIGURES .....	viii
LIST OF TABLES .....	ix
LIST OF APPENDICES .....	x
ABBREVIATIONS AND ACRONYMS .....	xi
ABSTRACT.....	xii
CHAPTER 1: INTRODUCTION.....	1
1.1 Background .....	1
1.2 Problem statement.....	3
1.3 Objectives .....	4
1.3.1 Main objective.....	4
1.3.2 Specific objectives.....	4
1.4 Research question .....	5
1.5 Hypothesis.....	5
CHAPTER 2: LITERATURE REVIEW .....	6
2.1 Riparian functions and values .....	6
2.1.1 Concept and definitions .....	6
2.1.2 Vegetation in riparian zones .....	6
2.1.3 Transfer of solar energy to the aquatic ecosystem .....	7
2.1.4 Wildlife habitat in riparian zones .....	7
2.2 Threats to riparian zones .....	8
2.2.1 Climate change and riparian areas.....	8

2.2.2 Invasive species .....	9
2.2.3 Land use change .....	9
2.2.4 Soil erosion .....	10
2.3 Restoration and rehabilitation of riparian zones .....	11
2.3.1 Bamboo in restoration .....	12
2.4 Bamboo plantings and national targets .....	13
2.4.1 Bamboo and Nationally Determined Contributions (NDC).....	15
2.4.2 Biodiversity, climate change mitigation and adaptation .....	15
CHAPTER 3: METHODS .....	16
3.1 Description of study area .....	16
3.1.1 Data source and description .....	17
3.2 The study design.....	18
3.3 Data collection.....	19
3.3.1 Vegetation inventories .....	19
3.3.2 Soil erosion assessment using GIS-based RUSLE Model.....	20
3.3.2.1 Computation of remote sensing metrics .....	21
3.4 Data analysis .....	23
CHAPTER 4: RESULTS .....	25
4.1 Plant species richness and diversity along Nyabarongo river banks.....	25
4.1.1 Plant species richness and diversity.....	25
4.1.2 Rarefaction curve and sample coverage curve in sampled riparian zones .....	26
4.1.3 Simpson diversity index .....	26
4.1.4 Community similarity index (SCSI and/or CC) .....	27
4.1.5 Average percent cover in bamboo and control sites.....	27
4.2 Diversity of understory vegetation .....	28
4.2.1 Plant densities in surveyed riparian zones .....	28
4.2.2 Comparison of life forms.....	29

4.2.4 Dominant families in bamboo and control sites .....	30
4.2.5 Relationship between plant species richness and land use types.....	31
4.2.6 Relationship between land use and the buffer zone width .....	32
4.3 Relationship between bamboo plantings and erosion .....	33
4.3.1 Slope categories and the presence of erosion .....	33
4.3.2 Relationship between mean width of the buffer zone and slope categories .....	33
4.3.4 Percent eroded width of the buffer zone.....	34
4.3.5 Erosion along Nyabarongo river buffer zone (C-factor value) .....	35
4.3.6 Annual soil loss estimates .....	36
CHAPTER 5: DISCUSSION.....	37
CHAPTER 6: CONCLUSION AND RECOMMENDATIONS .....	42
6.1 CONCLUSION.....	42
6.2 RECOMMENDATIONS .....	43
REFERENCES .....	44
APPENDIX.....	A

## LIST OF FIGURES

Figure 1: Location of the study area along Nyabarongo river in Ngororero District, Rwanda	16
Figure 2: Geographical location of sampled sites, in Nyabarongo River catchment, Rwanda	19
Figure 3: Workflow of C-factor estimated using NDVI.....	23
Figure 4: Plant species richness in riparian zone with and without bamboo plantings .....	25
Figure 5: Rarefaction curve and sample coverage curve in sampled riparian zones .....	26
Figure 6: Simpson diversity index (A) and relative abundance (B) computed in bamboo and control site.....	26
Figure 7: Average percent of herbaceous cover across studied riparian zones .....	28
Figure 8: Understory vegetation shown in bamboo riparian areas, along Nyabarongo river, Ngororero District.....	29
Figure 9: Life forms identified in the riparian zone of Nyabarongo river, Ngororero District	29
Figure 10: Relative abundance of plant families in the riparian zone of Nyabarongo river, Ngororero District, Rwanda.....	31
Figure 11: Relationship between land use types and plant species richness .....	32
Figure 12: Relationship between land use types and the buffer zone width.....	32
Figure 13: Correlation between slope categories and erosion .....	33
Figure 14: Relationship between slope and the average buffer zone width .....	33
Figure 15: Eroded buffer zone along Nyabarongo river, Ngororero District, Rwanda.....	34
Figure 16: Land use types adjacent to studied riparian zones .....	35
Figure 17: The C-factor value for the Nyabarongo river calculated between 1995 and 2023.	36
Figure 18: Soil losses in 1995 and 2023 for the Nyabarongo river buffer zone, Ngororero District, Rwanda .....	36

**LIST OF TABLES**

Table 1: Data source and description.....	18
Table 2: Number of plant species sampled in the study zone.....	25
Table 3: Common plant species shared by two sampled riparian zones.....	27
Table 4: Dominant plant species and species richness per life form .....	30
Table 5: Percent eroded width of the buffer zone.....	34

**LIST OF APPENDICES**

Appendix A: Critical values of chi-square (right tail) Table Significance level ( $\alpha$ )..... A

Appendix B: Total number of individuals recorded in different vegetation type..... B

Appendix C: Eroded buffer zones and bamboo due to adjacent land use .....D

Appendix D: Nyabarongo river’s morphological changes ..... E

## **ABBREVIATIONS AND ACRONYMS**

**ANOVA:** Analysis of Variance

**BIOCEM-RD:** Biodiversity Conservation Environmental Management and Rural Development

**CBD:** Convention on Biological Diversity

**COP 15:** Conference of the Parties (15<sup>th</sup>, meeting on Convention on Biological diversity)

**CL:** Crop Land

**DF:** Degree of freedom

**EPA:** Environmental Protection Agency of the United State of America

**GBF:** Global Biodiversity Framework

**GDP:** Gross Domestic Product

**GGCRS:** Green Growth and Climate Resilience Strategy

**GoR:** Government of Rwanda

**GPS:** Global Positioning System

**HD:** High density

**INABR:** International Bamboo and Rattan Organization

**IUCN:** International Union for the Conservation of Nature

**LD:** Low Density

**LVEMP:** Lake Victoria Environment Management Project

**NCD/NDC:** Nationally Determined Contribution

**NTFP:** Non-Timber Forest Product

**REMA:** Rwanda Environment Management Authority

**RWB:** Rwanda Water Resources Board

**RZ:** Riparian Zone

**SDGs:** Sustainable Development Goals

**SCSI:** Sorenson's Community Similarity Index

**UNEP:** United Nations Environment Programme

**UNFF:** United Nations Forum on Forests

**UV:** Ultra Violet

## ABSTRACT

Bamboo planting in Rwanda has been thought to be effective in restoring degraded riparian zones and controlling erosion along the river banks. However, in order to prevent any adverse effects from this non-native plant species, the ecological repercussion of such intense bamboo planting needs to be evaluated. The main goal of this research was to analyse the effects of bamboo on erosion control understory plant diversity (as an indicator of biodiversity) in riparian ecosystems planted with bamboo as a climate adaptation strategy. Riparian zones planted with bamboo were compared with areas not planted with bamboo (Control sites) along stretches of the Nyabarongo river in Ngororero District, Rwanda. Bamboo and woody stems found in the selected riparian zones were sampled in 100m<sup>2</sup> quadrats, with nested 1 m<sup>2</sup> subplots used to sample understory vegetation (herbaceous plants, sapling and shrubs). Riverbank erosion was assessed through physical measurements and RUSLE model to depict changes in Nyabarongo river in both C-factor value and annual soil loss from 1995 up to 2023. There was a significant difference in plant species diversity between the two riparian zones, with higher plant diversity found in the control sites. The bamboo-planted riparian zone, had a total of 28 plants species, with 42.9% being native species and 35.7% exotic. Of these exotic plant species, 21.4% were invasive. Control sites had a total of 45 species, 46.7% of these were native species, and 40% exotic, and only 13.3% were invasive. The two communities shared 20 species with four of them being invasive, eight native and the other eight exotics. The results of the study also show a significant difference between land use types and species richness. In non-bamboo riparian zones, Poaceae (41.75% cover) and Fabaceae (38.5% cover) family were most common while Poaceae (41.43% cover) and Asteraceae (18.27% cover) were more common in bamboo riparian zones. There was a significant difference between slope and presence of erosion and no significant difference was found between slope and mean width of the buffer zone. The C-factor changed from 1995 to 2023, with its maximum value changed from 0.320 to 0.1 and the minimum value shifted from 0.226 to 0.05. Results suggest that planting bamboo may have an effect on the diversity of understory plants. However, annual soil loss also had changed, as estimated to 577.182 tons/ha in 1995 and shifted to 55.9972 tons/ha in 2023, these results prove the effectiveness of bamboo in controlling erosion.

**Key words:** Bamboo, Climate adaptation, Biodiversity, Riparian zones and Nyabarongo River, Ngororero District, Rwanda.

## CHAPTER 1: INTRODUCTION

### 1.1 Background

Bamboo plays a vital role in socio-economic livelihoods of a large number of people around the world (Nahayo, Ekise, Sankaranarayanan, & Irangeneye, 2013). It has substantial environmental advantages throughout numerous nations, where it is used for ecological objectives including soil stability and erosion prevention on hills and rivers. Bamboo has gained popularity as a renewable resource due to its rapid growth, economic value, widespread availability and mechanical qualities similar to those of wood. Bamboo is a natural resource with a wide range of uses, including building materials, handmade items, paper and pulp products, household items, fencing, nutritious shoots and feed for animals. Furthermore, it has been shown to be very successful in preserving soils in ravines and allowing profitable use of gullies. Bamboo planting in ravine also provide certain indirect advantages notably the mitigation of soil erosion (Pande et al., 2012).

Bamboo is a woody forest product or non-timber forest product (NTFPs) and is industrially valued as such. Bamboo is among various species used to restore riparian zones in Rwanda (REMA, 2019) due to its high ecological and socioeconomic versatility, carbon capture storage capability and its particular significance in China's climate change mitigation (Song et al., 2011). Within the course of thirty years, one hectare of bamboo and its derivatives may store 600 tons of carbon, which is more than some tree species, but there is still a need to evaluate bamboo in different ecological conditions to balance its benefits to ecological ones (Yanxia & Frith, 2018).

Riparian zones are one of the more fragile locations on the planet, and are essential for maintaining high biodiversity. The way they deteriorate facilitates the proliferation of invasive alien plant species (Zelnik, Haler, & Gaberšček, 2015). When it comes to the effects of human and environmental stressors, riparian zones are among the most sensitive and vulnerable areas of earth (Zelnik et al., 2015). Due to the significant changes in environmental conditions necessary for the biotic community in the riverbed, riparian zones are becoming more vulnerable, just as the water body itself (Zelnik et al., 2015). Vegetation degradation and riparian zone degradation are frequently linked, which promotes the spread of alien plant species. It is believed that invasive alien plant species (IAT) damage native plant species and ecosystems. Introduction of invasive plant species dramatically lower native plant specie's richness, growth and fitness (Grandgirard, Poinot, Krespi, Nénon, & Cortesero, 2002).

Human activities are responsible for the earth's sixth global extinction catastrophe and the world's biological diversity stocks to be declining at rates 100-1000 times faster than before humans, biodiversity loss has become a critical environmental crisis. Significant contemporary decline in biodiversity at various spatial, temporal, and biological scales have raised concerns about and increased demand for biodiversity conservation (Ning, Lei, Yanxia, & Long, 2022). Simultaneously, an increasing amount of scientific data suggests that biodiversity not only adapts to changes in the environment, but also serves as predictor of a number of ecosystem services and functions that are critical to maintaining human well-being. Issues pertaining to biodiversity are, in fact, vital to human survival.

Riparian zones are seriously challenged by human activity when it comes to conservation. Riparian habitats are declining and disappearing globally as a result of flow regulation by dams, diversions, and other infrastructures to lessen flood danger, as well as conversion of riparian zones by forestry, agriculture, industry, and urban development. Rarely are damaged riparian zones to be restored to their pre-disturbance or minimal human impact states. Particularly dynamic and ever-evolving, riparian zones are prone to non-linear, frequently surprising trajectories and are always changing. The goal of riparian zone conservation must be to create a state that can change with the environment (González et al., 2017).

In Rwanda bamboo plantings has been used to restore degraded riparian zones, and as a resource to have an important impact in both development of society and ecological functions, through a bilateral relations and friendliness between Rwanda and China in 2009 (Ding & Kinnucan, 2011). The forest sector is a key driver of agricultural development in Rwanda, accounting for 36% GDP, 80% of employed people, along with more than 45% of export revenues. Forested watersheds provide an important share of the water needed for domestic, farming, manufacturing, cities and ecological purposes in upstream as well as downstream locations. The overriding challenges addressed for forests in Rwanda are how to optimize the environmental benefits versus increasing soil erosion, how to balance the growing demands for basic necessities of citizens with increased living and energy supply and how to establish a balance between increased wood cutting for fuel and protecting the forests (TIAN & Lili SI, 2016).

For the above purpose, six well-selected Chinese bamboo species namely *Dendrocalamus barbatus*, *Dendrocalamus asper*, *Dendrocalamus latiflorus*, *Indocalamus decorus*, *Bambusa textilis* and *Thyrsostachys siamensis* have been brought from China to Rwanda since 2009

(Ding & Kinnucan, 2011), in line with site-match principles and take into consideration biosecurity policies and growth that is meant to facilitate the establishment of new plantations (Xing, 2020). One of the most difficult tasks in land, forest and water management is maximizing a broad range of multi-sectorial forest benefits while not jeopardizing water supplies or the overall ecosystem.

To solve this problem, the Government of Rwanda has implemented four pilot projects to ensuring the preservation of watersheds around the rivers namely Nyabarongo, Nyabugogo, Sebeya and Muvumba using the mechanism of funding for ecosystem service (Xing, 2020). Rwanda therefore, has experienced promotion of bamboo planting as a strategy to control erosion along riparian zones but there have been few studies of the outcomes of these plantings. Therefore, this study will evaluate the effects of bamboo on understory plants diversity around Nyabarongo River, and its influences on riverbank erosion control in Ngororero District.

## **1.2 Problem statement**

Landslides have become an increasingly problematic in many regions across the globe, particularly in the face of climate change and significant rainfall events. These variables aggravate the natural dangers connected with landslides, resulting in more frequent and severe incidents (Gidon & Sahoo, 2020). In Rwanda known “the country of thousand hills” (Kinzer, 2010), this problem is observed in many parts of the country and there are high levels of erosion. There are various factors contributing to landslides, in which some occur due to natural factors, such as precipitation, earthquake, steep slopes while others are due to anthropogenic service, such as forest degradation, land interference, construction works, poor farming techniques, inadequate drainage and so on all contribute to this. Moreover, climate change and intense anthropogenic activities tend to accelerate the frequency and magnitude of the erosion events.

According to the International Bamboo and Rattan Organization (INBAR) diagnostics, the main problem behind is the lack of clear information on its effects and harmfulness to biodiversity, lack of evidence of competitiveness between bamboo and other species (Donfack, 2020), and lack of knowledge of its exact potentials limits its valuation in several countries. Besides that, there is evidence that bamboo grown on productive or arable land tends to take over the land that can then no longer easily be used for other purposes. In this case bamboo is recognized as an invasive plant (Donfack, 2020). The achievement of earlier restoration efforts continue to be insufficiently reported and shared in the majority of the surveyed countries

(Donfack, 2020), thus this limits deeper understanding of effectiveness for future restoration projects. Most lessons learned remain unpublished. Nyabarongo River in Rwanda is experiencing riverbank erosion and has been threatened by ever increasing population, and hence the poor and deteriorating cropping practices, accelerated cutting of forests in the catchments have increased runoff of water, riverbank erosion and added runoffs to the rivers (GoR, 2018). It is against this background that the Lake Victoria Environment Management Project (LVEMP) and other projects were implemented in Ngororero District to ensure that in upstream Nyabarongo catchment areas, and Nyabarongo river itself as well as the natural resources it contains, including biodiversity, are accomplished sustainably. To reach the goal, different activities have been carried out including: bench terraces construction, distribution of improved cooking stoves, and bamboo plantings along Nyabarongo River and its tributaries. (Rwanda Water Resources Board (RWB) and Water for Growth Rwanda, 2017).

