

MAKERERE



UNIVERSITY

**SOIL EROSION TOLERANCE RATES IN CONTRASTING LAND USES AND
SOIL**

TYPES IN THE RWENZORI HIGHLANDS OF UGANDA

NAMATOVU ANGELLA

BSc. BLUM (MAK)

2021/HD02/23254U

**A DISSERTATION SUBMITTED TO THE DIRECTORATE OF RESEARCH AND
GRADUATE TRAINING IN PARTIAL FULFILLMENT OF THE EQUIREMENTS**

FOR THE AWARD OF THE DEGREE OF MASTER OF SCIENCE IN

SOIL SCIENCE OF MAKERERE UNIVERSITY

JANUARY 2026

DECLARATION

I, Angella Namatovu, declare that this M.Sc. thesis is my original work and has never been submitted to any University or institution for award of any degree.

Signature: *Angella* Date: *13th JAN 2026*

APPROVAL

This thesis has been submitted to the Directorate of Research and Graduate Training with the approval of the following supervisors:

1. Prof. Twaha Ali Basamba Ateenyi

Department of Soil Science and Land Use Management,
Makerere University

Signature

Date


.....


13th JAN 2026
.....

2. Dr. Emmanuel Opolot

Department of Soil Science and Land Use Management,
Makerere University

Signature

Date


.....

13th JAN 2026
.....

DEDICATION

I dedicate this thesis to my parents Mr. Ssekyondwa Gervazio. M. and Mrs. Ssekyondwa Jane N. and my brothers and sisters who have tirelessly supported me in all aspects throughout my academic journey. I am deeply and extremely grateful for their existence and support and I pray that the Almighty God bless and keep them always.

ACKNOWLEDGEMENT

I am very grateful to the almighty God for the guidance, wisdom, health, grace and opportunities He has granted me throughout my life most especially throughout my academic journey.

I also wish to express my absolute gratitude to my supervisors Professor Twaha Ali Basamba Ateenyi and Dr. Emmanuel Opolot whose guidance, mentorship, input and encouragement have served as a pillar in my academic journey.

I am deeply grateful and indebted to my parents Mr. Ssekyondwa Gervasio. M. and Mrs. Ssekyondwa Jane whose emotional and financial support are the main reason as to why I was able to pursue this academic journey and complete it successfully.

I am also thankful to Mr. Kiirya David the chief laboratory technician at Makerere University School of Agricultural Sciences for his guidance and time while I conducted the soil laboratory analyses.

I am grateful to the leaders of Karangura Sub-County, Kabarole District, and Kilembe Sub-County, Kasese District, for their cooperation and support given during the inception and start of the project. In the same manner, I am thankful to Mr. Masereka Hassan for all the help given during field work.

I also extend my appreciation to the lecturers at the Department of Soil Science and Land Use Management for the knowledge imparted in me during my study at Makerere University.

I thank the Government of Uganda for funding this research through Makerere University Research and Innovation Fund.

I also appreciate the Institute for Water Research (IWR) at Rhodes University and the African Water Resources Mobility Network (AWaRMN) which received funding from the Intra-African Academic Mobility Scheme of the European Union for supporting the completion of this research.

I am very grateful to my brothers, sisters, family and friends for the emotional and moral support given to me.

TABLE OF CONTENTS

DECLARATION	i
APPROVAL	ii
DEDICATION	iii
ACKNOWLEDGEMENT	iv
LIST OF ABBREVIATIONS AND ACRONYMS	x
ABSTRACT	xi
CHAPTER ONE	1
INTRODUCTION	1
1.1 Background to the study	1
1.2 Statement of the problem	3
1.3 Objectives of the study.....	4
1.3.1 General objective.....	4
1.3.2 Specific objectives.....	4
1.4 Hypotheses	4
1.5 Justification	5
CHAPTER TWO	6
LITERATURE REVIEW	6
2.1 Soil as a resource	6
2.2 Soil erosion	7
2.2.1 The various forms and mechanisms of soil erosion	7
2.2.2 Factors influencing rates of soil erosion by water.....	8

2.2.3 Effects of soil erosion	11
2.2.4 Areas that are prone to erosion	12
2.3 Influence of land use on soil erosion	12
2.3.1 Land uses and their characteristics	12
2.3.2 Effects of different land uses on soil erosion rates.....	13
2.4 Soil erosion in different soil types	15
2.4.1 Soil types and their properties	15
2.4.2 Soil erosion rates in different soil types	16
2.5 Soil loss tolerance thresholds (T-values)	18
2.5.1 The framework for defining allowable soil erosion rates	18
2.5.2 Approaches used to determine acceptable soil erosion thresholds	19
CHAPTER THREE	21
MATERIALS AND METHODS	21
3.1 Description of the study area	21
3.1.1 Geographical Location	21
3.1.2 Climate	22
3.1.3 Topography	22
3.1.4 Geology and Soils	22
3.1.5 Hydrology.....	24
3.1.6 Vegetation and Land Use	24
3.2 Study design	25
3.3 Soil characterisation and sampling	27
3.4 Assessing variations in soil erosion rates from agricultural land uses on sites under Ferralsols and Andosols (Objective 1)	27
3.4.1 Runoff plots	27
3.4.2 Revised Universal Soil Loss Equation, RUSLE	30
3.5 Determining the soil loss tolerance thresholds of Ferralsols and Andosols under different agricultural land uses (Objective two)	34
CHAPTER FOUR	37

RESULTS	37
4.1 Soil erosion rates in Andosols and Ferralsols under four land uses (annual, perennial, grassland and woodland).....	37
4.1.1 Case study one on Andosols in Kabarole district, Rwenzori highlands (Objective 1)	37
4.1.2 Runoff and soil erosion rates in Andosols under four land uses (annual, perennial, grassland and woodland) in Kabarole district.	39
4.1.3 Soil erosion rates of Andosols under four land uses (annual, perennial, woodland and grassland) using runoff plots in Kabarole District.	40
4.1.4 Estimated soil erosion rates of Andosols using the Revised Universal Soil Loss Equation in Kabarole district	41
4.1.5 Case study two on Ferralsols in Kasese district, Rwenzori highlands (Objective 1)	42
4.1.6 Runoff and soil erosion rates in Ferralsols under four land uses (annual, perennial, grassland and woodland) in Kasese the Rwenzori highlands of Uganda	44
4.1.7 Soil erosion rates of Ferralsols under four land uses (annual, perennial, woodland and grassland) using runoff plots	45
4.1.8 Estimated soil erosion rates of Ferralsols using the Revised Universal Soil Loss Equation	46
4.2 Soil loss tolerance thresholds of Andosols and Ferralsols under four land uses (annual, perennial, woodland and grassland).	47
4.2.1 Sensitivity analysis of the parameters used to measure soil loss tolerance thresholds. ...	47
4.2.2 Case study one on Andosols in Kabarole district, Rwenzori highlands (Objective 2). ...	48
4.2.3 Case study two on Ferralsols in Kasese district, Rwenzori highlands (Objective 2).	49
CHAPTER FIVE	50
DISCUSSION	50
5.1 Soil erosion rates of Andosols and Ferralsols under woodlands, grasslands, perennial and annual land uses	50
5.2 Soil erosion tolerance thresholds of Ferralsols and Andosols under woodlands, grasslands, perennial and annual land uses	53
CHAPTER SIX	54
CONCLUSIONS, RECOMMENDATIONS AND LIMITATIONS	54
6.1 Conclusions	54

6.2 Recommendations	54
6.3 Limitations of the study	55
REFERENCES	56
APPENDICES	70
LIST OF TABLES	
Table 3.1: Locational attributes of the land uses in Kabarole under Andosols.	25
Table 3.2: Locational attributes of the land uses in Kasese under Ferralsols.	26
Table 3.3: C factors for different land uses (David, 1988; Morgan, 2005; Wang et al., 2016). ...	32
Table 3.4: Indicators of each soil function with their corresponding weights (Lenka et al., 2014).	34
Table 3.5: Soil Loss Tolerance Thresholds based on soil depth and quantified soil state (Q) (Lenka et al., 2014).	36
Table 4.1: Soil test results of samples collected from four land uses under Andosols (Kabarole district).	37
Table 4.2: The effect of land use on the soil erosion rates under Andosols in Kabarole district .	40
Table 4.3: Estimated soil erosion rates of land uses under Andosols in Kabarole district	41
Table 4.4: Soil test of soil samples collected from four land uses under Ferralsols in Kasese district.	42
Table 4.5: Effect of land use on the soil erosion rates under Ferralsols in the Rwenzori highlands	45
Table 4.6: Estimated soil erosion rates of land uses under Ferralsols in Kasese district	46
Table 4.7: Sensitivity analysis of the soil properties and rooting depth on soil loss tolerance thresholds.	47
Table 4.8: Soil loss tolerance thresholds of Andosols under four land uses.....	48
Table 4.9: Soil loss tolerance thresholds of Ferralsols under four land uses.	49
LIST OF FIGURES	
Figure 3.1: Location of the study area.	21
Figure 3.2: Soil types in Kabarole and Kasese districts, Rwenzori highlands	23
Figure 3.3: Illustration (a) and picture before connecting the pipe to a collecting tank (b) of the	

runoff plots constructed in this study to evaluate soil erosion rates 28

Figure 4.1: Runoff (bar graph) and soil erosion rates (line graph) of Andosols in annual, woodland, grassland and perennial land uses. 39

Figure 4.2: Runoff (bar graph) and soil erosion rates (line graph) of Ferralsols in annual, woodland, grassland and perennial land uses. 44

LIST OF ABBREVIATIONS AND ACRONYMS

AfSIS	Africa Soil Information Service
FAO	Food and Agricultural Organisation of the United Nations
T-values	Soil loss tolerance thresholds
USDA	United States Department of Agriculture
WRB	World Reference Base