It remains unclear whether the majority of non-native plant introductions are a threat to biodiversity (Sibiya, 2019). Yet, the ecological implications of intense bamboo planting must be evaluated in order to minimize any detrimental values caused by this introduced species. Other ecosystem services that could be gained if bamboo were not the only plant used for rehabilitating riparian zones is also not well understood or studied. In this work, I attempted to investigate the potential consequences of bamboo in restored riparian areas towards climate adaptability, (by assessing erosion management) and biodiversity (by analyzing understory plant diversity). Bamboo planting was my primary focus in this location because it not native.

### **1.3 Objectives**

#### **1.3.1 Main objective**

The primary objective of this research was to assess the influence of bamboo on understory plants species and riverbank erosion control, along Nyabarongo river in Ngororero District.

#### **1.3.2 Specific objectives**

The specific objectives of this research are:

- Determine if there is a difference in plant species diversity between riparian buffers planted with bamboo and those without bamboo, along Nyabarongo river banks;
- Identify the relationship between bamboo plantings and erosion stability, an indicator of climate adaptation along the riverbanks.

#### **1.4 Research question**

The following research questions were formulated based on problem statement and both main and specific objectives:

- Is there a significant difference in plant species richness between riparian zones planted with bamboo to those without bamboo?
- Do riparian zones planted with bamboo reduce riverbank erosion along the river?

#### **1.5 Hypothesis**

- There is no significant relationship between bamboo plantings and the control sites in plant species richness and abundance along Nyabarongo River bank;
- The implementation of bamboo plantings has no significant effect on riverbank erosion rates in riparian zones planted with bamboo and the control sites.

## **CHAPTER 2: LITERATURE REVIEW**

### **2.1 Riparian functions and values**

#### **2.1.1 Concept and definitions**

Riparian zone restoration and management has become more important with climate change impacts such as increased heavy rainfall, events which cause flooding and erosion. The term riparian refers to the area vegetated or partially vegetated area surrounding a river or a stream including but not limited to river or stream beds and banks (Kusler, 2016). Riparian ecosystems are varied, dynamic, and complex habitats. They are the edge between terrestrial and aquatic systems, covering numerous environmental gradients, communities and ecological processes (García & Jáuregui, 2021). The United States of America Environmental Protection Agency (EPA) describes riparian areas as overgrown areas alongside watercourses where materials, energy and water flow (Gashaw, Terefe, Soromessa, Ahmed, & Megersa, 2015).

Riparian zone areas can reduce wave and erosion damages by triggering waves to break at offshore places binding and holding the soil. Because of the presence of water, intact riparian areas support a wide plant community that are usually dense, fast growing and have many valuable functions including trapping pollution, sediments and nutrient (Jones, 2008), flood control, channel stability, and recreation and aesthetic values (Oates & Oswald, 2000). These ecosystems have consistently highlighted as critical sites for conservation under climate change scenarios impacting adversely to these important areas because they moist and cool microclimates relative to adjacent areas, and span climatic gradient (Krosby, Theobald, Norheim, & McRae, 2018). They frequently reside enormous amounts of species diversity alongside offering a variety of environmental services (Urbani, Politti, Rodríguez-gonzález, & Payne, 2022).

#### **2.1.2 Vegetation in riparian zones**

Riparian zones are amongst the world's most diverse and dynamic plant habitats (García & Jáuregui, 2021). The riparian vegetation encourages a variety of ecosystem services, including the stabilization of soil, organic matter production, and the provision of nutrients and shelter for aquatic organisms. They frequently host various shrub and tree flora that makes up refuge for mammals and birds, as well as woody decay that provide suitable conditions for both terrestrial and aquatic invertebrates (Berglund, 2014). These plants have to be more adaptive to inundation and flooding, hence flooding is considered to be the primary factor structuring

the vegetation in riparian habitats. The frequency, duration, rate, timing and depth all these factors exercise effects on riparian plants, in turn plant responses to flooding may be influenced by the seasonal timing of the flooding events for example the flood may coincide with plant germination, seed dispersal and finally impact riparian plant habitats (Capon, 2015).

Riparian vegetation acts as conduit, filters controlling the flow of water, sediments and nutrients, and can be impacted by a higher water table, or flooding's, as well as the soil water holding capacity. The width of the riparian areas and the degree to which it exercises an impact on the aquatic ecosystem relies heavily on the stream's size, topographical settings and hydrological system as well as extremely high diversity and diversification in ecological interactions (Bradley & Griffith, 2016). Riparian ecosystems perform biological roles such as filtering polluting upland, and underground flows strengthening riverbanks, and controlling in-stream ecosystems which constitute essential aspects of natural resources management (Vigiak et al., 2007). Despite their significant importance, riparian zones play a momentous role for human well-being and nature conservation, degradation of riparian zones is common and in some areas is even increasing (Urbani et al., 2022).

### **2.1.3 Transfer of solar energy to the aquatic ecosystem**

The vegetation in the riparian zone stimulates the quality and quantity of light in streams and rivers (Dosskey et al., 2010). There are consequences associated with altering light quality. Increased rates of thermal energy transfer from the atmosphere to aquatic environment in the absence of riparian zone could possibly impair development and use of resources for reproduction (Pusey & Arthington, 2003) and desynchronizing the temperature regime from regional parameters such as the flow regime, in addition to having an immediate effect on death rates, body shape, immunity to diseases, and metabolic activity. Increased ultraviolet (UV) B irradiation, changes the light quality and hence increases egg and larval mortality, diminished ability to differentiate between possible mates and higher conspicuousness to intruders (Pusey & Arthington, 2003). Trees shade the stream and hence reduce light and water temperature (Oates & Oswald, 2000).

### **2.1.4 Wildlife habitat in riparian zones**

One assemblage of riparian non-market ecosystem services is correlated to wildlife and fish habitat. Riparian zones support both aquatic and terrestrial habitat diversity. Various bird and fish species are dependent on riparian habitats for entire or significant portions of their life

cycles. Furthermore, many animals' species including amphibians, reptiles and arthropods, the aquatic insects, bird and fish diet require a healthy riparian habitat to complete their life cycles. Therefore, riparian habitats have a direct and significant effect on both production and quality of our freshwater supplies. Riparian areas supply food, cover, and water for a wide range of animals, and act as a corridor between habitats for a variety of wildlife, mainly ungulates and birds (Jones, 2008).

Additionally, pollinators such as butterflies and bees are necessary for the survival of a number of plant species, providing critical ecosystem services to a variety of habitats on the earth. Plant-pollinator interactions is typically driven by abiotic variables such as habitat destruction and division, which can modify pollinator visits to vegetation by generating losses in number of pollinators as well variations in in pollinators diversity (Zhang et al., 2022). Urban rivers and their related riparian zones are vital natural wildlife corridors, in this area the natural vegetation decreases while instantaneously, planted vegetation increases. Furthermore, these conditions can impact pollinator's function, particularly for plant species that depend on a specific pollinator (Zhang et al., 2022). Riparian zones can act as important corridors for movement of wildlife and propagules (e.g., seeds, pollen) connecting different parts of the landscape, when native vegetation in the riparian zone is intact.

## **2.2 Threats to riparian zones**

A wide range of stresses affects the riparian habitats. In most circumstances, it is difficult to determine the specific impact of any hazard. The impact of an obvious threat may obscure those of a more devious one. The following are among the major threats to riparian zones.

### **2.2.1 Climate change and riparian areas**

Climate change progress and concerns advance over the capability of species and ecosystem to familiarize. Extensive attempts have been made to identify landscape features that are likely to increase biological sensitivity to change. Riparian regions have been repeatedly deemed as essential regions to protect for climate change mitigation because of their substantial ecological services than near-by areas. Riparian areas are exceptionally active conservation umbrellas in the face of climate change because they dramatically help maintain regional species richness constitute habitat for many highlands' species, and are essential to climate resilience. Therefore, they are typically targeted in conservation planning initiatives (Krosby et al., 2018).

Riparian restoration could play a role in preparing ecological systems to face climate change concerns. Riparian habitats are intrinsically resilient, enable linear habitat connection unite terrestrial and aquatic ecosystems and establish thermal refuges for wildlife highland species (Dwire, Mellmann-Brown, & Gurrieri, 2018). Climate change increases challenges of conserving natural native plants and wildlife, the characteristics of riparian ecosystems makes them the most valuable part of landscape for maintaining critical habitat for plants and wildlife, key functions for communities, and basically the most cost-effective systems to restore (Evans, 2013).

The particular consequences of climate change vary, subject to the local hydrological supply( especially aquifers),geography, streamside small-scale climates, present circumstances, and different types of land use adjacent to riparian areas (Dwire et al., 2018). Water diversion and animal grazing degrade the ecological value of many riparian areas by reducing their resilience to extra stress from a warmer environment. The obstacle that restoration practitioner face is not minor. To meet these challenges restoration practitioners must stay adaptable and inventive (Seavy et al., 2009). Drought, a fundamental aspect of climate change, generates stress by lowering plants' ability to photosynthesize and restricting the moisture required for germination (Poff, Koestner, Neary, & Henderson, 2011).

### **2.2.2 Invasive species**

Invasiveness is defined as the arrival, survival, and successful reproduction and dissemination of organisms in non-native areas. Riparian zones are among the most vulnerable ecosystem to alien plant (Singh, Tiwari, & Singh, 2021). Invasive species in riparian areas are an environmental issue that harms biodiversity and challenges the ecological stability of river ecosystems (Burt, Pinay, Grimm, & Harms, 2013). These species are of high concerns because of their capacity to take over riparian sites and eliminate understory plant species (Stephen et al., 2020). However, invasive species lead to decreases in riparian plant diversity, faunal-plant assemblage, distinctiveness, and create changes in habitat structure (Theobald, Merritt, & Norman, 2010) alien species have an impact not only on terrestrial wildlife and plants, but also on macroinvertebrates living in streams (Poff et al., 2011).

### **2.2.3 Land use change**

Although riparian areas are extremely important for biodiversity they host, as well as the services they offer, they are among the threatened areas worldwide (Burt et al., 2013).

Expansion of anthropogenic activities such as agriculture, forest plantings and urban development drive changes in riparian structure, functions and services (Mohite & Samant, 2012), riparian ecosystems especially in relation to ground cover change and land utilization in catchments along with alteration to hydrological regimes. In agricultural landscape, the water flows from catchment may carry out nutrients from applied chemical fertilizers into riparian (Stephen et al., 2020).

Vegetation clearing and change, and agricultural encroachments by cutting the bank trees lead to loss of continuity along watercourse and connectivity within the riparian zone, and between riparian zone and upland areas (Mohite & Samant, 2012). Severe agricultural activities in riparian areas drastically alter the structure, diversity, and plant species richness (Koskey, Erimba, & Ogendi, 2021). Furthermore, intensive farming generates huge use of agrochemicals, including chemical fertilizers, and pesticides on land used for agriculture undermines the ecological roles in riparian areas (Singh et al., 2021).

#### **2.2.4 Soil erosion**

Unconsolidated river beds and banks, especially rapid runoff, often cause serious erosion and river meandering in riparian areas (Kusler, 2016). Soil erosion in the hill upper catchments due to deforestation, mining and other human developmental activities like road construction, brick manufacturing enhance the rate of siltation (Mohite & Samant, 2012). Such activities lead to destruction of river embankment and increase in soil erosion (Mohite & Samant, 2012). Riparian zones in most parts of the earth are experiencing substantial erosion that destroy and deteriorate the reservoir ecosystem (Bao, Tang, He, And, & Zhang, 2015). However, significant hydrological, biological and physical variations of the many negative consequences lead to geomorphologic transformation due to severe erosion, bank collapse and the associated sediments. Erosion process in riparian zones often come in forms of crumbling, transferring, scattering, falling, or sliding (Bao et al., 2015).

Erosion along stream banks, and formation of erosion gullies are major causes of nonpoint sources contaminants particularly in landscapes conquered with agriculture (Zaimes, Tufekcioglu, & Schultz, 2019). Implementing highland conservation measures in these areas limits the movement of debris more than runoff, resulting in considerable stream bank and gully erosion. Anthropogenic activities that alter the geomorphological changes in stream and river, topography, river shape, riparian land use, shifts in vegetation structure, bank material, bank slope and depth, climate conditions and watersheds characteristics are the primary causes of

increased river bank and gully erosion rates (Singh et al., 2021). Such activities involve changes in land use including: expansion in croplands in riparian zones and at the watershed level, building infrastructures along the river banks, landscaping development, dam construction, sand extraction, development of cities and channelization (Theobald et al., 2010). Human activities have much bigger influences on rivers, stream and gully erosion than natural phenomena like flooding (Zaimes et al., 2019).

### **2.3 Restoration and rehabilitation of riparian zones**

Plants species, mostly indigenous ones are often used to restore degraded riparian zones (Gashaw et al., 2015). According to the ecosystem-based adaptation guidelines in Rwanda 2019, indigenous plant species including *Acacia gerrardii* (Umugunga), *Acacia polyacantha* (Umuninya/Umugu), *Aeschynomene elaphroxylon* (Ikizira), *Albizia petersiana* (Umumeyu), *Allophylus africanus* (Umutete), *Bambusa vulgaris* (Umugano), *Cyperus latifolius* (Urukangaga), *Cyperus papyrus* (Urufunzo), *Erythrina abyssinica* (Umuko), *Ficus thonningii* (Umuvumu), *Ficus vallis-choudae* (Umudobori), *Grewia similis* (Umukomagore), *Lannea schimperi* (Umumuna), *Markhamia lutea* (Umusave), *Olea europea subsp. Cuspidata* (Umunzenze), *Pennisetum purpureum* (Urubingo), *Phoenix reclinata* (Umukindo), *Phragmites mauritianus* (Imiseke/Amaseke), *Sesbania sesban* (Umunyegenyeye), and *Typha comingensis* (Umuberanya) are listed and advised to be used. These plant species are identified to be the best option based on their effectiveness in the climate resilience role and livelihood impact role as well as their respective zone of intervention either riparian zone (RZ) or cropland (CL) (REMA, 2019).

Rehabilitation of riparian areas is regularly challenged with one of the following problems: decision making is frequently ad hoc and failure to consider drivers of problems at a scale adequate to capture the ecological process involved, project with relatively narrow riparian rehabilitation width can lead to persistent poor plant cover, erosion, an/or weeds, projects often address symptoms of the problem rather than the cause, actions are not implemented in the right way and/or combinations (eg: channel rehabilitation plus riparian vegetation planting) or at locations that would optimize benefits, and lack of consideration of socio-economic aspect (GoR, 2020).

There are many steps that can be taken to improve riparian zone health including: avoid the use of heavy equipment's like tractors, use best soil and water management practices along the borders in riparian zones such as grassed waterways and cover crops plant native tree and

shrubs species across the areas to enhance diversity and supply habitat for wildlife ; respect the crown land reserve of ten meters across the water bodies and fifty meters around the shoreline of lakes and sustain them efficiently (Rwanda, 2018).

### **2.3.1 Bamboo in restoration**

The life cycle, structure, development and ecology of bamboos must be considered in a complemented approach in forest landscapes as well as its relationship with riparian zones (Buziquia, Lopes, Almeida, & Almeida, 2019). Commercial bamboo has the potential to play an important role in accomplishing international restoration goals (Buckingham, 2016) by using dishonored and devastated lands to restore critical ecosystem functions at the same time producing a great source of fibre and meeting societal needs. Through its quick growth, soil binding qualities, and erosion control adaptive capacity, nutrient uptake and water conservation of land, provision of continuous and permanent canopy, all these ecological qualities enable bamboo to be chosen as succession species for the restoration of degraded land (Yanxia & Frith, 2018).

Despite socio-economic contributions to people and countries in general, bamboo plantations on agricultural lands may negatively impact crop productivity and food security (Akoto et al., 2018). Bamboo rhizomes are existing in top layers at around 0 to 30 cm where most crop rooting systems prefer in farmlands which may cause competition for nutrients. Bamboo provides mono-specific support in riparian zones and once established they cause changes in the structure and diversity of the plant communities in these zones.

Evaluation of the impact of *Bambusa tuldooides* on natural regeneration in riparian forests in the Rio Grande do Sul, Brazil has concluded that there was a loss of species diversity and abundance in riparian zones where bamboo was introduced (Buziquia et al., 2019). *Bambusa vulgaris* is noted by the Center for Agriculture and Bioscience International (CABI) to neutralize and create monospecific stands in roadside ditches, open ground, and riverbanks due to its quick-rooting culms and branches. Consequently, it was determined that *Bambusa vulgaris* has the potential to colonize undisturbed forests moving along the streams (Rojas-Sandoval & Acevedo-Rodríguez, 2014).

In Rwanda to reach the 2030 Forest Landscape restoration target, bamboo has been acknowledged to play a vital role to reduce the dependence on firewood as the main source of energy (IUCN, 2015). However, in the interest of promoting forests cover and watersheds protection, the promotion of non-timber forest products (NTFP) is a relevant strategy. Of

particular importance for watershed protection in Rwanda's riparian zones has been the planting of bamboo (IUCN, 2015). Two bamboo species were selected for riparian zone planting in Rwanda as identified by (Ntirugulirwa et al., 2013) including *Bambusa vulgaris*, and *Oldeania alpina* (Ntirugulirwa et al., 2013).

#### **2.4 Bamboo plantings and national targets**

Bamboo has been increasingly recognized as a useful planning tool for helping to safeguard nearby land uses and is important to help reduce sediments and pollutants and screen against human disturbances such as noise (Henshaw & Ursic, 2012). Bamboo has been spread out in Rwanda to protect riparian zone and has been recognized as crosscutting means to achieve SDGs, where 4 SDGs targets are involved including SDG 1, SDG 2, target 2.2,2.3 and 2.4, SDG 13,target 13.2 and 13.3 and SDG 15,target 15.2 (Ding, 2020). As a non-wood forest product, bamboo can play an important role in mitigating pressure on forest resources like wood that are in increasing demand for different countless uses to improve comfort and well-being (Clark et al., 2015).

To achieve national targets, Rwanda has made substantial achievements in environmental and climate change integration, and climate change has been tackled with knowledge by sectorial strategies , including Green growth and climate resilience strategy (GGCRS)and the Nationally Determined Contribution (NDC) for climate change adaptation and mitigation (Government of Rwanda, 2020). However, focus will be placed on enhancing monitoring and evaluation especially on high impact areas such as the adoption of environmental and social impact assessment, biodiversity and ecosystem management, minimize pollution and strengthening waste management. Bamboo has been recognized as priority plant species to improve climate resilience and safeguard riparian areas (REMA, 2019).

In order to accomplish the Global Forest goals and targets set by the United Nations Forum on Forests (UNFF), such as goal 1 to converse the loss of forest cover globally, Rwanda is engaged in planting Bamboo to reach 30% of forest cover target (Fred Hornaday and & Morris, 2023), goal 2 to enhance the socio-economic and environmental profits of forests, goal 3 to increase the number of hectares under protected forests globally, and goal 5 to encourage governance structure for implementing sustainable forest management, more bamboo has been planted (Yanxia & Frith, 2018). In many nations where it is utilized for ecological goals such improving natural resource conservation, increasing soil organic matter content, and controlling erosion

on hillsides and along river banks, it may offer major environmental benefits (Pande et al., 2012).

Due to its quick growth, high economic worth, wide availability, and similar physical characteristics to those of wood, bamboo has drawn more attention as a renewable resource. Bamboo is a natural resource that can be used for a wide variety of things, including furniture, fences, pulp and paper, construction materials, handicrafts, and edible shoots and animal feed. Additionally, it has been shown to be very good at preserving soil in ravines and allowing for the productive use of gullies (Pande et al., 2012). Bamboo planting in ravines also has some indirect advantages, such as minimizing soil erosion, intercepting rainfall, retaining moisture, rehabilitating the land, conserving water through litterfall, and preventing landslide (Ben-zhi, Mao-yi, Jin-zhong, Yang Xiao-sheng, & Zheng-cai., 2005).

According to research on bamboo's benefits on soil conservation done in Vasad, India, bamboo plantations may hold 80–100% of the precipitation that falls on them (Buziquia et al., 2019). In years with excessive rainfall, the sediment yield decreased to 1.4 t/ha. Further research also showed that bamboo has a conservation impact that improves soil health over time. Because of bamboo's fast growth and ability to limit soil erosion as well as the stabilization of banks in riparian zones, more research has been done on the possible use of bamboo for the restoration of damaged areas. Although ecological buffers cannot compensate for habitat scarcity, degradation and fragmentation, riparian areas are often degraded by several factors such as intensive agriculture, settlements and other developing anthropogenic infrastructures such as river engineering works (Urbani et al., 2022).

According to COP 15, POST-2020 GBF target number 2, 3 and 6, by 2030 at least 30% of degraded terrestrial, inland water, coastal, and marine ecosystems must be efficiently restored and this percent areas of terrestrial, inland water, coastal and marine areas must be properly conserved and managed as well as 50% decrease in the rate of introduced invasive alien species (UNEP & CBD, 2022) in order to improve biodiversity, maintain ecosystem function and services and promote sustainability and connectedness (UN, 2022). In addition to that, the CBD 2030, target number 2,4,6,8,10,and11, the Kunming-Montreal Global biodiversity Framework: 23 targets, in its target 2,11and 21 highlight the same target as aforementioned in COP15 (Collins, 2022).

#### **2.4.1 Bamboo and Nationally Determined Contributions (NDC)**

Rwanda through its NDC, is committed to reduce dependence on traditional biomass fuels, which lead to climate variability, thus enhancing reduced pressure on forests, forest biodiversity, food security through enhanced soil fertility, and reduced soil erosion and soil runoff. Rwanda's economy is based primarily on agriculture which mostly rain-fed. Land is prone to severe rains, connected with high topography and thus exacerbate soil erosion and landslides predominantly in northern and western parts of the country. To cope with these challenges, the country has set adaptation and resilience priorities drawn upon the Green Growth and Climate resilience strategy with a timeframe of 2050, where 14 programs of Action (PoA) have been developed (Government of Rwanda, 2020).

#### **2.4.2 Biodiversity, climate change mitigation and adaptation**

The magnitude at which biodiversity is declining calls for immediate action, including restoration, along with strategies for climate adaptation (McNeil et al., 2021). By doing so, we may stop and reverse this trend and reap many advantages of both conservation of biodiversity and climate adaptation at the same time (Krosby et al., 2018). Therefore, it is imperative to explore cross-sectorial solutions that address the biodiversity, climate, and other related problems in a coordinated manner, as well as to collaboratively integrate the diverse values of biodiversity into decision-making (McNeil et al., 2021). The preservative decline of biodiversity is caused by direct and indirect drivers (Díaz & Yadvinder, 2022). While direct drivers can be mitigated or even temporarily stopped, long-term success of these efforts is unlikely to occur unless the human-caused indirect drivers which are the primary causes of the current decline in biodiversity are addressed (Díaz & Yadvinder, 2022).

## CHAPTER 3: METHODS

### 3.1 Description of study area

The Nyabarongo River is a part of Nile basin and runs from south to north in the western part of Rwanda. The River covers eight districts namely Karongi, Ngororero, Rutsiro, Huye, Nyanza, Ruhango, Muhanga and Nyamagabe. The total surface of the catchment is 3,348 km squares, covering 12.7% of the total surface of the country (26,338 km<sup>2</sup>). Ngororero district covers 560.11 km<sup>2</sup> representing 16.7% of the catchment area (Rwanda Water Resources Board (RWB) and Water for Growth Rwanda, 2017). The study was conducted in three sectors of Ngororero District, namely Gatumba, Muhororo and Ngororero Sectors among four sectors adjacent to Nyabarongo River in the District, where Bamboo were planted to protect riparian zones (Figure1).

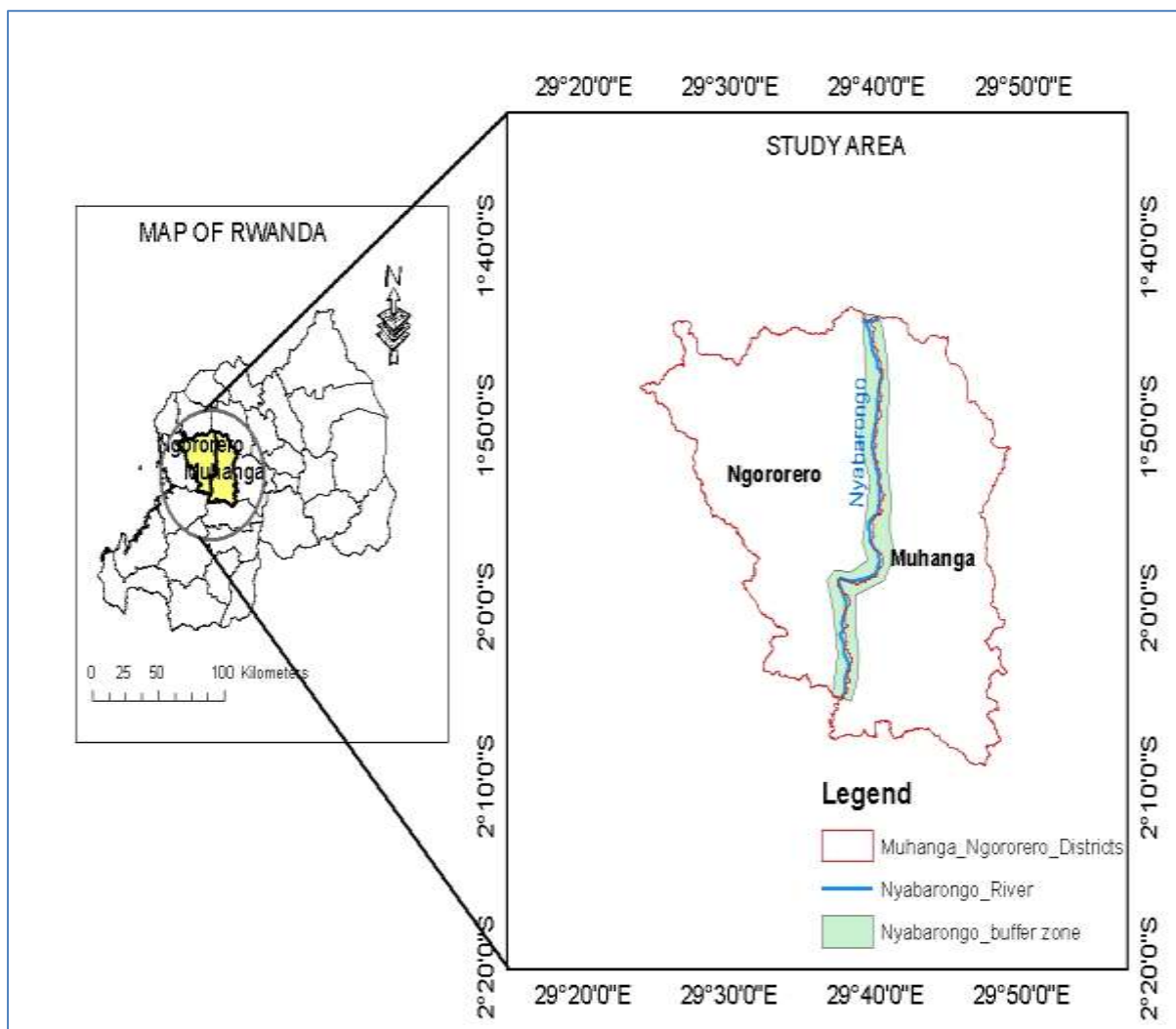


Figure 1: Location of the study area along Nyabarongo river in Ngororero District, Rwanda

The Nyabarongo river and its tributaries provide the majority of the local population's water and livelihoods. It is distinguished by hilly steep slopes that are highly prone to erosion, especially in the wet season. This slope characteristic together with continuous cultivation of land, devastation of shoreline of the streams, inefficient exploitation of forests, reduction of the forest cover, mining and quarries and minimum use of conservation and erosion control measures by the users, result in high riverbank erosion and perceptible siltation and flooding of the Nyabarongo River and its tributaries. It is therefore crucial that protection measures are implemented in this area. Protection of the upper Nyabarongo catchment had the main objective to significantly improve the environmental and ecosystems around the river and its tributaries and upstream areas and contribute to restraining the effects of erosion within the catchment. These interventions also aimed at increasing agricultural productivity and thus uplifting the welfare of communities (REMA, 2015).

Gatumba sector is one of sectors of Ngororero District, in which these important interventions have been implemented. The sector is adjacent to Nyabarongo River where its riparian zones has been planted with bamboo since 2009 and 2010 to protect this river against erosion at the same time protecting biological diversity. The sector covers 43.2-kilometer squares, with 693 people/km<sup>2</sup>. Gatumba is located in Upper Nyabarongo catchment area surrounded by Nyabarongo River. Muhororo sector is another sector of Ngororero District bordered with Gatumba Sector in the south also located in the upper Nyabarongo catchment area where bamboo is planted along Nyabarongo River in the same period. The site where the sampling has been conducted has been planted with bamboo (*Bambusa vulgaris*) in 2016, where 74 hectares are planted during LVEMP II implementation. Therefore, these bamboos are 8 years old. Ngororero Sector is also among areas which benefited bamboo plantings under Lake Victoria Environmental Management Project (LVEMP) I and II project (REMA, 2015).

### **3.1.1 Data source and description**

Table 1 provides a detailed description of data sources, including the type of data, its origin, the time it was acquired, and how it was used.

Table 1: Data source and description

s/ n	Data	Source	Data types	Period (year)
1	DEM	<a href="https://earthexplorer.usgs.gov/">https://earthexplorer.usgs.gov/</a>	Rasta	
2	Rainfall	<a href="https://power.larc.nasa.gov/data-access-viewer/">https://power.larc.nasa.gov/data-access-viewer/</a>	NetCD F file	2000- 2023
3	Soil	<a href="https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/faunesco-soil-map-of-the-world/en/">https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/faunesco-soil-map-of-the-world/en/</a>	shapefile	
4	Landsat8 (1995 and 2023)	<a href="https://earthexplorer.usgs.gov/">https://earthexplorer.usgs.gov/</a>	Rasta	1. 1995 2. 2023
5	Rwanda boundaries	<a href="https://datacatalog.worldbank.org/search/dataset/0041453/Rwanda-Admin-Boundaries-and-Villages">https://datacatalog.worldbank.org/search/dataset/0041453/Rwanda-Admin-Boundaries-and-Villages</a>	Shapefiles	2018

### 3.2 The study design

The study was carried out in three sectors (Gatumba, Muhororo and Ngororero) among five sectors adjacent to Nyabarongo River in Ngororero District as they have some similarities in terms of environmental factors such as temperature, precipitation and elevation, and similar land use types. This enabled the control of other variables under the study. Moreover, these sectors are vulnerable to erosion and flooding in rain season, and riparian protection measures have been implemented in the same period as mentioned in previous paragraphs. To ensure that my study is replicable, I followed these detailed steps to set up my sampling design. I selected two types of riparian zones: one dominated by bamboo and one without bamboo (non-bamboo) as a control site.

I selected four replicates bamboo-planted sites and four in control riparian zone along the river, in order to account for spatial variability. I positioned quadrats of 10 × 10 m in the riparian zones to identify plant species along the river buffer zone at regular intervals of 100 meters, and the samples were collected within 10 meters of the river buffer zone along Nyabarongo river. On non-bamboo planted riparian zones along the river (the control sites), where quadrats did not fit within 100 m, I collected the data to the nearby point. The specific sampling sites along the river in each sector were selected randomly, with eight quadrats sampled in each sector. Each quadrat was subdivided into four nested 1-m square plot, to sample herbaceous plants and seedlings, for a total of 24 quadrats with 48 nested plots within riparian zone planted

with bamboo and 48 without bamboo (control sites), sampled for the entire area of study (Figure 2).