ABSTRACT

Soil erosion is a primary factor contributing to environmental deterioration in the 21st century. High erosion rates experienced in the Rwenzori highlands undermine the soils' capacity to sustain productivity once the soil loss tolerance threshold is surpassed. Erosion rates differ across different land uses and soil types, and how these variations relate to soil loss tolerance thresholds remains poorly understood in the region. This study, therefore, aimed to assess the soil erosion tolerance thresholds of Ferralsols and Andosols under different agricultural land uses in the upper slopes of the Rwenzori highlands. Two case studies with the quasi-experimental research design were used in this research: one case study done in Kabarole on Andosols and the other in Kasese on Ferralsols, both under annual, woodland, grasslands, and perennial land use at slopes between 25% and 27%. Soil erosion rates were estimated using the RUSLE and measured using closed runoff plots. Runoff samples were collected after every rainfall event for 12 months. Soil loss tolerance thresholds were determined from a method developed by the USDA, which uses favourable rooting depth and bio-physical soil properties (bulk density, soil erodibility, pH, organic carbon, and infiltration rate) linked to erosion. While using runoff plots, Andosols had the highest mean erosion rate in annual land use ($14.21 \pm 2.15 \text{ tha}^{-1}\text{yr}^{-1}$) at 26% slope and the lowest in woodlands ($7.06 \pm 3.78 \text{ tha}^{-1}\text{yr}^{-1}$) at 25% slope. Similarly, Ferralsols had the highest mean erosion rate in annual land use ($8.50 \pm 1.26 \text{ tha}^{-1}\text{yr}^{-1}$) at 26% slope, and the lowest in woodlands ($4.49 \pm 2.05 \text{ tha}^{-1}\text{yr}^{-1}$) at 27% slope. Mean erosion rates estimated with the RUSLE were highest in annuals under Andosols at 26% slope ($78.33 \pm 5.36 \text{ tha}^{-1}\text{yr}^{-1}$) and were lowest in woodlands under Ferralsols at 27% slope ($2.52 \pm 0.26 \text{ tha}^{-1}\text{yr}^{-1}$). There are evident disparities between observed soil loss from runoff plots and estimations from the Revised Universal Soil Loss Equation (RUSLE). The average tolerance thresholds of Andosols were highest in grasslands ($11.67 \pm 1.29 \text{ tha}^{-1}\text{yr}^{-1}$) at 27% slope and lowest in annual ($8.33 \pm 1.29 \text{ tha}^{-1}\text{yr}^{-1}$) at 26% slope. For Ferralsols, the tolerance thresholds were highest ($8.75 \pm 1.37 \text{ tha}^{-1}\text{yr}^{-1}$) and lowest ($6.25 \pm 1.37 \text{ tha}^{-1}\text{yr}^{-1}$) in grasslands at 26% slope and perennials at 25% slope, respectively. Although annual land use was the only land use with soil erosion rates exceeding tolerance thresholds, grasslands, woodlands, and perennials are at risk of losing productivity due to the very small margin left for the erosion rates to exceed the tolerance thresholds. Thus, the soils in this study are vulnerable to degradation in the future. Therefore, there is a critical need to implement sustainable land management practices in order to curb degradation and prevent further soil erosion and future threshold exceedance.

CHAPTER ONE

INTRODUCTION

1.1 Background to the study

Soil erosion is the process of soil removal, transportation, and deposition by physical forces such as wind and water (Ji et al., 2024). As a natural process, soil erosion occurs at low, negligible rates that are balanced by soil formation. However, rapid erosion caused due to human interference and actions has disrupted this equilibrium, leading to acute soil deterioration and a decline in agricultural produce worldwide (Ahmed et al., 2024; Evangelista et al., 2023; Nasir Ahmad et al., 2024; Nearing et al., 2017; Negash et al., 2021; Quinton & Fiener, 2024; Zhai et al., 2024).

Worldwide, erosion processes constitute the dominant mechanism driving terrestrial ecosystem deterioration, with water erosion making up 95% of all erosion (Borrelli et al., 2021). On average, approximately 17 t ha^{-1} are lost annually to water erosion, negatively affecting over one billion hectares of land worldwide (Borrelli et al., 2017; Nasir Ahmad et al., 2024). Erosion depletes the topsoil of organic matter and required nutrients, undermining its capacity to sustain plant growth. Sartori et al. (2024) projected that by the year 2070, global primary production losses due to erosion could reach to up to 352 million tonnes, with associated economic losses estimated at 625 billion USD. Africa, in particular, is expected to bear the brunt of these losses, exacerbating food insecurity and economic vulnerability within the continent (Sartori et al., 2024).

In Uganda, soil loss is a critical issue. The Rwenzori highlands, a region of significant ecological and agricultural importance, are hotspots for soil erosion rates which have been estimated to exceed 100 t ha^{-1} (Karamage et al., 2017). These high erosion rates not only threaten soil productivity and food security but also contribute to downstream environmental impacts, including fluvial sediment deposition in aquatic systems and loss of biodiversity (Asempah et al., 2024; Sartori et al., 2024). High erosion rates undermine the capacity of soils to maintain stable, sustainable productivity when a limit is exceeded; this limit is termed as the soil loss tolerance threshold (T-value). Soil loss tolerance thresholds describe the highest average rate of annual permissible soil erosion that allows for stable and sustainable soil productivity (Di Stefano et al., 2023; Ostovari et al., 2020). Soil erosion tolerance is critical in understanding the sustainability of soil systems, as it provides a benchmark for evaluating whether erosion rates are within acceptable limits or if they pose a threat to soil health and the viability of agriculture (Di Stefano et al., 2023). The concept of soil loss

tolerance (T-value) is a well-established mechanism for developing effective soil and water conservation strategies.

Uganda's soils are predominantly old and Ferralitic (Semalulu & Kaizzi, 2013), covering about 75% of the land area and supporting the livelihoods of 68% of smallholder farmers. Therefore, sustainable agricultural production in the context of soil loss tolerance thresholds must be premised on a clear understanding of the soil's inherent capacity and resilience to stressors. Substantial evidence confirms that soil erosion is both widespread and increasing across Uganda, with approximately 39% of the country deemed prone to erosion (Karamage et al., 2017). Consequently, there is a dire and pressing need to establish scientifically sound soil tolerance thresholds for Uganda. The average soil loss tolerance thresholds (T-values) in temperate regions have been estimated and generalised to range between 1 and 10 tha^{-1} irrespective of the soil type, land use and other factors (Ostovari et al., 2020).

Soil loss tolerance thresholds are however dependent on soil type, climate, and land use, therefore, regions such as the tropics with distinct environmental and climatic characteristics from temperate regions cannot rely on the already established T-values (Ostovari et al., 2020). Estimated erosion rates in many regions, including the Rwenzori highlands, are very high and far exceed the European established tolerance thresholds, informing us of the potentiality of irreversible soil degradation and declining agricultural yields (Di Stefano et al., 2023). The increasing erosion rates are largely attributed to anthropogenic activities, including shifts in land use patterns and practices of land management that are unsustainable (Kusiima et al., 2022; Negash et al., 2021).

Land use significantly influences soil erosion rates, with variations caused by differences in vegetation cover, root density and distribution, litter fall, and management practices (Mohammed et al., 2020; Quinton & Fiener, 2024). However, land use is not the sole determinant of erosion susceptibility; soil type also serves a critical role in influencing the rates of soil loss (Nasir Ahmad et al., 2024; Negash et al., 2021). Erosion rates of soils vary depending on their properties, including organic content, texture, permeability, structure, and bulk density characteristics (Ahaneku et al., 2024; Ouyang et al., 2018; Zi et al., 2023). Soil types, though generally stable long-term, differ across locations, making localized studies necessary to evaluate their role in erosion rates and T-value relationships (Sartori et al., 2024).

1.2 Statement of the problem

Research has revealed significant complexities, showing large variability in T-values even among similar soil types (Duan et. al., 2017). This indicates that applying a uniform tolerance standard across a soil type and region is inaccurate and ultimately undermines land use and management (Duan et. al., 2017). It is now widely recognised that soil loss tolerance thresholds must be assessed for each given soil type (Bhattacharyya et. al., 2011), as the approximate T-values used in many countries are not universally applicable to different agricultural soils, land uses, and slope gradients since they are originally established in American and European countries (Bhattacharyya et. al., 2011; Duan et al., 2017).

Studies done in Uganda have consistently shown erosion magnitudes that are likely beyond tolerable levels (Jiang et al., 2014; Lufafa et al., 2003; Majaliwa, 2005). However, a critical constraint is that the erosion rates reported in some studies (Karamage et al., 2017) are derived from models rather than empirical observations. Compounding this issue, the actual soil tolerance thresholds for Uganda's fragile ecosystems remain entirely unknown and are currently speculative.

A generalised tolerance limit of $5 \text{ t ha}^{-1} \text{ yr}^{-1}$, intended for tropical soils in general, is routinely invoked in Ugandan soil erosion studies (Bamutaze, 2011; Lufafa et al., 2003; Luliro et al., 2013). However, the tropical region is highly heterogeneous, and the uncritical application of this single value across Uganda is problematic given the country's vivid variability in soil typology and ecological sensitivity. This generalised threshold is not based on a sensitivity understanding of Ugandan soils and their specific geographies and land uses, which renders it overly misleading. Therefore, establishing empirically derived, location-specific T-values is an essential prerequisite for effective and sustainable soil conservation in Uganda.

1.3 Objectives of the study

1.3.1 General objective

To contribute to improved understanding of soil erosion tolerance thresholds in the Rwenzori highlands.

1.3.2 Specific objectives

The study's specific objectives were:

1. To establish the variations in soil erosion rates from agricultural land uses on sites under Ferralsols and Andosols.

2. To determine the soil loss tolerance thresholds of Ferralsols and Andosols under different agricultural land uses.

1.4 Hypotheses

1. Soil erosion rates do not differ between Andosols and Ferralsols with similar land uses.
2. Soil loss tolerance thresholds are the same in both Ferralsols and Andosols, irrespective of land use.

1.5 Justification

The importance of establishing scientifically-grounded soil loss tolerance (T-value) thresholds for Uganda's diverse ecologies cannot be overstated, as this research forms a critical keystone for the nation's sustainable development. Uganda's developmental aspirations and its trajectory toward a middle-income country, as outlined in the Uganda Green Growth Agenda, are fundamentally premised on the protection of its natural capital, with soil being the most vital component of its land resources. This national commitment is further reinforced by Uganda's role as a signatory to the United Nations 2030 Agenda, which specifically aims for a Land Degradation Neutral (LDN) world by 2030. The concept of LDN, which seeks to achieve no net loss of land-based natural capital, provides a powerful framework but requires precise, measurable indicators to move from ambition to action (Lal, 2019). It is precisely at this nexus of policy and implementation that the proposed initiative on developing T-values finds its urgent justification.

The critical need for this research is highlighted by existing national policies that diagnose the problem of land degradation yet lack the specific scientific tools for targeted solutions. For instance, the National Policy for Disaster Preparedness and Management explicitly recognizes that over 60% of disasters in Uganda are soil-related, framing erosion as a primary national disaster risk. Similarly, the Uganda National Climate Change Policy serves as a key entry point for building smallholder resilience against threats like soil fertility reduction. However, without ecologically specific T-values to determine how much soil loss is tolerable, these policies cannot effectively prioritize interventions or quantitatively gauge their success. Therefore, this research directly addresses this operational gap by developing the baseline data required to transform broad policy goals into actionable, evidence-based strategies for land management.

Ultimately, by establishing these crucial thresholds, the research will have a profound synergistic effect, enabling Uganda to safeguard its agricultural foundation and secure its economic future. It will empower policymakers and farmers alike to prioritize conservation efforts in the most vulnerable areas, monitor the restoration of degraded soils, and objectively assess the impact of soil management practices. This work on T-values therefore provides the indispensable scientific foundation upon which the nation's long-term food security, climate resilience, and sustainable development depend.

CHAPTER TWO

LITERATURE REVIEW

2.1 Soil as a resource

Soil is a crucial component in the provision of biomass (food, fibre and energy) to man and animals with about 98% derived from soil (Kopittke et al., 2022). Soil is also responsible for ecosystem service regulation, support and functioning (Evangelista et al., 2023). Soil also plays a crucial role in nurturing healthy plant growth and development by providing nutrients, water, root development and favourable conditions that enhance plant growth (Quinton & Fiener, 2024). Soils provide numerous goods and services upon which the environment and life hugely depend for survival (Kopittke et al., 2022). Soil serves a vital function in regulating the global carbon cycle; it is the world's largest carbon sink, surpassing both vegetation and the atmosphere combined (Kopittke et al., 2022). The soil's capacity to serve as a carbon sink is crucial in lowering atmospheric carbon dioxide levels, which contribute to global warming and climate change (Lal, 2004). This ability of the soil resource emphasizes the need to protect and conserve it to ensure the continuity of the carbon regulation service and life sustainability (Evangelista et al., 2023; Kopittke et al., 2022; Pereira et al., 2018).

Soil regulates and mitigates floods through its ability to percolate and soak in rain water (Evangelista et al., 2023). The porous nature of soil facilitates its ability to infiltrate water into the ground water reservoirs and also facilitates interflow of water into lentic and lotic systems (Evangelista et al., 2023). Not only does soil act as a channel for water flow but also acts as a water storage in the vadose zone through its cohesion and adhesion forces (Evangelista et al., 2023). Soil is a natural habitat for numerous organisms from which they derive their livelihoods, therefore, soil

has the capacity and ability to sustain life of organisms (Rosinger et al., 2025). Through this, soil promotes environmental biodiversity and ecosystem restoration (Pereira et al., 2018). Soil protects organisms and the environment from contaminants through its ability to denature and breakdown contaminants, toxins, pollutants and heavy metals (Evangelista et al., 2023). Soil, being a habitat to many microorganisms that feed on sources of these pollutants, renders them immobile through ingestion.

Additionally, the presence of clays and organic matter in soil that adsorb heavy metals purify and clear the environment of any pollutants (Evangelista et al., 2023). Increased pressure and dependence on soils for most of human needs leads to their excessive exploitation and misuse, subsequently impairing the soil's ability to fulfil its functions resulting into degradation (Kopittke et al., 2022). Therefore, mismanagement of soil resources poses a great threat to their ability to perform all the necessary functions possibly to a point of no return (Evangelista et al., 2023). Soil resources are threatened by a number of processes including erosion, salinization, acidification, crusting, compaction and contamination, with soil erosion being reported as the most significant threat resulting into highest decline in crop productivity (Bayata, 2024; Sartori et al., 2024).

Soil erosion is a growing global risk intensified by human activities. Natural soil erosion on its own is not a threat, however, accelerated or human- induced erosion is a rising major threat. Accelerated soil erosion constitutes a critical environmental hazard to ecosystem biodiversity, food production, soil fertility and eutrophication (Ahmed et al., 2024; Evangelista et al., 2023; Nasir Ahmad et al., 2024; Negash et al., 2021; Quinton & Fiener, 2024; Zhai et al., 2024). Agents of soil erosion include water, wind, and tillage, among these, water-induced erosion impacts over one billion hectares globally (Borrelli et al., 2017; Nasir Ahmad et al., 2024). Worldwide, soil erosion on agricultural lands happens at approximately 17 tonnes per hectare each year, whereas soil formation happens at about 1 tonne per hectare per year. This inconsistency leads to ongoing soil depletion and progressive land degradation (Borrelli et al., 2017).

2.2 Soil erosion

2.2.1 The various forms and mechanisms of soil erosion

Soil erosion involves the removal and movement of soil particles from the surface layer of the pedosphere by natural forces and human activities, leading to the redistribution of sediments (Hacisalihoğlu et al., 2006; Ji et al., 2024; Verheijen et al., 2009). Soil erosion takes several forms including erosion by water, erosion through tillage, wind erosion, and erosion during crop harvest. Among these, erosion by water is the most prevalent, accounting for up to 95% of global erosion (Borrelli et al., 2021; Quinton & Fiener, 2024; Verheijen et al., 2009).

Water erosion causes soil particles to detach due to water movement (Quinton & Fiener, 2024).

Rainfall droplets hit the topsoil, causing exposed soil to detach particles, the detached topsoil is then susceptible to movement and transportation by soil surface running water (Quinton & Fiener, 2024). As a result of continuous and excess surface runoff occurring along drainage lines, rill, inter-rill, sheet and gully erosion also take place (Verheijen et al., 2009). Tillage erosion is the form of erosion that occurs due to tillage practices (Yuan & Fan, 2024). It involves breakdown and detachment of soil particles through cultivation of land and tillage operations. This form of erosion typically occurs in regions where water erosion is minimal and least common where water erosion is most intense (Quinton & Fiener, 2024; Verheijen et al., 2009). Tillage erosion is highly influenced by the characteristics of the tools used, frequency of tillage operations, topography and soil structure (Yuan & Fan, 2024).

Wind erosion refers to the process of soil particles being detached and removed by means of wind (Quinton & Fiener, 2024). This form of erosion is affected by wind speed, soil surface exposure and the stability of soil particles. Additionally, wind erosion is also influenced by slope, crop cover density, roughness of soil surface, sand and moisture content (Quinton & Fiener, 2024). Wind erosion is often experienced and more common in dry regions and semi-dry areas (Quinton & Fiener, 2024; Verheijen et al., 2009). Crop harvest erosion is defined as a form of soil loss that occurs during the reaping process of crops (Verheijen et al., 2009). Findings reveal that this form of erosion is more common during the harvest of root crops since the required food part of the plant is underground and covered in soil, however, this form of erosion is also present in other types of crops when the whole plant is uprooted with soil and taken out of the field (Kuhwald et al., 2022).

2.2.2 Factors influencing rates of soil erosion by water

Rain-triggered erosion is influenced by climatic, natural, environmental, anthropogenic and pedologic factors (Sartori et al., 2024). Climatic factors affecting soil erosion include rainfall, natural factors include topography, anthropogenic factors include crop cover, land use and tillage practices and pedologic factors include soil vulnerability to erosion (Asempah et al., 2024; Hacisalihoğlu et al., 2006; Verheijen et al., 2009). Rainfall influences erosion through several

aspects such as rainfall intensity, rainfall duration, amount of rainfall, terminal velocity, wind velocity, slope direction and size of rainfall droplets (Bellocchi & Diodato, 2020). These aspects influence rainfall erosivity through soil particle separation, breakdown and transportation (Bellocchi & Diodato, 2020; Li et al., 2023). Understanding these rainfall characteristics provides a clearer insight into how rain affects soil erosion rates. For instance, high rainfall intensity with large rainfall droplets increases the kinetic energy of the droplets which increases soil particle separation and soil erosion rates (Bellocchi & Diodato, 2020; Nasir Ahmad et al., 2024; Vaezi et al., 2017).

Topography describes the nature of landscape, relief, land surface and slope of the area (Li et al., 2023). Slope of an area is described by the slope gradient or steepness and the slope length (Li et al., 2023). Hacisalihoğlu et al. (2006) and Setyawan et al. (2019) found out that erosion rates were higher on a 40% slope than on a 20% slope. Therefore, higher slopes lead to increased soil erosion rates as rainfall or water do not have enough time to infiltrate into the soil profile before being acted on by the force of gravity which causes it to flow and runoff downslope. In addition, Li et al. (2023) found out that soil erosion rates increase with an increase in slope length because as runoff goes down a longer slope, more soil mass and runoff volume is generated and built up down the slope.

Soil erodibility is described as the susceptibility of soil to be eroded by erosion agents (Gupta et al., 2024; Yao et al., 2016). Soil erodibility is affected by the physical, chemical, and biological traits of soils. Physical aspects encompass particle size distribution, structure stability, organic matter content, consistency, and water permeability. Chemical factors include cation exchange capacity, soil chemistry, and clay mineralogy. Biological features involve macro and micro flora and fauna as well as their interactions (Bryan, 2000; Stanchi et al., 2015). Wang et al. (2016) stated that an increase in soil organic matter and water-stable aggregates leads to a reduction in soil erodibility. Soil organic matter increases the aggregation of soil particles, hence improving the soil structure and porosity, which improves water infiltration and percolation into the soil profile and therefore reduces soil erodibility (Wang et al., 2016).

Soil texture describes the percentage of sand, silt, and clay content in soils; these components directly influence soil erodibility (Detamo Aga, 2020). Finer textured soils result in reduced water infiltration, which leads to increased runoff because finer textured soils have poor structure and

stability, which are easily broken down and eroded. Fine textured soils can easily fill soil pores and result in soil seals, therefore reducing water infiltration and causing runoff (Detamo Aga, 2020).

Microorganisms present in soil secrete binding agents and mucilages that cause soil macro and micro aggregation (Bryan, 2000). Increased soil aggregate formation improves soil structure and water infiltration properties, which encourage water seepage and reduce soil erodibility and runoff occurrence (Bryan, 2000).

Land cover influences the rates of soil erosion through interception of rainfall droplets and reduction in its intensity (Gao et al., 2020). The presence of vegetation on a soil surface reduces raindrop impact through interception which reduces soil particle disintegration and detachment. Additionally, vegetation reduces runoff velocity by creating barriers that slow down running water (Gao et al., 2020; Obiahu & Elias, 2020). In a study done by Obiahu & Elias (2020), areas covered in forests and grasslands experienced low soil erosion rates because of the interception provided by the constant stable vegetation cover. The presence of vegetation cover also implies the presence of roots, which physically bind soil particles together and also excrete chemicals and exudates that bind soil particles together improving soil particle aggregation and reducing soil erodibility (Meng et al., 2021).

Tillage practices are usually done during the preparation of fields for crop sowing to ensure that the soil is favourable for seed germination and development (Chalise et al., 2020). Tillage practices result in movement, detachment, and breakdown of soil particles into smaller particles that can easily be transported by water. Tillage practices also bury surface vegetation, leaving the soil bare and exposing the soil surface, which increases its susceptibility to erosion and its agents (Lobb, 2008). Depending on the form of tillage used, its influence on soil erosion varies. Conventional tillage, which involves the loosening and breaking of soil particles and burying of surface crop residue, results into high rates of soil erosion compared to the no-till practice which minimizes soil disturbance and retains the surface crop residue (Chalise et al., 2020; Lobb, 2008).