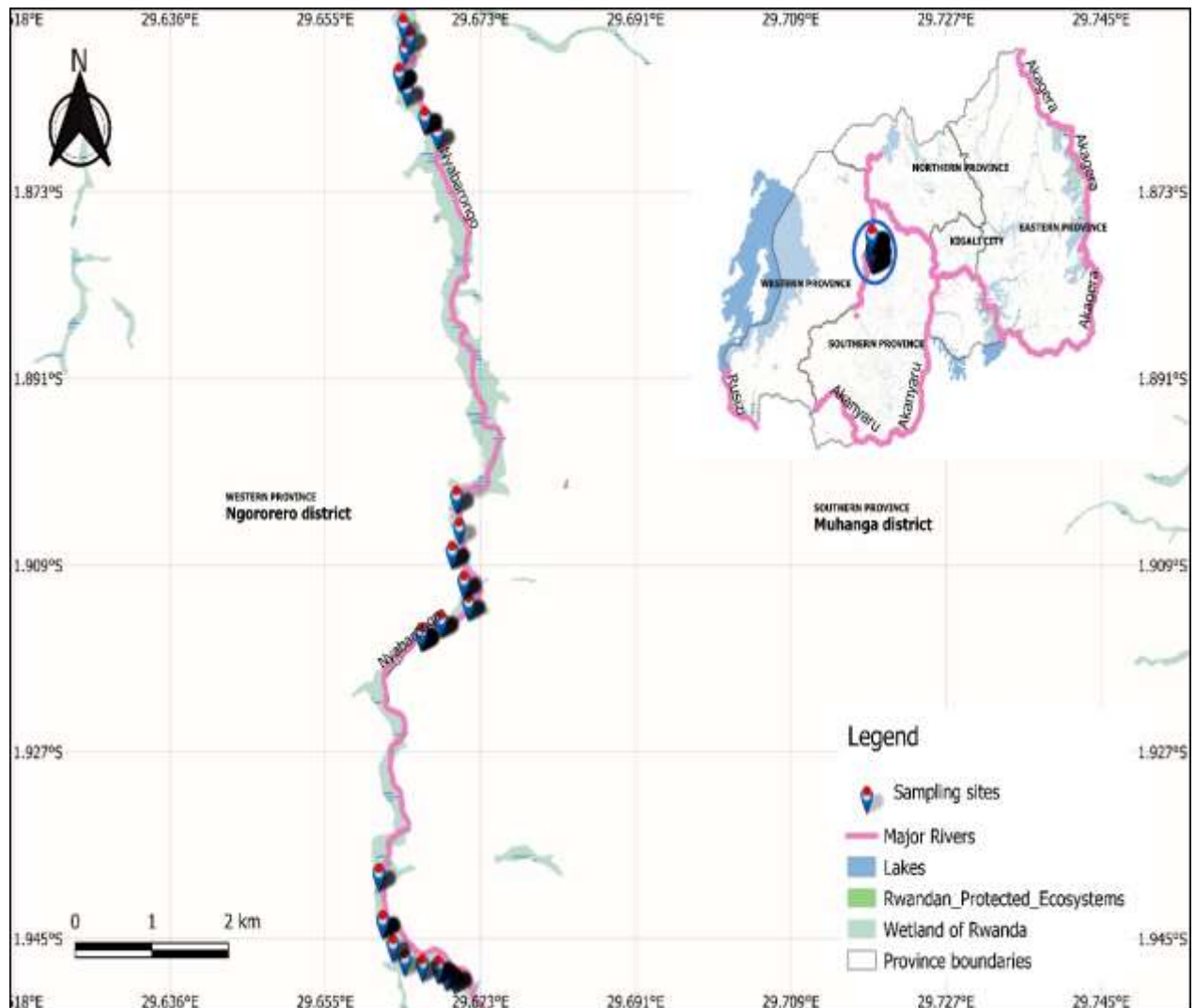


Figure 2: Geographical location of sampled sites, in Nyabarongo River catchment, Rwanda

### 3.3 Data collection

#### 3.3.1 Vegetation inventories

To evaluate the status of riparian areas, riparian vegetation is a crucial indicator. The condition of riparian zones has been evaluated using a variety of indicators utilized globally, including riparian zone width, vegetation overhang, and bank stability. To evaluate the efficacy of buffer conservation and restoration, it is crucial to measure riparian buffer width and biomass (Singh et al., 2021). I used an experimental approach in which the factors under analysis will show the effect relationship between two variables.

Systematic sampling using quadrats as described by Bryant *et al* (2005) cited in (Ajayi & Obi, 2016) were employed to assess species composition in the riparian zone. Before collecting the data, I requested permission from the District to allow me to do research in the study zone.

I counted the number of bamboo stems and any woody stems (non-bamboo species) present, the same in the control plots. I identified the species and record them in a prepared data sheet. In addition, at each point of the quadrat, GPS coordinates were collected. Understory vegetation was sampled in the 100 m<sup>2</sup> squared plots at each sampling point, and stems of woody understory vegetation were identified and counted, while the percent cover of herbaceous vegetation was estimated using visual-estimation in the 1 m<sup>2</sup> nested plots within the larger plots (Gupta, Yella, & Dougherty, 2013). All plants were identified with assistance from the National Herbarium of Rwanda. Specimens were collected to make sure they are well identified.

Moreover, websites such as IUCN Red List (<https://www.iucnredlist.org/search?query>) and Plants of the World (<https://powo.science.kew.org/results?>) were utilized for species identification. In addition, Dr. Vedaste MINANI an expert in plant identification assisted me in identifying plants on the field. At each sampling point and/or quadrat during the data collection, land use types adjacent to Nyabarongo river were identified and recorded in the field data sheet, and four categories of land use types were recorded including agriculture which consisted of rice crop, mixed cropping pattern, and monoculture, non-agriculture included areas adjacent to the riparian area covered with grasses, forest, and shrubs that were not cultivated, and other category comprised of forest-dominated land cover . These land use types were recorded to evaluate and look at the reason why plant species richness might differ in bamboo and in the control sites. The same sampling was done in the control sites where bamboo was not present.

### **3.3.2 Soil erosion assessment using GIS-based RUSLE Model**

Several methods have been tried to quantify soil loss from water erosion, the USLE was the first universal soil loss equation method, designed primarily for estimating soil erosion in croplands, or gently sloping landscapes. With its updated revised universal soil loss equation (RUSLE) and modified universal soil loss equation (MUSLE). The RUSLE has been accepted in numerous nations across the world as a soil loss equation that produces the best results when planning soil and water conservation in a sustainable way, and surface erosion models based

on RUSLE are widely accepted and increasingly used for applications at the field, catchment, national and even global scales (Eddefli, Ouakil, Khaddari, & Tayebi, 2023).

### 3.3.2.1 Computation of remote sensing metrics

#### a) Calculation of Normalized Difference Vegetation Index (NDVI)

Based on Google Earth satellite's high-resolution images, S2A MSI L2A images and layers, two remote sensing metrics were calculated: Normalized Difference Vegetation Index (NDVI) and A (annual soil loss) and to compute A, the following variables have been calculated R, K, LS and C. The Normalized Difference Vegetation Index (NDVI) was calculated for images acquired as per Eq. using bands 4 and 8 in Sentinel-2, which has been calibrated to measure radiation in the visible (Red) and near-infrared (NIR) regions of the spectrum, respectively. The equation used was  $NDVI = (NIR - RED) / (NIR + RED)$  (Almagro et al., 2019). The NDVI values range between -1.0 and 1.0, with values close to 1 indicating more greenness and vegetation activity. NDVI values nearing zero and below indicate non-vegetated areas (Karaburun, 2010).

#### b) Estimating C-factor along Nyabarongo river

Soil loss is very susceptible to vegetation cover, slope steepness, and length factor. To control soil erosion, soil loss must be estimated over the area of interest. Soil loss due to erosion can be approximated using a predictive model, in which I have utilized the revised universal soil loss equation (RUSLE) (Karaburun, 2010). One of the most important parameters in the equation used in this model was the C-factor that represents effects of vegetation type, stage of growth and other land cover (Martine Hagai, 2019). Land cover is estimated by interpreting remote sensing pictures using NDVI obtained from landsat8 photos from 1995 to 2023 which is a vegetation cover indication. Moreover, the final C-factor map was produced using the regression equation in spatial analyst tool of ArcGIS 10.2.2.

The regression equation used to calculate C-factor was:

$$C = 0.1 \left( \frac{-NDVI + 1}{2} \right) \text{ (Almagro et al., 2019)}$$

The C-factor depicts the effect of farming and management methods on soil erosion rate, and it indicates how conservation efforts affects the average yearly soil loss, as well as how that soil loss likely is distributed over a period of time. Other variables like annual rainfall erosivity

index was calculated based on available rainfall data from 2000 to 2023 of six meteo-stations namely Gatumba, Kabaya, and Nyange in Ngororero District and Rugendabari, Kibangu and Nyabinoni located in Muhanga District. Soil erodibility factor, slope length factor, and slope steepness factor (dimensionless) were also calculated (Table 1), while P factor was estimated using literature review.

### c) Estimation of annual soil loss (A)

To determine the impact of bamboo plantings along Nyabarongo river buffer zone situated between Ngororero and Muhanga Districts, I used the RUSLE model equation through ArcGIS 10.2.2., which is a convenient and compatible way to estimate yearly soil loss from a unit property in GIS (Rizinjirabake, Nyiramana, Kamizikunze, & Mukamugema, 2023). First, we used the digital terrain model to delimit the study region, identify the outlet, and extract it. The soil loss equation was constructed separately in raster data format, and erosion was estimated using map algebra. After combining maps and data, ArcGIS was utilized to map and model the dataset. The maps were georeferenced, digitalized, and analysed (Renard, G.R., G.A., & D.K., 1997) used the RUSLE model to present yearly soil loss (A) as expressed by the following equation:  $A=R*K*LS*C*P$

Where:

**A:** Annual soil loss ( $t. ha^{-1}. year^{-1}$ ), **R:** Annual rainfall erosivity index ( $MJ mm. ha^{-1}. hour^{-1}. year^{-1}$ ), **K:** Soil erodibility factor ( $t.ha^{-1}.MJ^{-1}.mm^{-1}$ ), **LS:** slope length factor, and slope steepness factor (dimensionless), **C:** soil cover and land management factor (This considered the C factor maps of 1995 and 2023, ranges from zero to one), dimensionless, **P:** conservation practice factor (dimensionless), and ranges from zero to one. In this study, I considered P factor of 0.3 which was computed for soil erosion losses in 1995 and 1 for soil erosion losses estimated in 2023 on the control sites. In addition to RUSLE model assessment physical measurements has been used to assess erosion along riverbanks, included the width of the riparian buffer zone, slope and land use types. The bank's stability and the rate at which erosion can happen are both influenced by the slope's steepness (Bandyopadhyay et al., 2014). The width of the buffer zone was measured using a measuring tape in order to evaluate erosion status in the riparian zones, and see if there is a change on both sides of the buffer zone. One side of the river bank if eroded, and the other side if affected by anthropogenic activities such as agriculture. In addition, evaluate the relationship between the categories of erosion with the presence or absence of bamboo in studied riparian zones. These values are then compared to

the NDVI data produced from photography from the same time period. Furthermore, the regression equation from the subjected area was used to generate a C-factor map for the district. For creating the C-factor, the NDVI was estimated using the mosaiced IRS LISS III picture of 2023.

#### d) Workflow of C-factor estimated using NDVI

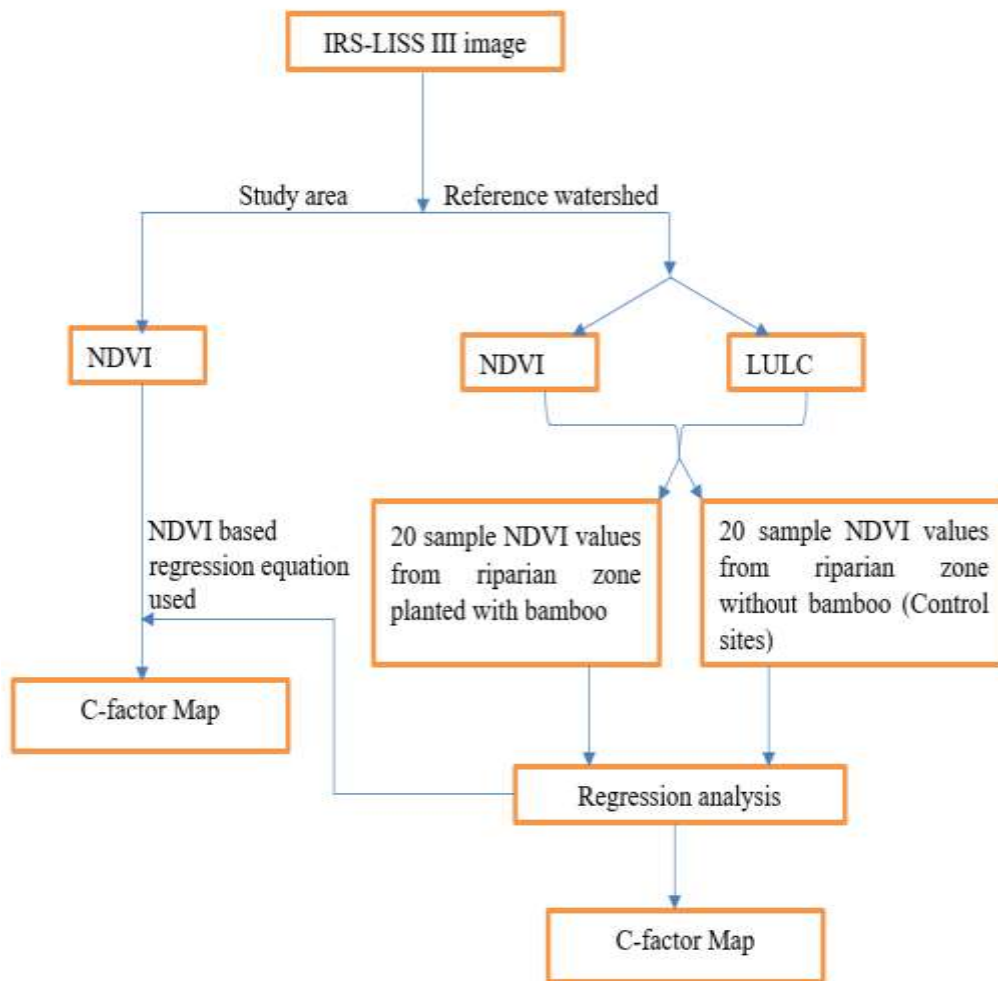


Figure 3: Workflow of C-factor estimated using NDVI

### 3.4 Data analysis

Percent cover, relative importance, relative abundance, cover estimates and dominance were calculated using the data collected on the field. Species collected in the quadrats were categorized as native, exotic and invasive, as well as IUCN Red List category of threatened and endangered species. I compared the data from areas planted with bamboo, and areas with no bamboo planted, to detect the effects of bamboo on plant diversity and climate adaptation

as indicated by soil erosion evidence. To test for differences in density, diversity, and abundance, I used ANOVA test and t test to test for differences between the two treatments (with and without bamboo) and has been performed in R statistical software.

The Shannon and Simpson diversity index were calculated to estimate the diversity of species within a community. The results were the Shannon diversity index, evenness, richness, the total number of individuals, and the average population size.

$$H = \sum_{i=1}^s (P_i \times \ln P_i)$$

Where **H**: Shannon diversity index;

**P<sub>i</sub>**: is the proportion of individuals of i-th species in a whole community

**s**: number of species encountered

**Σ**= the sum from species 1 to species s

And **p<sub>i</sub>**= n/N, where **n**= individuals of a given types/species, and **N**= the total number of individuals in a community.

**Simpson diversity index (D):**

$$\text{Simpson Index (D)} = \frac{1}{\sum_{i=1}^s p_i^2}$$

$$D = 1 - \frac{\sum n(n-1)}{N(N-1)}$$

Numerous techniques exist for computing similarity indices, including the Bray-Curtis similarity, Sørensen similarity, and Jaccard similarity. These indices give numerical values between 0 and 1, where 0 denotes no similarity and 1 denotes total species composition similarity between samples.

To evaluate community similarity, similarities index was computed including Sorenson's coefficient has been computed to represent what community have in common in terms of species.

$$\text{Sorenson's coefficient (CC)} = \frac{2C}{S_1 + S_2}$$

Where C is the number of species the two communities have in common, s 1 is the total number of species found in community one, while s 2 is the total number of species found in community two.

## CHAPTER 4: RESULTS

### 4.1 Plant species richness and diversity along Nyabarongo river banks

Plant species richness was significantly higher in the control sites than the riparian areas planted with bamboo (T test=-5.428, Df=1 and P value=0.05). Control sites had more native plant species than the riparian zone planted with bamboo (Table 2) and higher species richness (Figure 4).