Land use and land cover change have increasingly happened over the years, where natural forests are converted into agricultural lands through deforestation (Quinton & Fiener, 2024). Deforestation of land on steep slopes and converting it to arable land has increased the rates of soil erosion due to soil exposure to cultivation. Deforestation leads to a reduction of soil-root binding properties,

reduced vegetation cover, reduced litter fall and reduced soil organic carbon, all of which are characteristics that influence the rates of soil erosion (Khodadadi et al., 2021). Deforestation destroys the structural and physico-chemical properties of the soils, resulting into destabilization of soil particles and increased soil erosion rates (El Mazi et al., 2022). Overgrazing involves repeated heavy feeding of livestock on rangelands, grasslands, or vegetation for several years, resulting in decline in vegetation cover, production, vigour and biodiversity (Hacisalihoğlu et al., 2006). Overgrazing presents the risk of soil erosion by reducing vegetation cover and exposure of the soil surface. Soil surface exposure and reduced vegetation cover lead to increased soil particle breakdown and transportation by rainfall and other erosive agents (Hacisalihoğlu et al., 2006; Kairis et al., 2015).

2.2.3 Effects of soil erosion

Effects of soil erosion manifest as both on-site (where soil has been lost) and off-site (where soil has been deposited) (Asempah et al., 2024; Nasir Ahmad et al., 2024). On-site effects include removal of topsoil, loss of soil fertility, disruption of ecosystem services and functioning, loss of biodiversity, and decline in agricultural production. Off-site effects include disruption of ecosystem services and functioning, nitrification, eutrophication, siltation, river braiding, and mudflow (Hacisalihoğlu et al., 2006; Rawat et al., 2012; Sartori et al., 2024).

Soil fertility is lost when the top fertile soils, clay, and organic matter are washed away (Asempah et al., 2024). Clay and organic matter are responsible for soil's ability through adsorption of nutrients and making them available for plant up-take. Organic matter further decomposes to release nutrients that are required for plant growth (Duressa et al., 2024). Loss of soil fertility results in reduced agricultural production since there are no nutrients in the soil available to support plant growth and development (Asempah et al., 2024; Duressa et al., 2024; Sartori et al., 2024; Verheijen et al., 2009).

Soil erosion leads to the disruption of ecosystem services and functioning (Asempah et al., 2024). Soil erosion results in loss of organic and inorganic matter on which flora and fauna depend for their livelihoods; this loss leads to organism starvation and death. Death of flora and fauna results in loss of biodiversity and ecosystem dysfunction (Telo da Gama, 2023). Deposition of nutrients

in open waters results in the growth of vegetation and formation of algal blooms, which deplete water of oxygen, leading to loss of aquatic life (McDowell & Hamilton, 2013). Nutrifaction of aquatics refers to the excessive deposition of nitrogen, phosphorus and other nutrients into the water, leading to eutrophication and the formation of algal blooms (McDowell & Hamilton, 2013). Eutrophication is the increase in the amount of biomass in water ecosystems caused by an increase in soil and plant nutrients. An increase in biomass on the water surface leads to a reduction in light penetration into the water, resulting in reduced plankton growth and hence food deprivation for aquatic life (Akinawo, 2023; Bhuyan et al., 2024; McDowell & Hamilton, 2013).

2.2.4 Areas that are prone to erosion

Soils undergo natural erosion; however, due to increased human populations and activities, soil erosion rates have increased over the years (Kusiima et al., 2022). Soil erosion rates vary temporally and spatially depending on the prevailing characteristics, for example, humid regions characterised by high rainfall intensities and amounts experience high soil erosion rates (Asempah et al., 2024). Mountainous regions are known to be among the most fragile ecosystems because of their unique characteristics, which include high relief, steep slopes, and high amounts of rainfall (Muhumuza & Byarugaba, 2009; Roller et al., 2012).

The Rwenzori highlands are classified as humid tropical regions, with one of the major threats to the fertile topsoil being soil erosion (Ahmed et al., 2024). The Rwenzori highlands are susceptible to severe erosion due to the nature of their topography, high rainfall amounts, and poor land management practices (Negash et al., 2021). The highlands also have diverse land uses, which are characterized by canopy cover that varies temporally and spatially. The land in the highlands is also subjected to different land management practices, and differences in these characteristics demonstrate variations in soil erosion rates (Negash et al., 2021).

2.3 Influence of land use on soil erosion

2.3.1 Land uses and their characteristics

Land use describes the arrangements, activities, usage and inputs humans undertake in a land cover type to produce, change or maintain it (FAO, 2024). Land cover is the observed physical cover on

the earth's surface, including natural or planted vegetation and human constructions (FAO, 2024). Land use types include; croplands, forestlands, woodland, pasturelands, rangelands, grasslands, wetlands, and urban areas (FAO, 2024). The Rwenzori highlands are characterized by crop cultivation, animal husbandry, built-up areas, abandoned lands, wetlands, national parks, game reserves, forests, and woodlands (Ekesa et al., 2015).

Crop cultivation is the growing of annual and perennial crops for consumption or for sale (Jacobs et al., 2016; Muhumuza & Byarugaba, 2009). Subsistence farming involves the growth of annual or perennial crops in small holdings for personal use, whereas commercial agriculture refers to farming activities carried out for the primary purpose of producing goods for sale (Nakakaawa et al., 2011). Annual land use is characterized by crops that grow, develop, and complete their life cycle in one year, whereas perennial land use is characterized by crops that grow, develop, and complete their life cycle in more than one year; both of these crops can be grown for either subsistence or commercial purposes (Tibasiima et al., 2023). Woodlands are characterised by trees covering at least 6% of the land area with aerial stems of at least 2 meters in height that persist for more than one season and can be comprised of deciduous, evergreen, or mixed vegetation. Grasslands are land areas dominated by native grasses with little or no woody tissue used primarily for pasture and grazing (FAO, 2002).

2.3.2 Effects of different land uses on soil erosion rates

Vegetation coverage on the soil surface significantly influences the control, prevention, and reduction of soil erosion rates through its roots, canopy, and litter fall (Hacisalihoğlu et al., 2006). Numerous studies have consistently demonstrated that loss of vegetation cover and canopy, primarily caused by deforestation, overgrazing, bush burning, and crop harvest, leads to significant escalation in soil erosion rates (Mohammad & Adam, 2010). When soil is left bare and exposed to direct rainfall and other erosion agents, the natural structure of the soil is destabilised, and soil particles are broken down. Smaller soil particles clog soil pores, decreasing porosity and impairing the soil's capacity to absorb, percolate, and retain water, therefore increasing the rates of runoff and soil erosion (Hacisalihoğlu et al., 2006).

Forests, grasslands and woodlands tend to experience lower rates of soil loss (Mohammad & Adam, 2010). This is because the canopy intercepts rain, slowing down the velocity of raindrops, thus

preventing them from directly hitting the soil. Rain droplets that are intercepted may even remain on the leaf surface or tree stem and evaporate without ever reaching the soil surface and exerting any pressure on the soil particles (Mohammad & Adam, 2010; Rawat et al., 2012). Forests play a crucial role in minimizing soil loss due to the abundant organic matter content in these ecosystems (Mohammad & Adam, 2010). Organic matter significantly contributes to improving soil structure, enhancing aggregate stability and reducing susceptibility to erosion, organic matter also fosters increased porosity and water infiltration, leading to a decrease in runoff rates (Mohammad & Adam, 2010).

Zi et al. (2023) reported that soils in forests are more prone to erosion than those in grasslands, this was attributed to the difference in root systems between the two types of vegetation. The fine roots of grasses in grasslands are better at increasing the stability of soil aggregates compared to the thicker roots of trees, roots also play a vital role in improving soil porosity and infiltration rates (Hacisalihoğlu et al., 2006; Mohammad & Adam, 2010; Zi et al., 2023). Shrublands and areas covered in natural vegetation also have low rates of soil erosion due to the high amounts of organic matter and vegetation cover in these areas, the high organic matter content in these areas improves the stability of the soil aggregates, reducing soil detachment when raindrops hit the soil (Mohammad & Adam, 2010). The dense vegetation provides better protection for soil against raindrop impact, reducing soil erosion rates (Mohammad & Adam, 2010).

Annual land use or lands that are continuously and frequently cultivated experience high levels of soil erosion due to the loss of vegetation cover, soil aggregate breakdown and exposure of soil particles to the direct impact of rain droplets (Hacisalihoğlu et al., 2006; Mohammad & Adam, 2010). Croplands characterised by annual crops were found to have higher soil loss rates than grasslands and forests which do not have tillage operations (Abdalla et al., 2020). Zi et al. (2023) found out that the erodibility of soil in croplands was higher than that in grasslands, forests, shrublands and plantations, this was attributed to the continuous disturbance of top soil in croplands and weeding done by the use of hoes.

Croplands on slopes are particularly susceptible to soil erosion, as steep gradients and repeated tillage operations act synergistically to accelerate soil loss (Kumar Mishra & Mishra, 2017). Agricultural fields that are left unploughed and equipped with effective soil and water conservation measures experience very low soil loss rates due to the stability of the soil particles and the

protection provided by the vegetation canopy and reduced runoff velocity (Abrha et al., 2018). Annual land use is characterised by tilling of land and burying plant residues at the onset of rains to prepare the land for sowing, however, this increases the rates of soil erosion since the soil surface is exposed to heavy consistent rains (Rawat et al., 2012). Integration of perennial vegetation in land use practices has been proven to significantly reduce and manage soil erosion rates. This approach ensures continuous coverage of the soil, minimizing the impact of erosion agents (Kumar Mishra & Mishra, 2017).

Type and formation of vegetation cover play a vital role in the interception of rainfall droplets, thereby influencing soil erosion rates (Mohammad & Adam, 2010). Broad-leaved vegetation has a greater impact on reducing the raindrop effect on soil, thus reducing soil loss rates as compared to narrow-leaved vegetation (Kumar Mishra & Mishra, 2017). According to a study done by Hacisalihoğlu et al. (2006) in Turkey, cultivated land exhibited the greatest soil loss ($42 \text{ t ha}^{-1} \text{ yr}^{-1}$), exceeding grassland erosion by 8-fold and forest erosion by 42-fold. The high soil erosion rate in grasslands was attributed to overgrazing, which led to soil surface exposure, direct impact of rain droplets, and easy soil particle detachment and transportation. Abrha et al. (2018) reported that grasslands, which had been overgrazed and had their vegetation cover reduced, had an erosion rate of $110 \text{ t ha}^{-1} \text{ yr}^{-1}$; the study showed that due to reduced vegetation cover and continued grazing, the soil surface was exposed to more disturbances by the livestock and this led to soil disintegration and formation of gullies which accelerated the soil erosion rates.

2.4 Soil erosion in different soil types

2.4.1 Soil types and their properties

The Rwenzori highlands are comprised of a variety of soil types that vary with altitude (Lara et al., 2013). Leptosols are the dominant soils in altitudes greater than 3300m above sea level; Leptosols and Ferralsols are the dominant soil types between 2000 and 3300m above sea level. Andosols, Nitisols, Leptosols, Fluvisols and Luvisols are dominant between 1000 and 2000m above sea level (Jacobs et al., 2016).

Ferralsols are highly weathered soils typically found in the humid tropics. They are well-drained, with a sandy clay loam to sandy loam texture, a stable microstructure, and a distinctive red or

yellow coloration (WRB, 2022). Ferralsols are characterized by the dominance of low-activity kaolinite clays and a high content of sesquioxides (iron and aluminium oxides). Some of the major challenges associated with these soils are low pH and phosphorus fixation, which factors limit agricultural productivity (WRB, 2022).

Andosols form from glass-rich volcanic ejecta in nearly any climate, or from other silicate-rich materials through acid weathering in humid and per-humid environments. These soils are usually dark coloured, found in volcanic regions, very fertile and face a problem of phosphorus fixation

(WRB, 2022). Leptosols are characterised by very thin shallow soils rich in coarse fragments that overlie hard, continuous rock. They are characterised by rapid water percolation and low water retention capacity. These soils are usually found in medium to high altitudes of strongly eroding mountainous regions of all climatic zones (WRB, 2022).

Nitisols are deep, productive, well-drained, reddish brown tropical soils containing at least 30 percent clay and exhibiting a moderate to strong angular blocky structure. These soils are dominant on levelled and in hilly landscapes under tropical rainforest or savannah vegetation. These soils have good water drainage and a deep nature, which permits deep rooting, making these soils resistant to erosion. Nitisols are also rich in kaolinite and iron minerals (WRB, 2022). Fluvisols are fertile soils developed in fluvial, lacustrine, and marine deposits. These soils have a good natural fertility, are periodically flooded, have a weak horizon differentiation but a distinct topsoil horizon (WRB, 2022). Luvisols are fertile soils characterised by clay migration from the top soil to the subsoil layers, hence an argic subsoil horizon. These soils contain highly active clays with a high base saturation. Additionally, they have a high silt content, making them vulnerable to structure deterioration and erosion (WRB, 2022).

2.4.2 Soil erosion rates in different soil types

Soil types have varying properties that influence their nature and response to erosive forces and agents (Zi et al., 2023). Soil properties influence different soil aspects such as infiltration rate, soil particle detachment, soil particle transportation, water retention, and hydraulic conductivity, which influence soil erosion rates (Ouyang et al., 2018).

Andosols have been found to have low soil erosion rates in undisturbed natural conditions of high vegetation cover, low erosive rainfall and low erodibility; however, with change in the soil's land

use and management, several soil erosive properties are triggered, resulting into increased soil erosion rates (Rodriguez et al., 2002). In a study carried out by Rugendo et al. (2023), it was observed that Ferralsols had a significantly higher runoff and sediment loss than Nitisols. This was because the Ferralsols had a very fine, medium and coarse sub-angular blocky structure, which was weaker and porous; on the other hand, the Nitisols had a moderately strong coarse angular and sub-angular blocky structure.

The texture of a soil, which describes the composition of sand (coarse particles), silt and clay (fine particles) has a major effect on the infiltration rates of the soil (Vaezi et al., 2017). Infiltration rate is the speed at which water enters the soil. Infiltration in soils will take place until the soil is saturated; when this happens, water can no longer enter the soil and this can lead to runoff (Vaezi et al., 2017). Soils with a coarse texture, such as Ferralsols, tend to have higher infiltration rates, whereas fine-textured soils that have limited macro-porosity have low infiltration rates (Vaezi et al., 2017).

Humic Nitisols, which are characterised by high clay content, tend to have high erosion rates, which are attributed to surface sealing which occurs when clay particles clog soil pores and block water infiltration into the soil (Ekwue & Harrilal, 2010; FAO, 2006; WRB, 2022; USDA, 2014). Additionally, Nitisols, which are well-aggregated soils are less eroded compared to Luvisols which are comprised of pulverized silts and very fine sands which are easily transported by water and easily eroded (Hacisalihoğlu et al., 2006). Soil that is well aggregated and has water-stable aggregates has a low soil detachment capacity due to the fact that soil aggregates can resist separation when impacted by rain, hence resisting soil erosion (Zi et al., 2023). A high silt content improves soil structure and aggregate stability which makes the soil more resistant to erosive forces and agents (Descroix et al., 2001). Other studies also found out that soil erosion rates are higher in soils with low clay and organic carbon contents (Ma et al., 2023; Qu et al., 2023). The presence of clay and organic matter in a soil increases adhesive and cohesive forces between and within soil particles, hence increasing soil aggregate formation and stabilization and decreasing soil erodibility (Rugendo et al., 2023; Yao et al., 2023).

Soil types such as Ferralsols and Nitisols that have a high clay, iron and or aluminium content have high soil aggregate stability which reduces the soil's susceptibility to erosion (Hacisalihoğlu et al., 2006). On the other hand, soils with low clay content generate more run off due to weaker soil

aggregates. In a study done by Ekwue & Harrilal (2010), it was observed that soil erosion was greater in sandy loam than in clay and clay loam soils; the low erosion rates in the clay loam were attributed to the soil's high infiltration rate. Ekwue & Harrilal (2010), also indicated that Histosols which are characterised by presence of peat have a low bulk density which increases infiltration and in turn decreases soil erosion rates. The high organic matter content in Phaeozems, Chernozems and Kastanozems plays a major role in influencing the rates of soil erosion; organic matter increases soil aggregation and improves structure stability, which reduce the soil erosion rates (WRB, 2022; Vaezi et al., 2017). Therefore, practices that reduce organic matter availability in soils, such as frequent tillage which exposes organic matter on the surface leading to its rapid decomposition, should be minimized.

Bulk density also influences soil porosity and water infiltration, the higher the bulk density, the lower the porosity and this leads to reduced water infiltration and increased runoff and soil erosion (Vaezi et al., 2017). Increased bulk density can be caused by compaction from farm mechanization or over grazing with livestock (Nahib et al., 2024). Sodium Absorption Ratio (SAR), which is defined as the ratio of dissolved sodium to calcium and magnesium, is a soil property used to measure and estimate the amount of salinity in soils. High amounts of sodium in soil result into soil dispersion, which disrupts the formation of stable soil aggregates. And for this reason, soils with high sodium absorption ratios experience high erosion rates (Kimiaghalam et al., 2014).

2.5 Soil loss tolerance thresholds (T-values)

2.5.1 The framework for defining allowable soil erosion rates

Soil loss tolerance threshold is a concept used in the description of the maximum soil loss that can still support the soil's productivity (Di Stefano et al., 2023). Soil loss tolerance is the extent of soil erosion that allows the soil to maintain stable and sustainable fertility over time. Ostovari et al. (2020) described soil loss tolerance as the highest average annual soil loss allowed without impairing the soil's main functions, productivity. Li et al. (2009) suggested that soil loss tolerance is a concept used to evaluate the potential risk of soil erosion, productivity decline, and off-site damage. They highlighted that soil loss tolerance represents the maximum soil loss amount that does not harm or impact off-site productivity, such as water resources. Exceeding soil loss tolerance thresholds leads to ecosystem degradation (Di Stefano et al., 2023). Soil productivity decreases

when soil erosion outpaces both the rate of soil formation and the soil loss tolerance threshold; this imbalance in soil dynamics can lead to a range of detrimental outcomes, including diminished soil depth, decreased fertility and lower crop yields due to the depletion of essential nutrients (Chandel & Hadda, 2018).

Excessive soil loss contributes to water pollution and sedimentation in reservoirs, thereby impacting overall aquatic health and functioning. It is crucial to address these issues to maintain the long-term productivity and sustainability of agricultural lands and natural resources (Di Stefano et al., 2023). It has been proven that soil loss tolerance thresholds vary based on factors such as soil type, soil depth, climatic conditions and land management practices (Chandel &

Hadda, 2018; Chornyy, 2022). Quantifying soil loss tolerance is crucial for assessing soil quality and implementing effective soil erosion control measures and conservation practices (Di Stefano et al., 2023; Pretorius & Cooks, 1989). Soil erosion rates surpassing soil loss tolerance thresholds lead to significant land degradation, soil fertility decline, reduced crop production, increased accumulation of sediments in aquatic environments and decline in biodiversity and ecosystem functions. This is made worse considering that soil is a non-renewable resource that takes a very long time to regenerate (Mandal & Sharda, 2011).

2.5.2 Approaches used to determine acceptable soil erosion thresholds

Soil loss tolerance thresholds (T-values) have been assessed by different scholars using different methods. T-values can be estimated by use of soil formation rate, soil thickness, productivity index and guidelines of the USDA-NRCS methods (Lenka et al., 2014; Mandal & Sharda, 2011). The soil formation rate method uses the mass of weathered rock, mass of inorganic soil formed from the parent material, concentrations of elements in unweathered rock and soil and the removal rate of an element dissolved in runoff to estimate the tolerance thresholds (Li et al., 2009). Measuring different elements in rocks and soil is a complex task that is difficult to do accurately (Li et al., 2009).

The soil thickness approach utilises soil profile measurements to determine acceptable soil loss limits. This method was developed by Skidmore (1982) who used present, minimum allowable and optimum soil depths of a given soil at a given time and place to define soil loss tolerance. The method requires measurement of different soil depths, which is time-consuming and requires substantial financial resources. In addition, it only uses soil thickness (soil depth) as the only variable parameter to determine soil loss tolerance threshold, yet this is not the only indicator of

soil productivity (Duan et al., 2017). The soil productivity method uses present, lowest tolerable, and optimum soil productivity indices to estimate soil tolerance threshold (Li et al., 2009). This method is a modification of the soil thickness method, where soil productivity measurement is used instead of soil depth. The soil productivity index is calculable with the EPIC model which uses slope, soil bulk density and erosion rates (Li et al., 2009).

The USDA Natural Resources Conservation Service (USDA-NRCS) guidelines use properties of the soil in the rooting zone and subsurface layers to estimate soil loss tolerance thresholds (USDANRCS, 1999). This method estimates soil loss tolerance threshold while taking into account soil properties that sustain plant growth, influence soil resilience, soil quality, water entry and transport in the soil (Lenka et al., 2014). The model estimates soil loss tolerance threshold based on biophysical soil properties and soil quality attributes related to the soil's ability to resist soil erosion (Mandal & Sharda, 2011). This method requires measurement of many soil parameters, which is labour-intensive and time-consuming. These soil properties are used to assess the current state and overall performance of the soil (Bhattacharyya et al., 2008).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Description of the study area

3.1.1 Geographical Location

The study was conducted in the western region of Uganda in the Rwenzori highlands, specifically in Kabarole and Kasese districts (Figure. 3.1), which have been documented to be severely prone to high erosion rates (Karamage et al., 2017). The study was done in Kaisamba, Bukukuru, Kyambogho and Kathulu villages.