Table 2: Number of plant species sampled in the study zone

Riparian zone	Exotic species	Native species	Invasive species
Bamboo	10	12	6
Non-bamboo (Control sites)	18	21	6

#### 4.1.1 Plant species richness and diversity

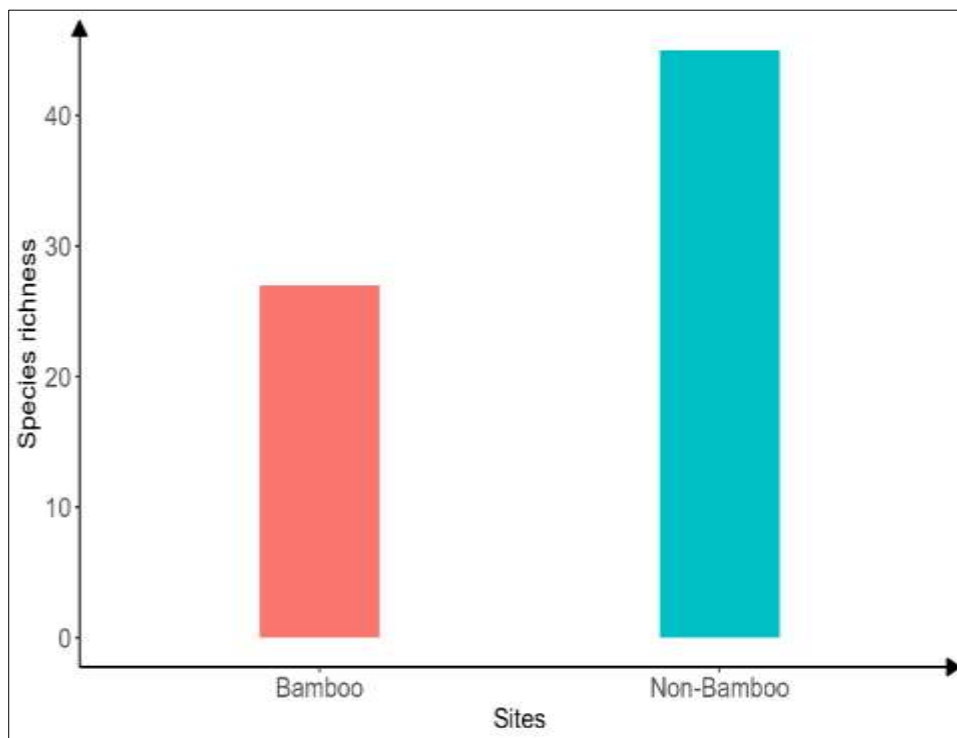


Figure 4: Plant species richness in riparian zone with and without bamboo plantings

#### 4.1.2 Rarefaction curve and sample coverage curve in sampled riparian zones

The control sites (non-bamboo) had higher species diversity than the riparian zone with bamboo plantations (Figure 5 A). The upper curve in blue is the riparian zone without bamboo (control site) showing higher species diversity and the orange is the bamboo riparian zone.

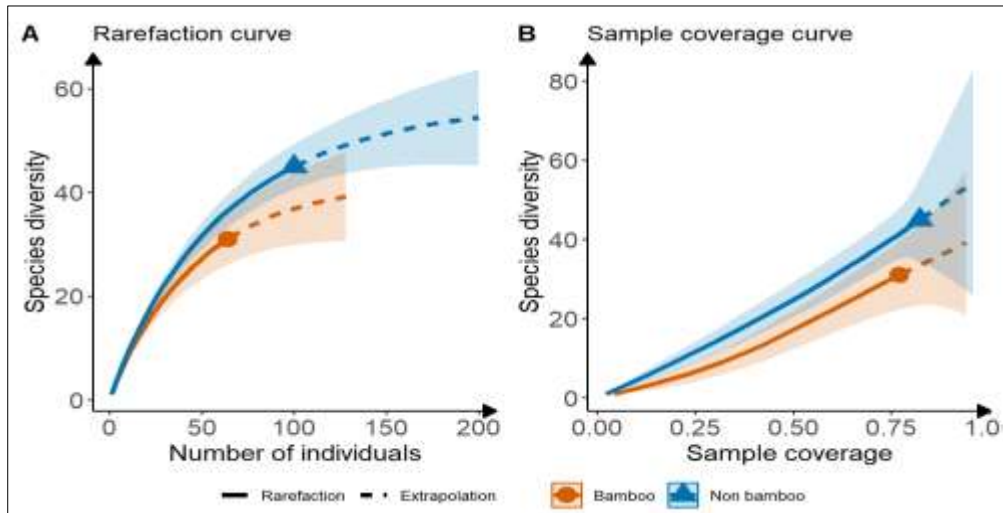


Figure 5: Rarefaction curve and sample coverage curve in sampled riparian zones

#### 4.1.3 Simpson diversity index

Compared to the bamboo riparian zones which demonstrated a Simpson Index of 0.061, the non-bamboo riparian zones have a higher plant species diversity score of 0.068 (Figure 6). Despite the small difference, this indicates that the non-bamboo riparian zones have higher evenness and a higher species richness.

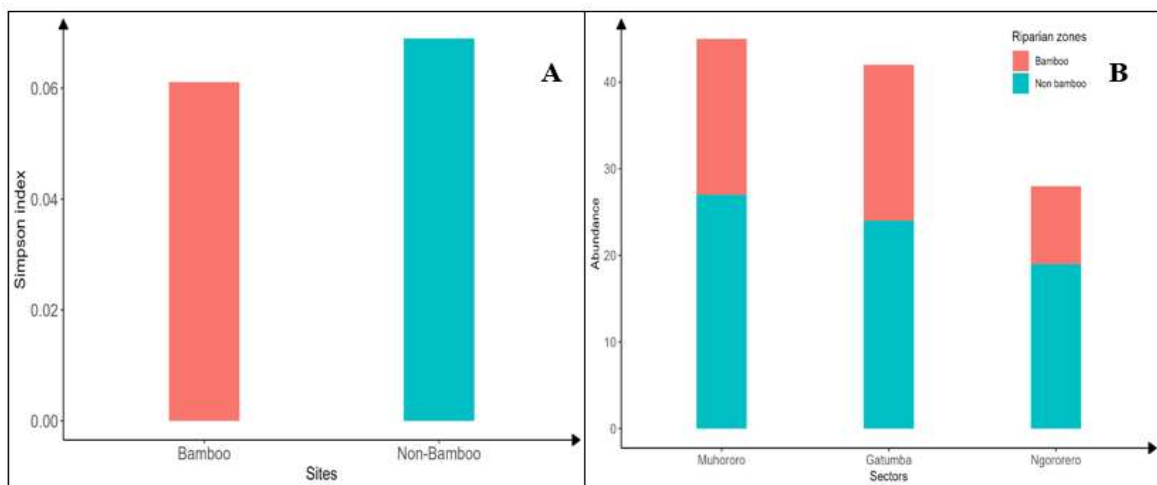


Figure 6: Simpson diversity index (A) and relative abundance (B) computed in bamboo and control site

#### 4.1.4 Community similarity index (SCSI and/or CC)

Table 3: Common plant species shared by two sampled riparian zones

S/N	Species name	Family	Native/Non-native	Invasive (Yes/No)	IUCN status
1	<i>Gymnanthemum amygdalinum</i>	Asteraceae	Exotic	No	NE
2	<i>Morus nigra</i>	Moraceae	Exotic	No	NE
3	<i>Persicaria amphibia</i>	Polygonaceae	Exotic	No	NE
4	<i>Manihot esculenta</i>	Euphorbiaceae	Exotic	No	NE
5	<i>Psidium guajava</i>	Myrtaceae	Exotic	Yes	LC
6	<i>Calliandra houstoniana</i>	Fabaceae	Exotic	Yes	LC
7	<i>Phyllanthus fischeri</i>	Phyllanthaceae	Exotic	No	NE
8	<i>Leonotis nepetifolia</i>	Lamiaceae	Native	Yes	NE
9	<i>Persicaria senegalensis</i>	Polygonaceae	Native	No	LC
10	<i>Ocimum gratissimum</i>	Lamiaceae	Native	Yes	NE
11	<i>Lantana camara</i>	Verbenaceae	Exotic	Yes	NE
12	<i>Acanthus polystachyus</i>	Acanthaceae	Native	No	NE
13	<i>Lantana trifolia</i>	Verbenaceae	Exotic	Yes	NE
14	<i>Bridelia micrantha</i>	Phyllanthaceae	Native	No	LC
15	<i>Persicaria bungeana</i>	Polygonaceae	Exotic	No	NE
16	<i>Phragmites mauritianus</i>	Poaceae	Native	No	LC
17	<i>Hibiscus ludwigii</i>	Malvaceae	Exotic	Yes	NE
18	<i>Crotalaria retusa</i>	Fabaceae	Exotic	No	NE
19	<i>Hibiscus diversifolius</i>	Malvaceae	Native	No	NE
20	<i>Triumfetta rhomboidea</i>	Malvaceae	Native	No	NE

The riparian zones planted with bamboo and the control sites shared some plant species. Therefore, species composition was compared using Sorensen's coefficient. There were twenty common plant species identified across the two communities (Table 3). The results indicated a considerable amount of resemblance through calculated Sorensen's coefficient of 0.55 between the bamboo riparian zone and the control site, with a significant overlap between the sets.

#### 4.1.5 Average percent cover in bamboo and control sites

The plant families including Poaceae and Asteraceae were the most prevalent, with percent covers of 41.43% and 18.27%, respectively, while ferns were the least predominant, with only 1% cover in bamboo riparian zones. In non-bamboo riparian zones, Poaceae and Fabaceae family were the most prevalent, with 41.75% cover and 38.5% cover, respectively (Figure 7).

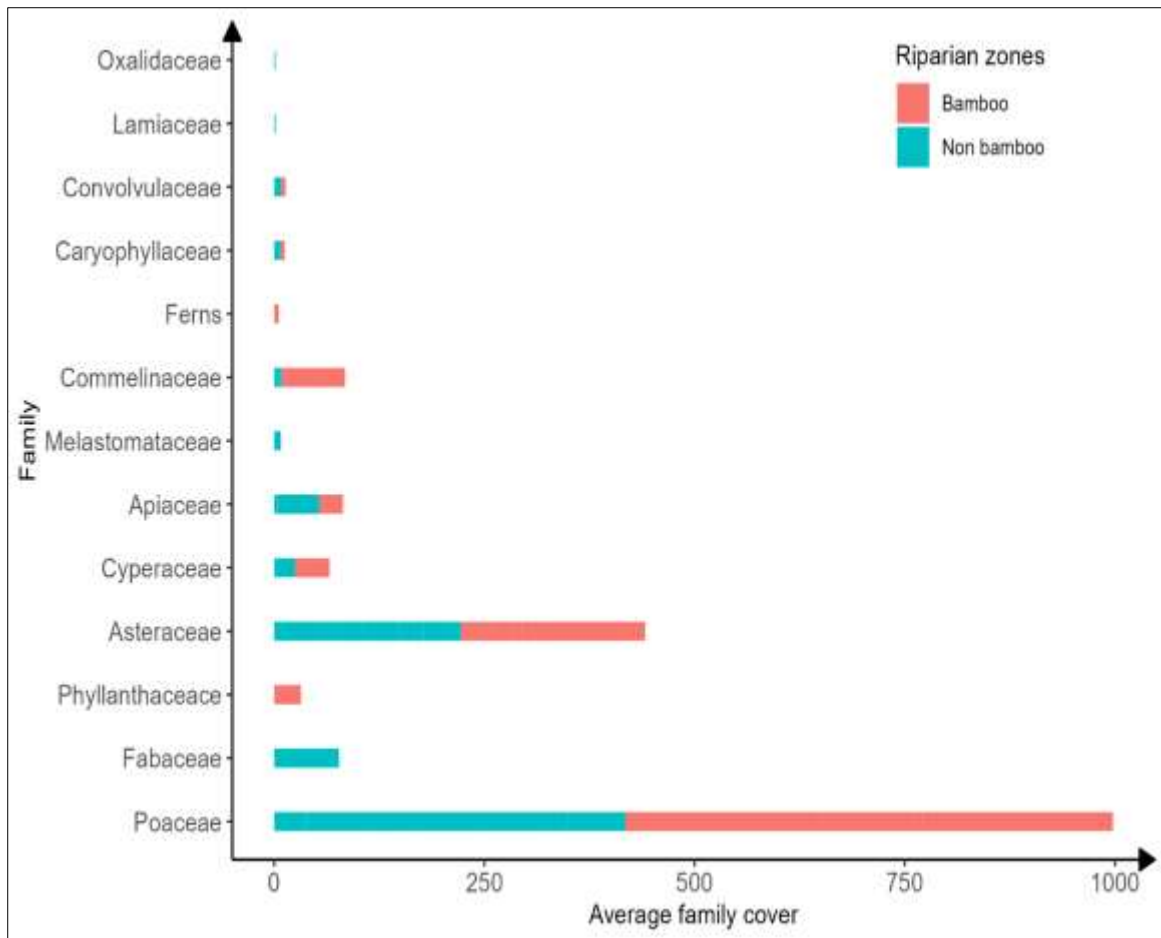


Figure 7: Average percent of herbaceous cover across studied riparian zones

## 4.2 Diversity of understory vegetation

### 4.2.1 Plant densities in surveyed riparian zones

*Oryza sativa* was the plant species with high plant density (0.78) observed in the control site followed with *Gomphocarpus physocarpus* (0.71) identified in bamboo riparian zone and *Phyllanthus urinaria* (0.68) identified in the control site; Appendix 2). Bamboo make up up to 41.8% of the total vegetative cover, depending on the density and age of the bamboo stands. The situations where the percentage of bamboo cover can be considerably higher, is especially in dense bamboo plantings. These bamboos are 8-years-old; planted in 2016 through the LVEMPII project of REMA. This indicates that the richness of understory plant species decreases with increasing bamboo density and coverage (Figure 8).



Figure 8: Understory vegetation shown in bamboo riparian areas, along Nyabarongo river, Ngororero District.

#### 4.2.2 Comparison of life forms

More species of shrubs were found than any other life form in both bamboo and control sites, and the number of shrubs, herbaceous plants, and trees were higher in control sites than bamboo sites (Figure 9), more trees and bushes were present in non-bamboo riparian zones, and a large amount of space is taken up by fallen bamboo leaves in bamboo riparian zones (Figure 8).

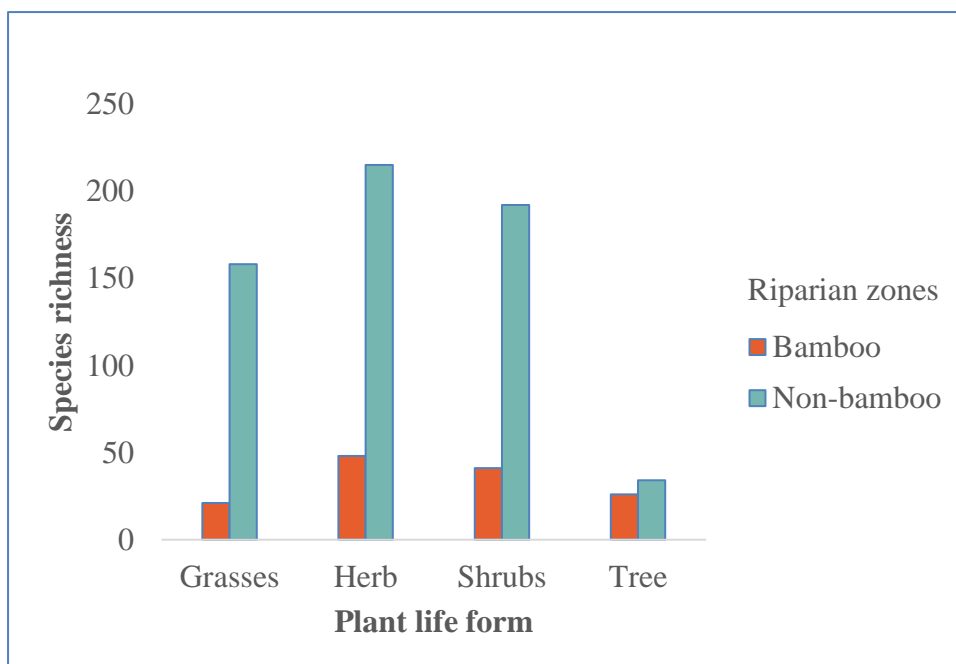


Figure 9: Life forms identified in the riparian zone of Nyabarongo river, Ngororero District

### 4.2.3 Dominant plant species per life form

Polygonaceae and Phyllanthaceae were the most dominant plant families in the riparian zones with bamboo and without bamboo respectively (Table 4).