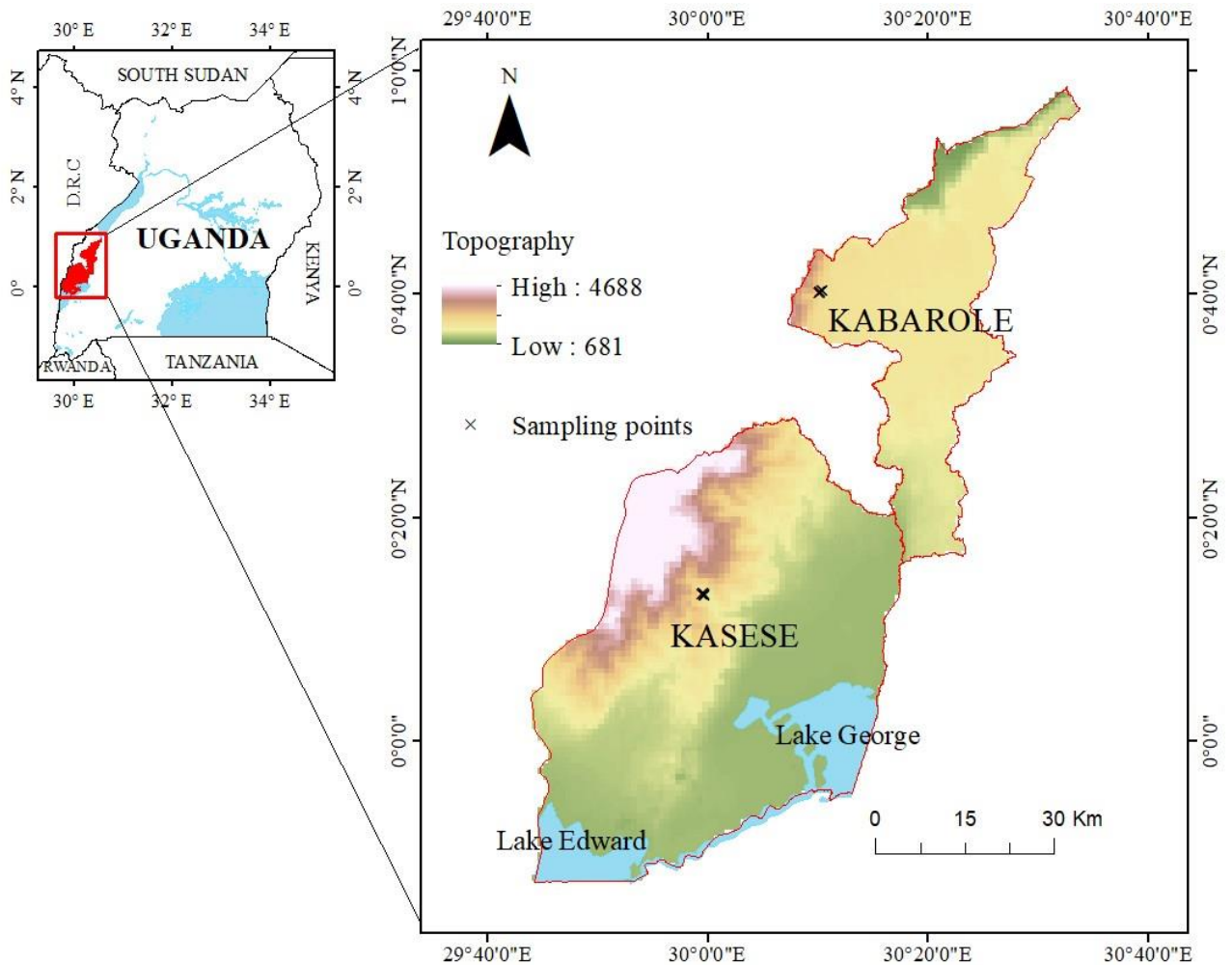


Figure 3.1: Location of the study area.

Kabarole District is bordered by Ntoroko, Kibaale, Kyenjojo, Kamwenge, Bunyangabu and Bundibugyo districts to the north, northeast, east, southeast, south and west, respectively. It is approximately 320 kilometres from Kampala, the capital city of Uganda (Nyakaisiki et al., 2019). Kasese district is located along the equator. It is bordered by Bunyangabu, Kamwenge and Rubirizi districts to the north, east, and south, respectively, and the Democratic Republic of Congo to the west (Mbabazi et al., 2023).

3.1.2 Climate

Kasese and Kabarole districts receive bimodal annual rainfall ranging from 1200 to 1500 mm in two seasons, with long rains received from March to May and short rains from October to December (Lara et al., 2013). The average monthly temperature of Kabarole district is 19°C, with a range between 12 and 26°C; the average annual temperature of Kasese district is 23°C, with a range between 11 and 36°C (Lara et al., 2013). Kabarole and Kasese districts also face a problem of extreme rainfall patterns explained by El Niño Southern Oscillation, and this has been manifested as increased flooding of nearby rivers, especially in the wet season, causing transport disruptions, outbreaks of pests and diseases and prolonged dry seasons that lower crop yields (Nyakaisiki et al., 2019).

3.1.3 Topography

Kasese and Kabarole districts are characterised by very steep slopes ranging from 35% to greater than 150% in some of the regions, especially those in the Rwenzori ranges (Lara et al., 2013). Parts of the districts are characterised by the Albertine rift valley and the great lakes (Edward and George). Kabarole district is characterised by dormant volcanoes, though it occasionally experiences some seismic activity (Lara et al., 2013).

3.1.4 Geology and Soils

The study area comprises sedimentary bedrocks of Pre-Cambrian age (4570 – 541 million years old) in some regions, whereas other regions are comprised of younger rocks, being metamorphic and igneous in origin (Lara et al., 2013).

Several soil mapping units including the Fort Portal series, Bubandi series, Saka series, Mulinda series, Kazo series, Kyanzabo series, Kyamatoma series, Kasese series and Nyakatonzi series have

been established and used to describe the soil characteristics in this region (Musis et al., 1960). According to the World Reference Base for Soil Resources classification system, (WRB, 2022; Jacobs et al., 2016) the Rwenzori highlands are characterised by Leptosols, Ferralsols, Andosols, Nitisols, Fluvisols and Luvisols (Figure 3.2).

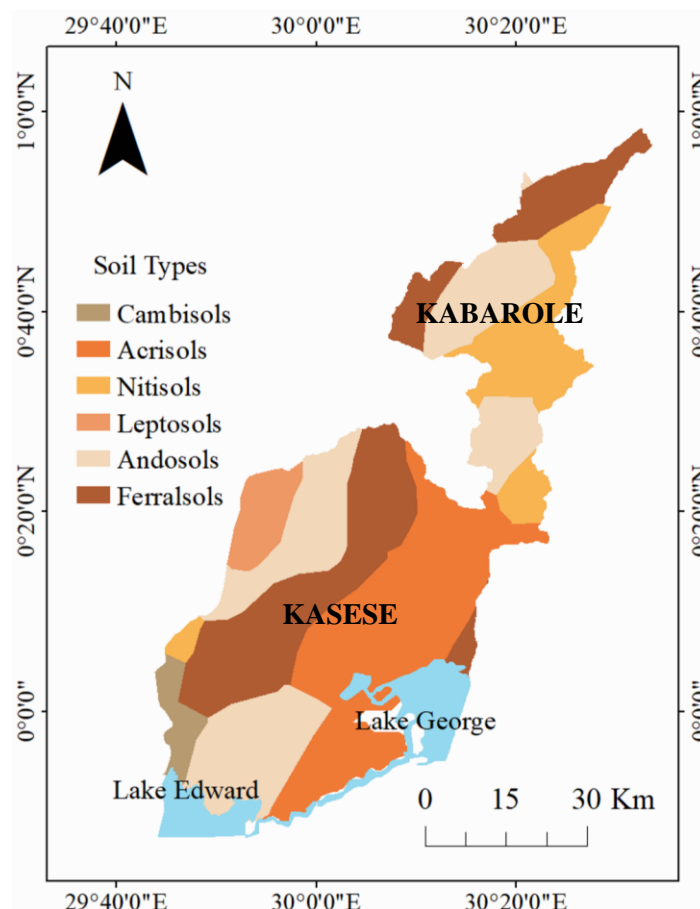


Figure 3.2: Soil types in Kabarole and Kasese districts, Rwenzori highlands

Isabirye et al. (2004) and Semalulu and Kaizzi (2013) have also classified the soils in the Rwenzori region as Histic Andosols, Luvic Andosols, Leptic Andosols, Gleysols, Euric Gleysols, Histosols, Lixic Ferralsols, Acric Ferralsols, Vertisols, Luvisols and Dystric Regosols using the World Reference Base for Soil Resources.

The texture soils in high altitudes, above 3050m have been described as loams, sandy loams and clay loams derived from volcanic ash, whereas soils in the low altitude, below 3050m have been described as peaty loams and clay loams and clays. Soils around the lakes Edward and George are predominantly sandy clay loams and sandy clays (Lara et al., 2013).

3.1.5 Hydrology

The study area is comprised of two major lakes; Edward and George found in Kasese district. The major rivers in Kasese are Nyamwamba, Mubuku, Nyamusangani and Rukoki, which drain into L. Edward via the Kazinga channel that connects L. George to L. Edward. The major rivers found in Kabarole district include Mpanga, Nsonge, Mahoma and Dura, which drain into L. George. Several streams also emerge from the high altitudes of the Rwenzori ranges, feeding water into L.

Edward and L. George (Lara et al., 2013).

3.1.6 Vegetation and Land Use

Natural vegetation in the Rwenzori highlands is classified into five distinct zones based on altitude. The afro-alpine moorland vegetation dominates the highest elevations, ranging from 4000 to 4500 m. Between 3000 and 4000 m, the landscape is characterised by heather vegetation (UNESCO, 2025). Bamboo vegetation thrives in the zone between 2500 and 3000 m, while montane forests cover the altitudinal range of 2000 to 3000 m. At the lower elevations, from 1000 to 2000 m, the region is predominantly covered by grasslands (UNESCO, 2025).

The Rwenzori highlands have also been greatly influenced by human activities such as setting up of settlements, cultivation and grazing resulting into diverse vegetation and land use types. Several land uses, including woodlands and planted forests, grasslands and cultivated crops, are dominant in this region (Ekesa et al., 2015; Lara et al., 2013). The commonly cultivated crops are: *Musa spp.* (bananas), *Coffea arabica* (coffee), *Manihot esculenta* (cassava), *Camellia sinensis* (tea), *Solanum lycopersicum* (tomatoes), *Pisum sativum* (peas), *Zea mays* (maize), *Phaseolus vulgaris* (beans) and fruit trees.

Methods

3.2 Study design

Two case studies with the quasi-experimental research design were used to assess the variations in soil erosion rates and to determine the soil loss tolerance thresholds of Ferralsols and Andosols

under different agricultural land uses. Case study one was done in Kabarole District and case study two was done in Kasese.

Study one was conducted in Kabarole on Andosols (Figure 3.2). During the study period (December 2021 to November 2022) Kabarole received 1518 mm of total rainfall (Appendix 1.4). Four already existing land use types (annual, perennial, woodland, and grassland) on hilly slopes between 25% and 27% as classified by USDA were used (Table 3.1). Annual land use was comprised of maize (*Zea mays*) monocrop, perennial land use was comprised of *Musa spp.* (bananas) that are mulched with banana leaves and banana fibres, woodlands were comprised of planted *Eucalyptus spp.* (eucalyptus) trees of 2-3 years old with an average height of 4m and the grasslands for this study were comprised of native grasses in the regions that are often grazed by livestock.

Table 3.1: Locational attributes of the land uses in Kabarole under Andosols.

Runoff Plot	Location		Land use	Slope (%)	Altitude (m)
	°N	°E			
1	0.672455556	30.17244167	Annual	26	1727
2	0.672436111	30.17256667	Annual	26	1724
3	0.672563889	30.17259167	Annual	26	1729
1	0.669183333	30.16880278	Perennial	25	1829
2	0.669291667	30.16903611	Perennial	25	1823
3	0.669552778	30.16908611	Perennial	25	1826
1	0.669905556	30.16923611	Grassland	27	1818
2	0.670033333	30.16920833	Grassland	27	1819
3	0.670116667	30.16915278	Grassland	27	1822
1	0.672452778	30.17292222	Woodland	25	1715
2	0.672361111	30.17290278	Woodland	25	1714
3	0.672413889	30.17301944	Woodland	25	1712

Study two was conducted in Kasese on Ferralsols (Figure 3.2). During the study period (December 2021 to November 2022) Kasese received 996 mm of total rainfall (Appendix 1.4). Four already existing land use types (annual, perennial, woodland, and grassland) on hilly slopes between 25% and 27% as classified by USDA were used (Table 3.2). Annual land use was comprised of maize

(*Zea mays*) monocrop, perennial land use was comprised of *Musa spp.* (bananas) that are mulched with banana leaves and banana fibres, woodlands were comprised of planted *Eucalyptus spp.* (eucalyptus) trees of 2-3 years old with an average height of 4m and the grasslands for this study were comprised of native grasses in the regions that are often grazed by livestock.

Table 3.2: Locational attributes of the land uses in Kasese under Ferralsols.

Runoff Plot	Location		Slope Land use	%	Altitude M
	°N	°E			
1	0.221527778	29.99254722	Annual	26	1541
2	0.221575	29.99254167	Annual	26	1541
3	0.221583333	29.99255556	Annual	26	1540
1	0.2191	29.99181667	Perennial	25	1580
2	0.219169444	29.99182222	Perennial	25	1577
3	0.219105556	29.99164444	Perennial	25	1578
1	0.217519444	29.994	Grassland	26	1579
2	0.217597222	29.99398611	Grassland	26	1576
3	0.217558333	29.99403056	Grassland	26	1575
1	0.21925	29.99460278	Woodland	27	1530
2	0.219305556	29.99463333	Woodland	27	1527
3	0.219211111	29.99471389	Woodland	27	1527

3.3 Soil characterisation and sampling

Digital soil maps downloaded from the Africa Soil Information Service (AFSIS)

(<https://www.isric.org/projects/africa-soil-information-service-afsis>) were used to locate the target each study are for each soil types (Ferralsols and Andosols). Using the attained GPS locations from the maps, four representative soil profile pits were dug and used to describe and classify soils following FAO guidelines for soil description (FAO, 2006) and World reference base for soil resources (WRB, 2024), respectively (Appendix 1.1).

A total of 144 disturbed soil samples of about 1kg were collected from the top soil (0-30cm) and sub soil (30-60cm) of each runoff plot. Thirty-six (36) undisturbed core samples were also collected from each horizon of the soil profile pits. Laboratory analysis was conducted on the soil samples to examine their physical and chemical attributes such as texture, organic matter, pH, nitrogen, phosphorus, potassium, sodium and calcium content following procedures described in Okalebo et al. (2002).

3.4 Assessing variations in soil erosion rates from agricultural land uses on sites under Ferralsols and Andosols (Objective 1)

To assess soil erosion rates, this study employed two methods: direct field measurement and predictive modelling. Direct, observed rates were obtained from standardized runoff plots, which physically capture and quantify the soil lost from a defined area during rainfall events. These observed rates were then compared to indirect, estimated rates calculated using the Revised Universal Soil Loss Equation (RUSLE), a widely applied model that predicts average annual soil loss by integrating key factors: rainfall erosivity, soil erodibility, slope topography, land cover, and conservation practices (Boix-Fayos et al., 2006; Karamage et al., 2017).

3.4.1 Runoff plots

Soil erosion rates were measured using closed runoff plots. Twenty-four (24) runoff plots measuring 15m x 2m were constructed, representing four land uses (annual, perennial, woodland and grassland), two soil types (Ferralsols and Andosols), and three replicates. Iron sheets, divisors, bricks, cement, sand, water, steel rods, and rubber pipes were used to construct the runoff plots (Figure 3.3). A collecting tank at the end of the runoff plots was used to collect the runoff, which was used to quantify the soil erosion rates (Boix-Fayos et al., 2006).

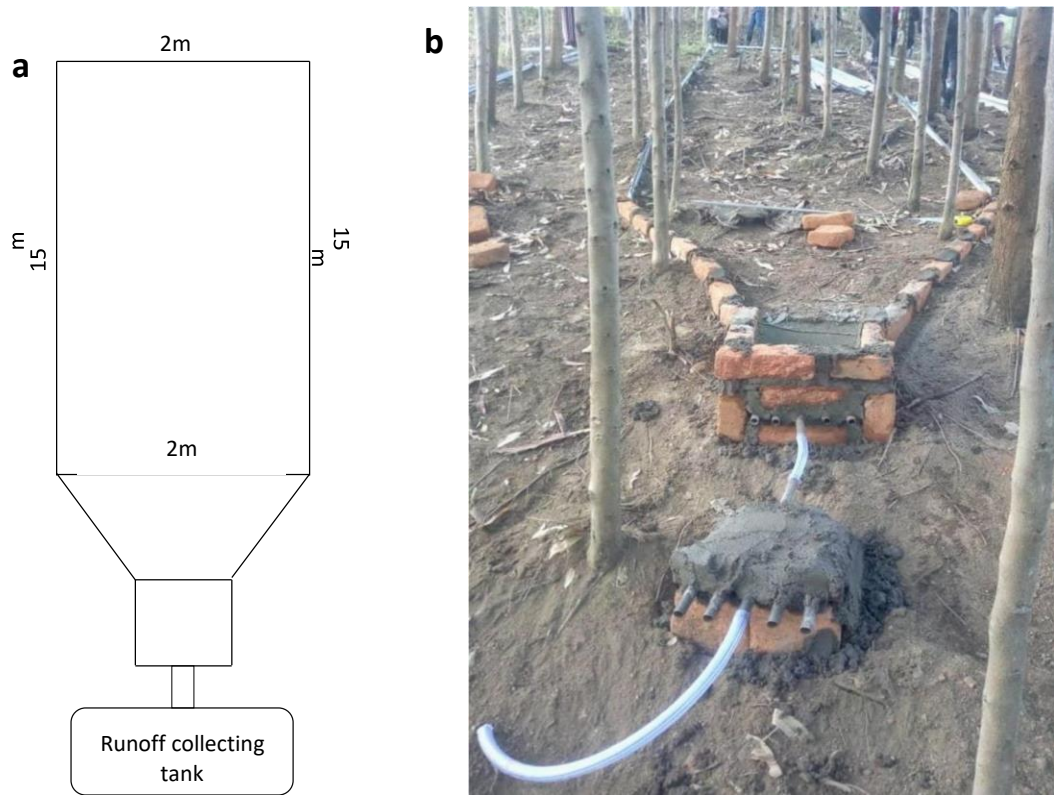


Figure 3.3: Illustration (a) and picture before connecting the pipe to a collecting tank (b) of the runoff plots constructed in this study to evaluate soil erosion rates

Data collection

Runoff samples were collected from the collecting tanks of the runoff plots. The runoff plots were constructed with divisors that connected to the collecting tanks. Divisors were used due to the potential high rainfall events that result in large volumes of runoff that cannot be collected in the tank. The divisors were fabricated and calibrated to collect runoff; each runoff plot was constructed with two divisors, each of which had 5 outlets of the same length and diameter. Calibration was done in the laboratory by mixing a known mass of dry soil into a known volume of water. The solution was then discharged into the collection channel that led to the divisors and the collecting tank. The volume of runoff collected was then measured, and the solution filtered. The residue was oven-dried to determine the collected soil mass, while the filtrate was used to determine the volume of water collected. The measured soil and water volume collected was multiplied by 10 (total number of outlets as a divisor) and then compared to the known total mass discharged and volume. The divisors were considered accurately calibrated when the collected mass and volume

consistently measured with ± 2 of the expected mass and volume. The runoff samples were collected from the runoff plots by a trained field assistant after every a rainfall event for a period of 12 months (from 1st December 2021 to 30th November 2022) and transported to the laboratory every 2 weeks. Measurements of runoff volume (litres), sediment concentration (g/l) and mass of dry soil (g) were made from each runoff plot.

Data analysis

Runoff samples were collected and taken to the laboratory for analysis. The volume of the samples was measured in a cylinder; samples were weighed on a weighing scale and filtered for separation. The residue was then oven-dried and weighed to get mass of dry soil (g); the mass of soil was used to quantify the soil erosion rates in $\text{tha}^{-1}\text{yr}^{-1}$. The mass of soil collected in the tank was subsequently multiplied by a factor of 10 to calculate the total estimated soil loss for the entire plot area. The data was subjected to a one-way analysis of variance (ANOVA) to compare variances across the land uses in the two soil types. Prior to using ANOVA, the basic assumptions of normality and homogeneity of variances were checked for using the Shapiro-Wilk test and the Levene's test, respectively. Least significant difference (lsd) test and Tukey's honestly significant difference post-hoc tests were used to compare means of sample groups and identify pairs of group means that were significantly different from each other. Box-and-whisker plots were used to explore and visualise a summary of statistics, including quartiles, medians, non-outlier ranges and outliers. Descriptive statistical analyses covering means, standard deviation, coefficient of variation and ranges were also conducted. These statistical analyses were conducted using the R Statistical programming software package version 4.3.2 and Microsoft Excel since they provide extensive quantitative statistical and data manipulation capabilities and are easy to use.