Table 4: Dominant plant species and species richness per life form

Life form	Riparian with bamboo			Riparian without bamboo		
	Dominant plant family	Dominant plant species	Species richness	Dominant plant family	Dominant plant species	Species richness
Grasses	Poaceae	<i>Hyparrhenia rufa</i>	21	Poaceae	<i>Oryza sativa</i>	158
Herbs	Polygonaceae	<i>Persicaria amphibia</i>	48	Phyllanthaceae	<i>Phyllanthus urinaria</i>	215
Shrubs	Malvaceae	<i>Triumfetta rhomboidea</i>	41	Malvaceae	<i>Hibiscus ludwigii</i>	192
Trees	Phyllanthaceae	<i>Bridelia micrantha</i>	26	Phyllanthaceae	<i>Bridelia micrantha</i>	34

### 4.2.4 Dominant families in bamboo and control sites

Malvaceae family was the most common family observed in both control and bamboo sites. However, there were more families and greater abundances of plants in the control sites (Figure 10).

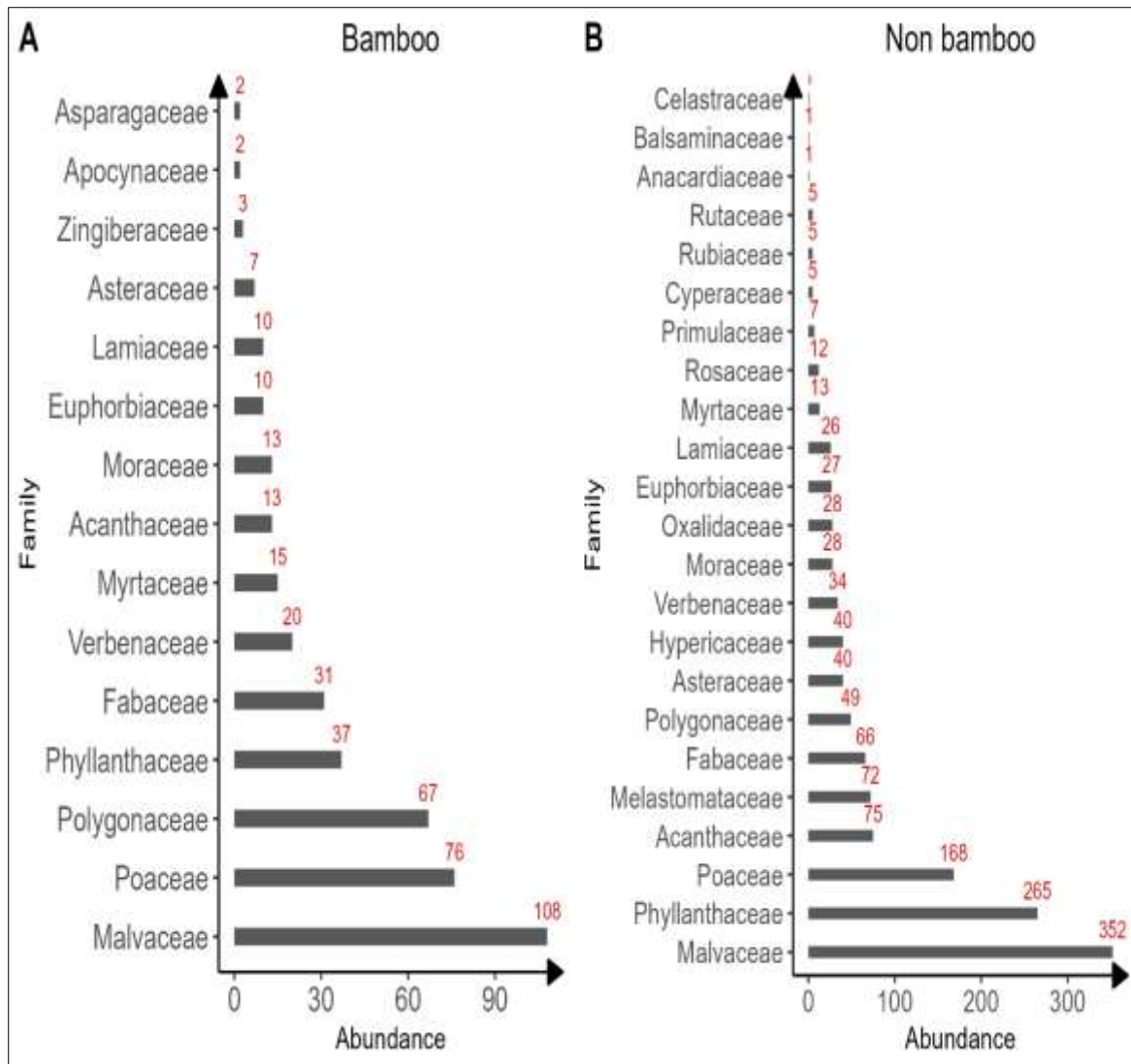


Figure 10: Relative abundance of plant families in the riparian zone of Nyabarongo river, Ngororero District, Rwanda

#### 4.2.5 Relationship between plant species richness and land use types

There was a significant difference between land use types and plant species richness (T test = -8, Df=2 and P value= 0.05; Figure 11). In riparian zone planted with bamboo, the buffer zone width was less than in the control sites and was less than 10 min in certain locations where agriculture was practiced. Farmers cut bamboo shoots in pursuit of greater area for crops, and as such, larger proportion of the marshland was used for agricultural production.

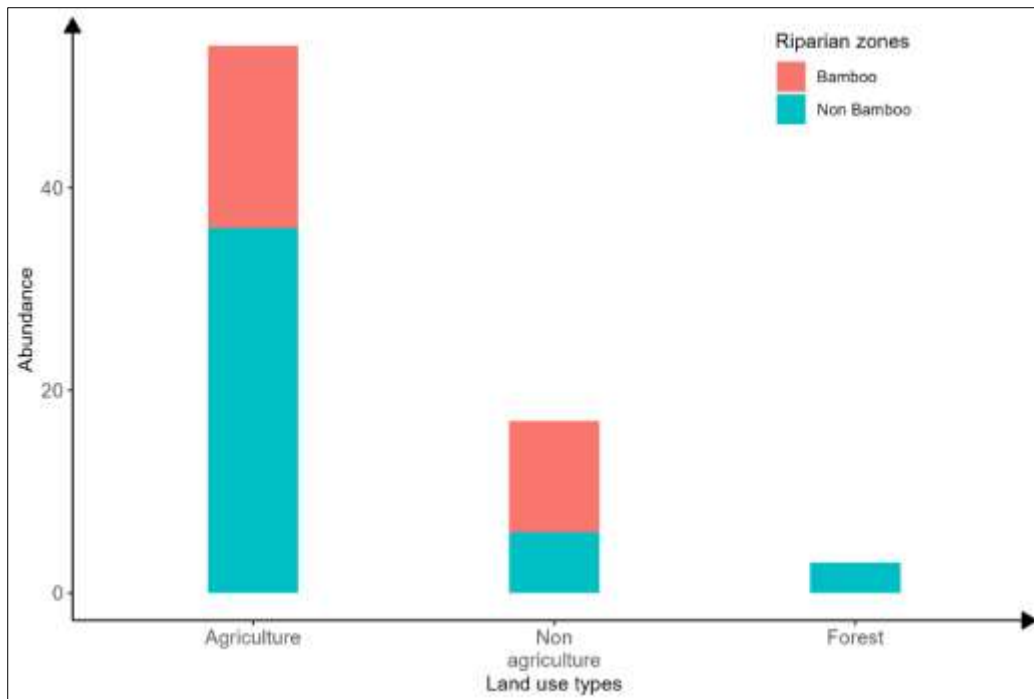


Figure 11: Relationship between land use types and plant species richness

#### 4.2.6 Relationship between land use and the buffer zone width

There was a significant difference between land use types and the mean width of the buffer zone (T test = -0.44, Df=2 and P value= 0.05, Figure 12).

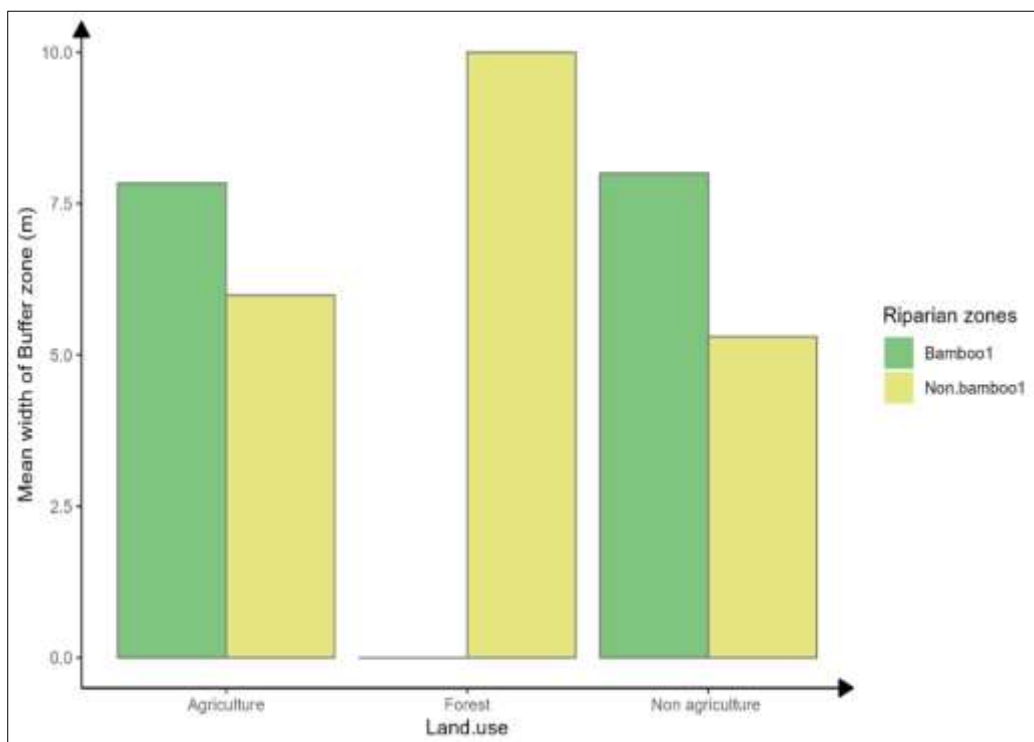


Figure 12: Relationship between land use types and the buffer zone width

### 4.3 Relationship between bamboo plantings and erosion

#### 4.3.1 Slope categories and the presence of erosion

There was a significant linear correlation between slope categories and erosion in bamboo sites but not correlated for the control sites ( $R^2=0.6369$ ,  $R^2=0.0198$ , Figure 13).

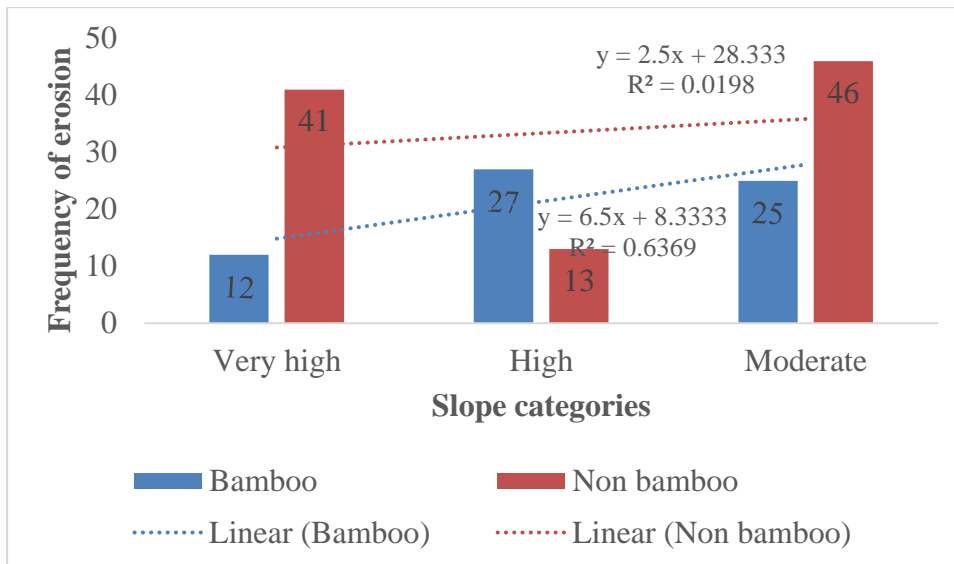


Figure 13: Correlation between slope categories and erosion

#### 4.3.2 Relationship between mean width of the buffer zone and slope categories

There was no significant difference between slope and the mean width of the buffer zone (T test = 1.17, Df=2 and P value= 0.05, Figure 14).

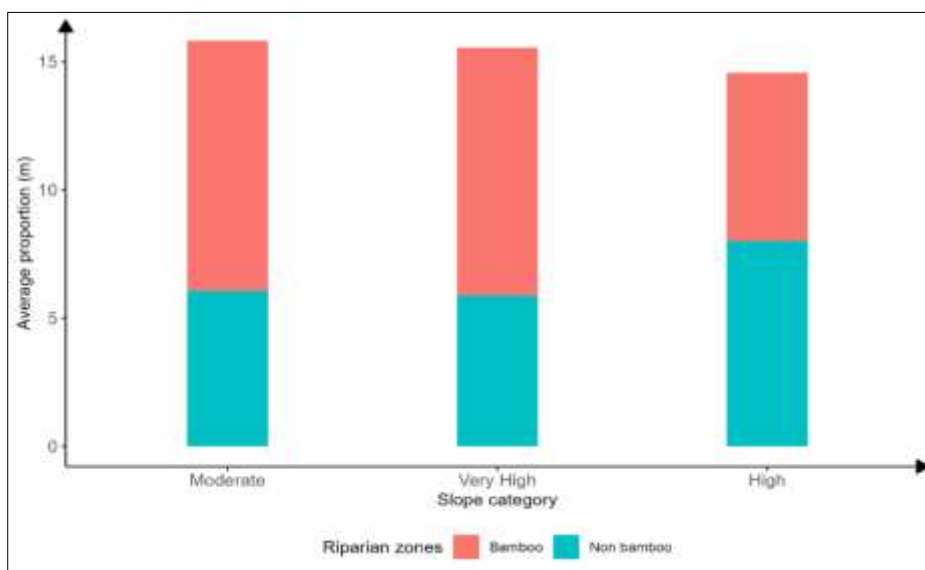


Figure 14: Relationship between slope and the average buffer zone width

The figure below depicts a 10-meter buffer zone that had been completely eroded, with grass dominating along the shoreline (Figure 15).



Figure 15: Eroded buffer zone along Nyabarongo river, Ngororero District, Rwanda

#### 4.3.4 Percent eroded width of the buffer zone

Both riparian zones with bamboo and the control sites declined in buffer zone width there was 20% of the bank eroded at bamboo sites and 38.6% eroded in the control sites. The riparian zone planted with bamboo presented a significant difference in river bank stability compared to riparian without bamboo with 18.6% of difference (Table 5).

Table 5: Percent eroded width of the buffer zone

Quadrat#	Recommended width of the buffer zone (m)	Measured width of the buffer zone		% decrease	
		In bamboo (m)	In non-bamboo (m)	In bamboo	In non-bamboo
1	10	10	3.7	0	63
2	10	9	10	10	0
3	10	9	9	10	10
4	10	10	10	0	0
5	10	7	4	30	60
6	10	8	5	20	50
7	10	5	6	50	40
8	10	6	0	40	100
9	10	8	6	20	40
10	10	9	9	10	10
11	10	8	7	20	30
12	10	7	4	30	60
<b>Mean</b>	10	<b>8</b>	<b>6.1</b>	<b>20.0</b>	<b>38.6</b>



Figure 16: Land use types adjacent to studied riparian zones

Figure 16 A indicates that agriculture is the predominant land use type in the study zone, and Figure 16 B shows that some areas of the riparian zones are flanked by grassland and forest. The primary cause of buffer zone deterioration is agriculture, farmers have cultivated marshes up to the legal distance of 10 meters from river edge, primarily on habitat that wasn't covered with bamboo. Bamboo here serves as a barrier for the farmers to protect the river banks. This is the primary cause of buffer zone degradation (38.6) and 6.1 meters in width. As a result, there is a strong correlation between the types of land uses and adjacent buffer zone.

#### **4.3.5 Erosion along Nyabarongo river buffer zone (C-factor value)**

The RUSLE model analysis, showed that there was a change in the C-factor from 1995 to 2023 (Figure 17), where the maximum value varied from 0.320 to 0.1, and the minimum value shifted from 0.226 to 0.05. This change has more implications on soil erosion by water, hence the higher the C-factor, the more the quantity of soil lost by erosion.

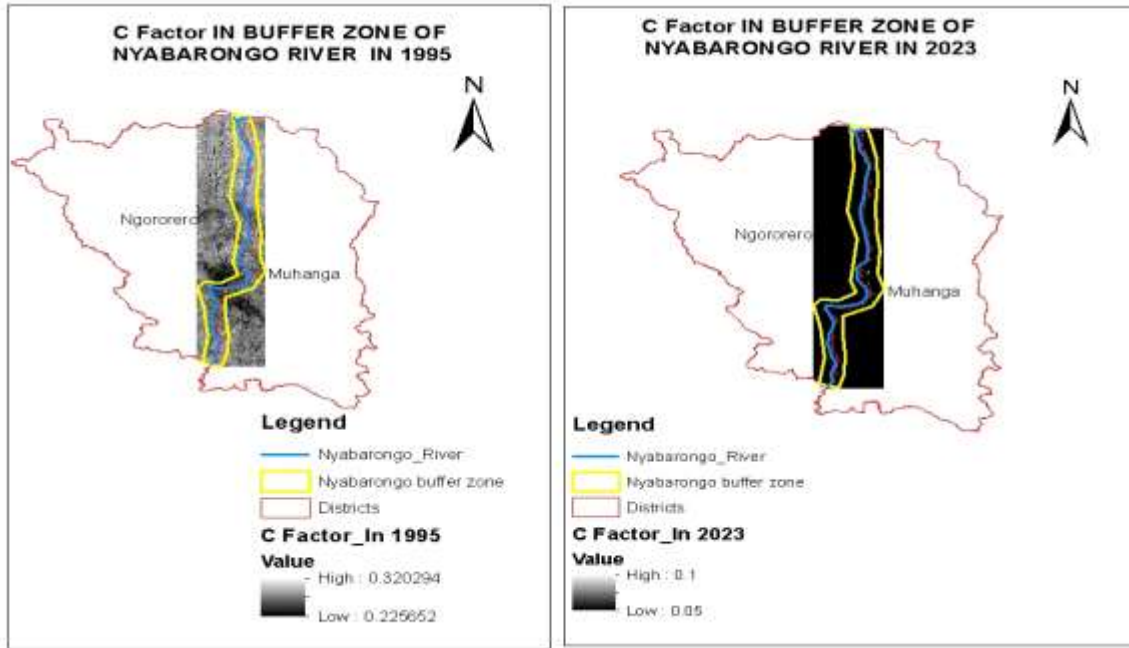


Figure 17: The C-factor value for the Nyabarongo river calculated between 1995 and 2023.

#### 4.3.6 Annual soil loss estimates

The analysis of the RUSLE model indicates that there is a reduction in soil loss between 1995 and 2023. The quantity of soil loss was estimated to be 577.182tons/ha in 1995 and to 55.9972 tons/ha in 2023 (Figure 18).

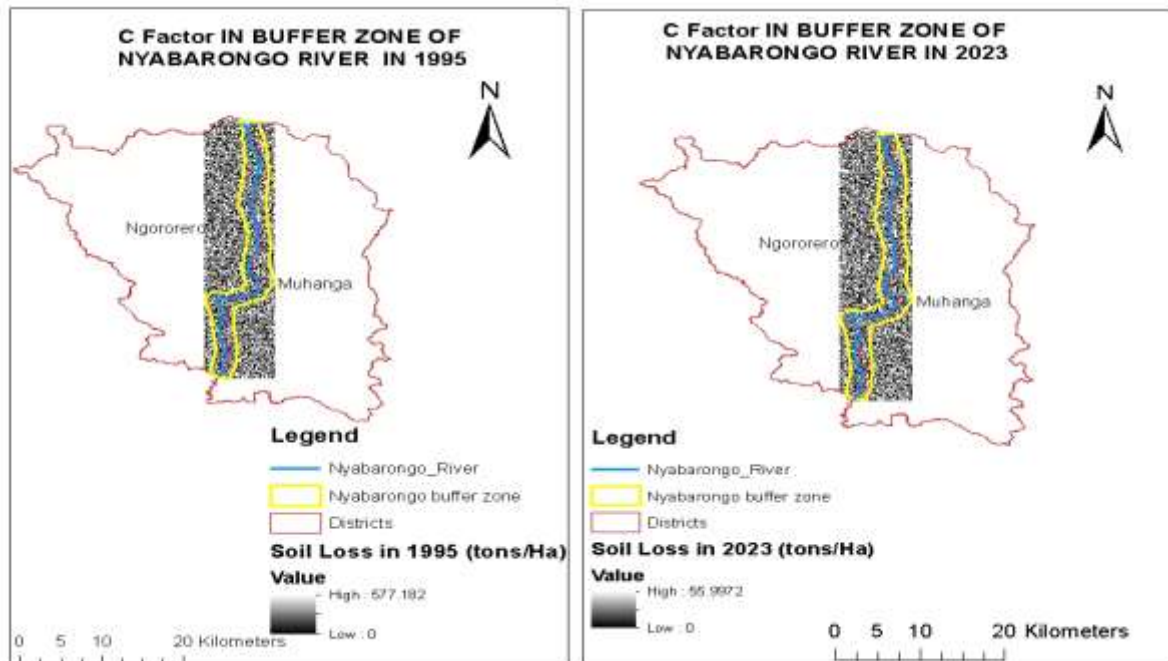


Figure 18: Soil losses in 1995 and 2023 for the Nyabarongo river buffer zone, Ngororero District, Rwanda

## CHAPTER 5: DISCUSSION

Vegetation is an essential component of the riparian zone perspective because it helps to stabilize river banks and hence reduce erosion. That's why 74 hectares of bamboo were planted along the Nyabarongo river banks in order to build resilience to climate risks and support sustainable land and water management practices (Ngororero, 2018). In this regard, a study on evaluation of the effects of bamboo on understory plant species diversity and soil erosion control was conducted in three sectors of Ngororero District adjacent to Nyabarongo river. The results of this study showed that the plant species richness in the riparian zones without bamboo were higher than that in the riparian zones planted with bamboo.

These results obtained match with the findings from the study conducted by (Wang, Shi, Peng, Zhong, & Tao, (2012) in China, where stepwise multiple regression analyses showed that all plant richness indices decreased significantly with the bamboo density in all plots, contrarily to the control sites, the same study demonstrated that understory total plant species richness also decreased significantly with bamboo coverage. Overall, understory plant total species richness, woody richness, and herbaceous richness decreased with increased bamboo density. The results found also agree with the findings from Tianmu Mountain nature reserve where plant species were negatively impacted by the invasion of *Phyllostachys edulis* (Bamboo), the three indicators (Plant species, Simpson's Diversity index, Pielou's Evenness index) reduced considerably over the monitoring period compared to the control sites in the tree and shrub layers of forests having bamboo growing in both needle and broad-leaved plant species (Shangbin et al., 2013), Madawala & Wijewickrama, 2021).

The authors concluded that removal of *Phyllostachys edulis* (Bamboo) resulted in increased in plant species richness and Simpson diversity index in the control sites (tree and shrubs layers). The results also match the findings of (Lacerda & Kellermann, 2019) highlighted by signifying that the control site was more diverse than bamboo forest they showed that effective number of plant species in the control site (35) was approximately double to that of bamboo forestry (Lacerda & Kellermann, 2019). Furthermore, a study conducted in India, found similar results when compared the species diversity between *Yushania maling* invasion and the decrease of plant species in the Eastern Himalayan temperate forest, the control site (non-Maling plots) had 165 species, 120 genera, and 67 families, while bamboo dominated plots had 119 species, belonging to 85 genera in 53 families.

Additionally, there was a discernible decline in the species abundance across vegetation strata in the bamboo-dominated sites (Rai & Rai, 2023). It was found that 20.8% of evergreen forests in India were threatened due to invasion of bamboo (*Ochlandra travancorica*), another bamboo species *Yushania maling* has reached alarming levels of invasion potential. *Bambusa vulgaris* and *Bambusa dendrocalamus* also introduced in Rwanda, *B. longispiculata*, *B. tulda*, *B. tuldoidea* introduced in the United States of America, has been naturalized and continued to invade around waterways and in the riparian zones (Xu et al., 2020). The same results were presented by (Jian-Ping Tao, 2012) the dense the bamboo had invaded and occupied the above/underground growth space which led other shrubs and herbs have no space to live. It was discovered that the understory vegetation's composition changes when the bamboo is present. Bamboo occasionally produced a dense canopy that hindered light penetration, which decreased the diversity and richness of plant species in bamboo riparian zones.

The present study has identified that the dominant plant family and species between these communities based on the total number of individuals was Malvaceae, while based on the lifeform, the two primary dominant families were different with Phyllanthaceae, with 215 individuals of *Phyllanthus urinaria* species in bamboo sites, and Polygonaceae, belonging to 48 individuals of *Persicaria amphibia* species. A study done by (Rai & Rai, 2023) demonstrated that the two ecosystems studied had different dominant plant families: In bamboo-dominated plots, the dominant families were Asteraceae, and Rosaceae whereas in the control plots, the prominent families were Lauraceae, Rosaceae, Urticaceae, and Asteraceae.

The results of the study also revealed that there is a significant difference in species diversity, Simpson diversity index, and effective number of species between riparian zones with bamboo and the control site. Also, a significant difference in species diversity was observed between sectors investigated between the riparian with bamboo and the control sites. A similar trend was observed by (Jian-Ping Tao, 2012), reported that high density of bamboo *F. nitida* greatly decreased understory plant species diversity in Southwest China, Shannon index of shrubs layer was significantly lower under high density bamboo than under lower density of bamboo.

The results found were articulated with (Lacerda & Kellermann, 2019) which found that the presence of bamboo reduced plant diversity of shrub and herbaceous layer. These results agree with the findings from (Kudo, Kawai, Amagai, & Winkler, 2017) in Japan, found that the tall, dense clonal patches of dwarf bamboo strongly suppressed alpine plants and reduced plant

species diversity. My results are also articulated by the findings from a study conducted on bamboo and plant diversity which highlighted that bamboo-free communities (control sites), shown comparatively high plant species richness, diversity, and evenness. In contrast, bamboo communities showed a poor plant species richness, poor diversity and weaker evenness (Li, Manfred, & Thomas, 2004).

Similar study also demonstrated the same results, where various diversity indices were compared between bamboo-dominated plots and the control sites. All diversity parameters showed lower values in bamboo-dominated plots when compared to the control sites. As the Mailing density increased, there was a trend toward a declining species diversity, shrubs, and herbs. In the control sites, increasing bamboo density was also correlated with a declining trend in the densities of trees, shrubs, and herbs (Rai & Rai, 2023).

Moreover, the same species trends were demonstrated by several communities. According to the findings, the bamboo layer has a detrimental effect on species diversity in terms of both species' richness and evenness in the vegetation that it was surrounded by (Li et al., 2004). Additionally, similar positive trends were observed in Shannon's diversity index, where H values in the control plots appeared stable throughout the experiment, contrary to bamboo dominated plots (Kudo et al., 2017). The results of the study also found that the percent of invasiveness of the total species richness in Nyabarongo river riparian zones both in bamboo and the control sites were 13.3% and 21.4% respectively across all sampled sites. The difference in percent invasiveness provides insights into how the presence of bamboo might influence the spread of invasive species in riparian areas. Regardless of whether they are native to the area or have been introduced, running bamboo particularly *Phyllostachys spp.*, have been demonstrated over time to overrun and replace nearly by woods (Xu et al., 2020).

To stop their spread, comprehensive action must be taken immediately. Generally speaking, the invasion of bamboo reduces plant variety (Xu et al., 2020). A higher percentage in bamboo sites might suggest that bamboo facilitates the spread of invasive species, possibly due to change in habitat structure, soil conditions, or other ecological factors. Therefore, the results agree with (Singh et al., 2021) who found that the macro-channel floor regions of the riparian zones of South Africa rivers are highly vulnerable to invasion by exotic vascular plants. The percent exotic ranged from 5% to 11% of total species richness for the banks. Species richness and percent exotics were negatively correlated for the banks. (Singh et al., 2021).

The study's findings, which were analysed in South Africa, at genus level, showed similar results that a large percentage of introduced bamboo species belonged to the following genera: *Arundinaria* (100%), *Thyrostachys* (100%), *Semiarundinaria* (71.4%), *Phyllostachys* (63%), *Shibateae* (57.1%), *Himalayacalamus* (50%), and *Bambusa* (25.6%). The two most invasive species were *Pseudosasa* (n=2) and *Phyllostachys*(n=5). The other invasive species were *Bambusa* (n=3), *Dendrocalamus* (n=1), and *Pleioblastus* (n=1). Additionally, they discovered a positive correlation between the number of invasive locations a species had been introduced to and the number of regions it was determined to be invasive (Canavan et al., 2017).

As reflected, land use types in Nyabarongo riparian zones was divided into three categories namely: agriculture, non-agriculture, and forest. Intensive farming activities in riparian zones drastically change the composition, diversity and richness of native plant species of the riparian zones. There was a significant difference between land use types and plant species richness. Similar study found out that intensive agriculture is a primary cause of vegetation deterioration near river and streams banks (Singh et al., 2021). The findings from my research using RUSLE Model depicted that bamboos are effective in controlling soil erosion along Nyabarongo river, in Ngororero District. The C-factor changed from 1995 to 2023, with the maximum value ranged from 0.32 to 0.1, and the minimum value shifted from 0.226 to 0.05, with an amount of annual the soil losses to water estimated and decreased from 577.182 tons. ha<sup>-1</sup> in 1995 to 55.9972 tons. ha<sup>-1</sup> in 2023.

The results are similar to the findings of (Uwamahoro et al., 2024) who conducted an assessment on soil loss analysis along Nyabarongo tributaries and found out that tiny tributaries cause soil erosion, and the Nyabugogo catchment has substantial average yield soil loss ranging from (50-56.12 tons.ha<sup>-1</sup> per year). Bamboo is an inexpensive, and effective in mitigating erosion, flooding and preserve terrain in a wide variety of situations due to its complex root system (Fred Hornaday and & Morris, 2023). It has proven effective around the world, in Asia, Africa, Europe, and the America. Live bamboo, particularly its vigorous root network, works in a variety of ways to consolidate top soils, stabilize slopes, preserve beds, prevent runoff, discourage trampling, and reduce evapotranspiration.

The same author highlighted that bamboo can be used as an effective erosion control alternative to retaining walls and other man-made structures. The massive roots of a well-established bamboo plant give an excellent answer to erosion and other associated issues (Hornady, 2020), (Goswami, Ansari, Mishra, Chauhan, Shailja, & Singh, 2022). Bamboo plants have deep roots

that aid in soil water absorption, the system contributes to the stability of riverbanks. Bamboo has an amazing ability to retain rainfall for use at a later time. Therefore, using bamboo reduces erosion and the amount of water that ends up in rivers and streams. Previous studies have shown that five years of bamboo planting on riverbanks can reduce soil erosion by 85%, P factor for bamboo vegetation is typically around 0.2 to 0.3 for bamboo comparing P equal to 1 for are without soil erosion conservation practices put in place (Singh et al., 2021) and (Bhattacharyya et al., 2016).

The same idea was expressed by (Rizinjirabake et al., 2023) who conducted an analysis at the source of Nyabarongo river at Mbirurume and find out that 0-1012 tons.ha<sup>-1</sup>year<sup>-1</sup> with a mean and standard deviation of 39.96 tons.ha<sup>-1</sup>year<sup>-1</sup>, and 93.834 tons.ha<sup>-1</sup> year<sup>-1</sup>. This low erosion rate is due to the impacts of bamboo planting along the riparian buffer zone at Nyabarongo river. A study conducted in Maojianshan Town, Yuexi Country, in Anhui Province highlighted similar results and found that bamboo woods have a monthly average surface runoff of 0.10m<sup>3</sup>.ha<sup>-1</sup>, and a sediment delivery rate of 0.18 kg. ha<sup>-1</sup> (Song et al., 2011). Moreover, when discussing the eco-hydrological benefits of bamboo plantings, 64% of respondents stated that it prevents erosion (Kumar & Singh, 2021).

The results of the study revealed that there was a significant difference between land use types and the mean width of the buffer zone. In Rwanda current practice typically involve 10 m wide riparian zone along rivers (Rwanda, 2018). However, both riparian zones (bamboo and the control sites) showed a decrease in mean buffer zone width (20%, and 38.6%), respectively. Moreover, the riparian zones with bamboo showed a significant difference in riverbank stability compared to the control sites with 18.6% of difference. Similar findings were expressed by(Hansen, Reich, Lake, & Cavagnaro, 2010) riparian buffer width of less than 10 m on either side of stream have been proven inadequate to allow optimal ecosystem functions, and significantly greater buffers (>30 m) are deemed suitable for the maintenance of natural ecosystems.

## CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

### 6.1 CONCLUSION

The effects of bamboo on understory plant species diversity and riverbank erosion control, was studied in 3 sectors of Ngororero District adjacent to Nyabarongo River, in Rwanda. The results of the study on the diversity of understory plant species showed a significant difference in species richness between riparian zones planted with and without bamboo. The Simpson diversity index showed a significant difference (0.061) between riparian areas planted with bamboo and those without bamboo (0.068). Furthermore, land use types adjacent to river buffer zone also showed a significant difference on plant species richness. Thus, the presence of bamboo in riparian zones changed the understory vegetation's composition. Bamboo sometimes developed a dense canopy that hindered light penetration, which decreased the diversity and richness of plant species. On the other hand, on non-bamboo riparian zones showed improved microhabitats and less competition, the understory plants species displayed more diversity. Moreover, based on results findings, from GIS-based RUSLE model, bamboo was found to be effective and efficient in riverbank erosion control measures. This is due to a decline in both C-factor values from 0.226 in 1995 to 0.05 in 2023, and soil loss occurred from 577.182 tons/ha in 1995 to 55.9972 tons/ha in 2023 when compared before and after planting bamboo, this is also due to its rooting system, which can sometimes anchor the soil, minimizing runoff, decreasing riverbank erosion an essential trait in areas vulnerable to erosion. Riparian zone planted with bamboo presented a significant difference in river bank stability compared to the control site with 18.6% of difference. Land use types adjacent to river buffer zone played a significance difference in reduction of the buffer zones width. While its ability to control riverbank erosion is beneficial, the potential negative impact on understory biodiversity must be carefully managed. This dual effect underscores the need for balanced management practices that maximize bamboo's soil stabilization benefits while mitigating its adverse effects on plant diversity. In order to maximize the bamboo's beneficial ecological roles and minimize its negative effects, future study should concentrate on optimizing bamboo management techniques. Furthermore, combining bamboo with other native plant species may results in ecosystems that are better balanced and promote soil health and biodiversity. These findings should be considered by policymakers and land managers in order to create sustainable methods that maximize bamboo's advantages without sacrificing ecological integrity.

## 6.2 RECOMMENDATIONS

The findings from the research about the effects of bamboo on the diversity of understory plant species and the management of riverbank erosion allow for the formulation of a number of recommendations that would maximize ecological advantages while reducing potential adverse effects. These include the following:

### **Government:**

- Formulate policies that promote sustainable cultivation practices, ensuring that bamboo planting is balanced with the conservation of understory plant species and provide rewards that encourage environmentally friendly bamboo farming and biodiversity conservation;
- Conduct studies of native plant species that could be important in restoration of degraded riparian zones instead of non-native bamboo species.

### **Academic institutions and researchers:**

- Encourage students to evaluate the effectiveness of different bamboo species in riverbank erosion control, tolerant species in bamboo and select the most suitable ones for specific conditions;
- Combine bamboo planting with native plant species to build a more resilient and well-balanced ecosystem. In addition, to improve soil stabilization, mixed plantings have complementing effects on biodiversity;

### **Local community engagement:**

- Promote community-based conservation programs that use traditions and expertise to manage bamboo and other exotic species; and engage local community in bamboo management projects.

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## APPENDIX

Appendix A: Critical values of chi-square (right tail) Table Significance level ( $\alpha$ )

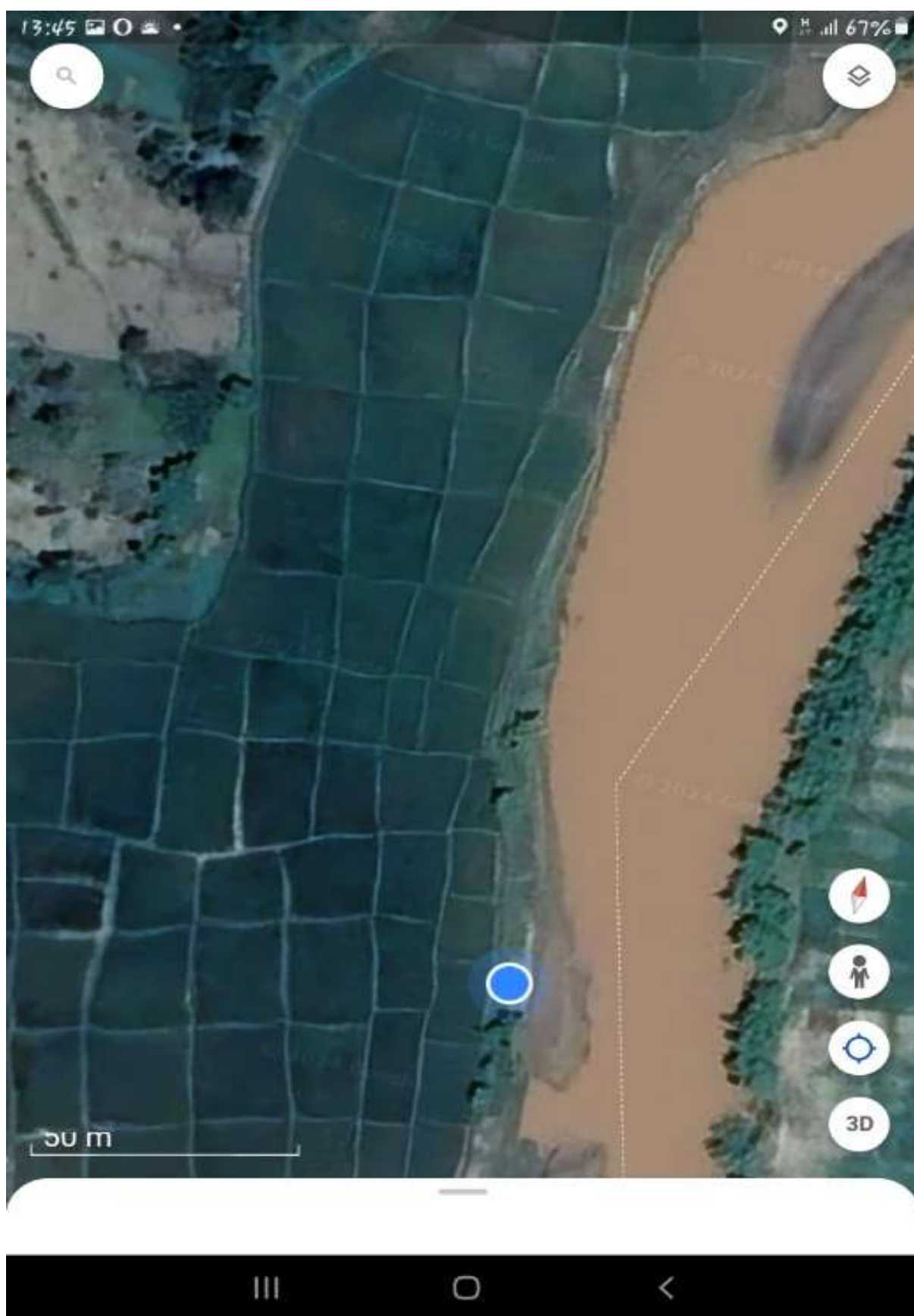
Degrees of freedom (df)	.99	.975	.95	.9	.1	.05	.025	.01
1	-----	0.001	0.004	0.016	2.706	3.841	5.024	6.635
2	0.020	0.051	0.103	0.211	4.605	5.991	7.378	9.210
3	0.115	0.216	0.352	0.584	6.251	7.815	9.348	11.345
4	0.297	0.484	0.711	1.064	7.779	9.488	11.143	13.277
5	0.554	0.831	1.145	1.610	9.236	11.070	12.833	15.086
6	0.872	1.237	1.635	2.204	10.645	12.592	14.449	16.812
7	1.239	1.690	2.167	2.833	12.017	14.067	16.013	18.475
8	1.646	2.180	2.733	3.490	13.362	15.507	17.535	20.090
9	2.088	2.700	3.325	4.168	14.684	16.919	19.023	21.666
10	2.558	3.247	3.940	4.865	15.987	18.307	20.483	23.209
11	3.053	3.816	4.575	5.578	17.275	19.675	21.920	24.725
12	3.571	4.404	5.226	6.304	18.549	21.026	23.337	26.217
13	4.107	5.009	5.892	7.042	19.812	22.362	24.736	27.688
14	4.660	5.629	6.571	7.790	21.064	23.685	26.119	29.141
15	5.229	6.262	7.261	8.547	22.307	24.996	27.488	30.578
16	5.812	6.908	7.962	9.312	23.542	26.296	28.845	32.000
17	6.408	7.564	8.672	10.085	24.769	27.587	30.191	33.409
18	7.015	8.231	9.390	10.865	25.989	28.869	31.526	34.805
19	7.633	8.907	10.117	11.651	27.204	30.144	32.852	36.191
20	8.260	9.591	10.851	12.443	28.412	31.410	34.170	37.566
21	8.897	10.283	11.591	13.240	29.615	32.671	35.479	38.932
22	9.542	10.982	12.338	14.041	30.813	33.924	36.781	40.289
23	10.196	11.689	13.091	14.848	32.007	35.172	38.076	41.638
24	10.856	12.401	13.848	15.659	33.196	36.415	39.364	42.980
25	11.524	13.120	14.611	16.473	34.382	37.652	40.646	44.314
26	12.198	13.844	15.379	17.292	35.563	38.885	41.923	45.642
27	12.879	14.573	16.151	18.114	36.741	40.113	43.195	46.963
28	13.565	15.308	16.928	18.939	37.916	41.337	44.461	48.278
29	14.256	16.047	17.708	19.768	39.087	42.557	45.722	49.588
30	14.953	16.791	18.493	20.599	40.256	43.773	46.979	50.892
40	22.164	24.433	26.509	29.051	51.805	55.758	59.342	63.691
50	29.707	32.357	34.764	37.689	63.167	67.505	71.420	76.154
60	37.485	40.482	43.188	46.459	74.397	79.082	83.298	88.379
70	45.442	48.758	51.739	55.329	85.527	90.531	95.023	100.425
80	53.540	57.153	60.391	64.278	96.578	101.879	106.629	112.329
100	61.754	65.647	69.126	73.291	107.565	113.145	118.136	124.116
1000	70.065	74.222	77.929	82.358	118.498	124.342	129.561	135.807

Appendix B: Total number of individuals recorded in different vegetation type

Family	Species name	Native/N on-native	Invasive (Yes/No)	IUCN status
Acanthaceae	<i>Acanthus polystachyus</i>	Native	No	NE
Apocynaceae	<i>Gomphocarpus physocarpus</i>	Exotic	No	NE
Asteraceae	<i>Gymnanthemum amygdalinum</i>	Exotic	No	LC
Euphorbiaceae	<i>Manihot esculenta</i>	Exotic	No	NE
Fabaceae	<i>Calliandra houstoniana</i>	Exotic	No	LC
	<i>Crotalaria retusa</i>	Exotic	No	NE
	<i>Dracaena afromontana</i>	Native	No	LC
	<i>Mimosa pudica</i>	Exotic	No	NE
Lamiaceae	<i>Ocimum gratissimum</i>	Native	No	LC
	<i>Leonotis nepetifolia</i>	Native	No	NE
Malvaceae	<i>Hibiscus diversifolius</i>	Native	No	NE
	<i>Hibiscus fuscus</i>	Native	No	NE
	<i>Hibiscus ludwigii</i>	Exotic	No	NE
	<i>Triumfetta cordifolia</i>	Native	No	NE
	<i>Triumfetta rhomboidea</i>	Native	No	NE
Moraceae	<i>Morus nigra</i>	Exotic	No	NE
Myrtaceae	<i>Psidium guajava</i>	Exotic	Yes	LC
Poaceae	<i>Bambusa vulgaris</i>	Exotic	Yes	NE
	<i>Hyparrhenia rufa</i>	Native	No	NE
	<i>Phragmites mauritianus</i>	Native	No	LC
Polygonaceae	<i>Persicaria amphibia</i>	Exotic	No	NE
	<i>Persicaria bungeana</i>	Exotic	No	LC
	<i>Persicaria senegalensis</i>	Native	No	NE
Phyllanthaceae	<i>Bridelia micrantha</i>	Native	No	LC
	<i>Phyllanthus fischeri</i>	Exotic	No	NE
Verbenaceae	<i>Lantana camara</i>	Exotic	Yes	NE
	<i>Lantana trifolia</i>	Exotic	No	NE
Zingiberaceae	<i>Hedychium coronarium</i>	Exotic	No	NE
Acanthaceae	<i>Acanthus polystachyus</i>	Native	No	NE
Anacardiaceae	<i>Searsia natalensis</i>	Exotic	No	LC
Asteraceae	<i>Erigeron sumatrensis</i>	Exotic	No	NE
	<i>Gymnanthemum amygdalinum</i>	Exotic	No	NE
	<i>Microglossa densiflora</i>	Native	No	NE
	<i>Tagetes minuta</i>	Exotic	No	NE
Balsaminaceae	<i>Impatiens burtonii</i>	Native	No	NE
Celastraceae	<i>Gymnosporia senegalensis</i>	Native	No	NE
Cyperaceae	<i>Cyperus papyrus</i>	Native	No	LC
Euphorbiaceae	<i>Manihot esculenta</i>	Exotic	No	NE

Fabaceae	<i>Albizia gummifera</i>	Native	No	LC
	<i>Calliandra houstoniana</i>	Exotic	No	LC
	<i>Crotalaria retusa</i>	Exotic	No	NE
	<i>Erythrina abyssinica</i>	Native	No	LC
Hypericaceae	<i>Harungana madagascariensis</i>	Native	No	LC
Lamiaceae	<i>Leonotis nepetifolia</i>	Native	No	NE
	<i>Ocimum gratissimum</i>	Native	No	LC
	<i>Rotheca myricoides</i>	Native	No	NE
	<i>Volkameria glabra</i>	Exotic	No	NE
Malvaceae	<i>Hibiscus diversifolius</i>	Native	No	NE
	<i>Hibiscus ludwigii</i>	Exotic	No	NE
	<i>Sida acuta</i>	Native	No	NE
	<i>Triumfetta rhomboidea</i>	Native	No	NE
	<i>Triumfetta rotundifolia</i>	Exotic	No	NE
Melastomataceae	<i>Dupineta brazzae</i>	Native	No	NE
	<i>Heterotis rotundifolia</i>	Exotic	No	LC
Moraceae	<i>Morus nigra</i>	Exotic	No	NE
Myrtaceae	<i>Eucalyptus globulus</i>	Exotic	Yes	LC
	<i>Psidium guajava</i>	Exotic	Yes	LC
Oxalidaceae	<i>Biophytum helenae</i>	Native	No	NE
Phyllanthaceae	<i>Bridelia micrantha</i>	Native	No	LC
	<i>Phyllanthus fischeri</i>	Exotic	No	NE
	<i>Phyllanthus urinaria</i>	Exotic	No	NE
Poaceae	<i>Oryza sativa</i>	Exotic	No	NE
	<i>Phragmites mauritianus</i>	Native	No	LC
Polygonaceae	<i>Persicaria amphibia</i>	Exotic	No	NE
	<i>Persicaria bungeana</i>	Exotic	No	NE
	<i>Persicaria senegalensis</i>	Native	No	LC
	<i>Rumex abyssinicus</i>	Native	No	NE
Primulaceae	<i>Maesa ramentacea</i>	Exotic	No	LC
Rosaceae	<i>Rubus apetalus</i>	Exotic	No	NE
Rubiaceae	<i>Pavetta lanceolata</i>	Exotic	No	LC
Rutaceae	<i>Zanthoxylum asiaticum</i>	Native	No	NE
Verbenaceae	<i>Lantana camara</i>	Exotic	Yes	NE
	<i>Lantana trifolia</i>	Exotic	Yes	NE

Appendix C: Eroded buffer zones and bamboo due to adjacent land use



Appendix D: Nyabarongo river's morphological changes