3.4.2 Revised Universal Soil Loss Equation, RUSLE

The RUSLE model was employed as another method to estimate soil erosion rates in selected land uses and soil types in Kasese and Kabarole districts. The RUSLE equation estimates soil erosion rates as a product of five input factors, namely soil erodibility (K), land cover management factor (C), slope-length and steepness (LS), support practice factor (P) and rainfall erosivity (R) (Wischmeier & Smith, 1978) (Equation 1).

$$A = K \times C \times LS \times P \times R \dots\dots\dots \text{Equation 1}$$

where A is the average soil erosion rate ($\text{tha}^{-1}\text{yr}^{-1}$); K is soil erodibility factor ($\text{Mg ha h ha}^{-1} \text{MJ}^{-1} \text{mm}^{-1}$); C is land cover management factor (dimensionless, ranging between 0 and 1); LS is slope length and steepness factor (dimensionless); P is support practice factor (dimensionless, ranging between 0 and 1); R is rainfall erosivity factor ($\text{MJ mm ha}^{-1} \text{h}^{-1} \text{yr}^{-1}$).

Rainfall erosivity (R)

Rainfall erosivity is the capacity of precipitation to induce soil erosion (Wang et al., 2024). Rainfall erosivity measures rainfall intensity and kinetic energy. Rain-drop size, distribution, terminal velocity, and rainfall duration influence the detachment of soil particles, their breakdown, and transportation, and therefore the rainfall erosivity (Wang et al., 2024).

In this study, a method based on annual rainfall proposed by Sholagberu et al. (2016) was used because of its simple equation, wide application range in tropical regions, and the ease of obtaining data. Annual precipitation that was observed from the rainfall stations in Kasese and Kabarole from 1st December 2021 to 30th November 2022 was used to estimate rainfall erosivity for the study, following the equation proposed by Sholagberu et al. (2016) (Equation 2).

$$R = 0.0003 * P^{1.771} \dots\dots\dots \text{Equation 2}$$

where R is the rainfall erosivity, and P is annual precipitation

Soil erodibility (K)

Soil erodibility defines the soils’ susceptibility to erosion by water (Ahaneku et al., 2024). It assesses how quickly soil will erode when subjected to erosive agents. Several factors, including soil organic matter content, permeability, soil structure, particle size distribution, shear strength, bulk density, and porosity, influence soil erodibility (Ahaneku et al., 2024).

Top soil (0 – 30cm) samples collected from the field study sites were analysed for soil texture and soil organic carbon. These properties were used to estimate soil erodibility by applying equations 3 to 7, as proposed by Williams and Renard (1983).

$$K = f_{sand} * f_{clay} * f_{OC} * f_{silt} * 0.1317 \dots\dots\dots \text{Equation 3}$$

$$\text{where } f_{sand} = \left[0.2 + 0.3 \exp \left(0.0256 * sand * \left(1 - \frac{silt}{100} \right) \right) \right] \dots\dots\dots \text{Equation 4}$$

$$\left(\frac{silt}{clay+silt} \right)^{0.3} \dots\dots\dots f_{clay} = \dots\dots\dots \text{Equation 5}$$

$$f_{OC} = \left(1 - \frac{0.25 * OC}{OC + \exp(3.72 - 2.95 * OC)} \right) \dots\dots\dots \text{Equation 6}$$

$$f_{silt} = \left[1 - \frac{0.7 \left(1 - \frac{sand}{100} \right)}{\left(1 - \frac{sand}{100} \right) + \exp \left(-5.51 + 22.9 * \left(1 - \frac{sand}{100} \right) \right)} \right] \dots\dots\dots \text{Equation 7}$$

K is the erodibility factor; 0.1317 is the value used to convert the K factor from the American system to the metric International System of Units; Sand, silt, and clay are percentages of sand, silt, and clay in the top soil, respectively; and OC is the percentage organic carbon content in the topsoil.

Slope length and steepness factor (LS)

The combined slope length and steepness (LS) factor includes the S-factor, which assesses the influence of slope gradient, and the L-factor, which reflects the effect of slope length. Together, the LS factor illustrates how topography affects soil erosion (Bamutaze et al., 2021; Karamage et al., 2017; Ssewankambo et al., 2023).

In this study, the slope lengths, together with the slope gradients of the of the runoff plots in the study sites were used to compute the LS factor. The slope length and gradient were used estimate the slope-length factor by applying equations 8 to 11, as proposed by Renard et al. (1997).

$$L = \left(\frac{\lambda}{72.6} \right)^m \dots\dots\dots \text{Equation 8}$$

where L is the slope length factor and λ

is slope length (ft)

$$m = \frac{\beta}{1 + \beta} \dots \dots \dots \text{Equation 9}$$

$$\beta = \frac{\text{Sin}\theta / 0.0896}{3 (\text{Sin}\theta)^{0.8} + 0.56} \dots \dots \dots \text{Equation 10}$$

$$S = \begin{cases} 10.8 \times \text{Sin}\theta + 0.03; & \text{if slope is } < 9\% \\ 16.8 \times \text{Sin}\theta - 0.50; & \text{if slope is } \geq 9\% \end{cases} \dots \dots \dots \text{Equation 11}$$

where S is the slope steepness factor and θ is the slope angle in degrees.

Land cover management (C)

The C factor measures the combined effect of all land cover, crops, and crop management practices in a land area on soil erosion rates (Karamage et al., 2017; Xiong et al., 2023).

This study assigned C values to different land uses in the study sites (perennial, woodland, annual and grasslands) where runoff plots were constructed (Table 3.3) according to existing literature (David, 1988; Morgan, 2005; Wang et al., 2016).

Table 3.3: C factors for different land uses (David, 1988; Morgan, 2005; Wang et al., 2016).

Land Use	C value
Woodland	0.05
Bananas (perennial)	0.20
Maize (annual)	0.50
Grassland	0.10

Support practice factor (P)

The support practice factor indicates how soil and water conservation methods, such as strip cropping, terracing, contouring, soil or stone bunding, and trenches, affect soil erosion rates

(Bamutaze et al., 2021). Soil and water conservation efforts help protect soil and decrease the rate of soil erosion.

The P factor values range from 0 to 1, with 1 representing minimal or no support practices and 0 indicating efficient support practices (Wischmeier & Smith, 1978). In this study given that the slope angle was greater than 20%, and there were no substantial erosion control practices in the land uses at the study sites, a P value of 1 was considered.

Annual Soil Loss (A) ($\text{tha}^{-1}\text{yr}^{-1}$)

Soil erosion rates of the land uses in the study sites were estimated by multiplying the five factors i.e. soil erodibility (K), support practice factor (P), rainfall erosivity (R), land cover management factor (C) and slope length and steepness factor (LS) (Equation 12):

$$A = K * P * R * C * LS \dots \dots \dots \text{Equation 12}$$

Data analysis

The estimated erosion rates data was subjected to a one-way analysis of variance (ANOVA) to compare variances across the land uses in the two soil types. Prior to using ANOVA, the basic assumptions of normality and homogeneity of variances were checked for using the Shapiro-Wilk test and the Levene's test, respectively. Least significant difference (LSD) test and Tukey's honestly significant difference post-hoc tests were used to compare means of sample groups and identify pairs of group means that were significantly different from each other. Box-and-whisker plots were used to explore and visualise a summary of statistics, including quartiles, medians, nonoutlier ranges and outliers. Descriptive statistical analyses covering means, standard deviation, coefficient of variation and ranges were also conducted. These statistical analyses were conducted using the R Statistical programming software package version 4.3.2 and Microsoft Excel since they provide extensive quantitative statistical and data manipulation capabilities and are easy to use.

3.5 Determining the soil loss tolerance thresholds of Ferralsols and Andosols under different agricultural land uses (Objective two)

Data collection

A method developed by the USDA-NRCS (1999) was used to estimate the soil loss tolerance thresholds. This method estimates the tolerance thresholds using favourable rooting depth, biophysical soil properties, and soil quality attributes related to the soil's capacity to prevent erosion (Mandal & Sharda, 2011). Five soil functions representing their impact on soil erosion were selected. These functions include promoting water entry and transfer, water retention, resistance to physical and biochemical degradation, and the capacity to support plant growth and ground stability cover (Chandel & Hadda, 2018; Lenka et al., 2014; Mandal & Sharda, 2011). Specific indicator soil properties were identified for each soil function; the soil functions were used to derive integrated indices based on weights for each selected indicator soil property (Lenka et al., 2014) (Table 3.4).

Table 3.4: Indicators of each soil function with their corresponding weights (Lenka et al., 2014).

Function	Indicator	Weight
Facilitate water entry and transfer	Infiltration rate	0.35
Resist physical degradation	Soil erodibility	0.25
Resist biochemical degradation	Organic carbon	0.15
Sustain plant growth and ground cover	pH	0.15
Water transport and retention	Bulk density	0.10
Total score		1.00

Soil augers and soil profile pits were used in each land use to determine the favourable rooting depth (Appendix 1.2). Favourable rooting depth is the depth of soil that is evident of root growth and permits unimpeded root development, with no restrictive layers limiting root growth (Lenka et al., 2014). Infiltration rate was measured in the field using the auger hole method. Forty-eight (48) soil samples were collected from the 0-30 cm depth of each land use, including disturbed and undisturbed samples. The disturbed soil samples were analysed for pH using a pH meter, organic carbon using loss on ignition method, texture using the hydrometer method, and soil erodibility was determined from particle size distribution while the undisturbed soil core samples were analysed for bulk density (Okalebo et al., 2002).

Transformation of measured soil parameters

The measured soil parameters (infiltration rate, soil erodibility, soil organic carbon, pH and bulk density) were transformed into dimensionless scores of values between 0 and 1 using equations 13 and 14 (Lenka et al., 2014).

Equation 17 was used to transform infiltration rate, soil organic carbon and pH.

$$q(x_i) = [1 / (1 + \{(x_i - b_1 - d_1)/d_1\}^2)] \dots\dots\dots\text{Equation 13}$$

where $q(x_i)$ is the individual membership function for the i th soil property x , x is the measured soil parameter, $b_1 = 3.0$, $d_1 = 2.0$

Equation 18 was used to transform bulk density and soil erodibility.

$$q(x_i) = [1 / (1 + \{(x_i - b_2 + d_2)/d_2\}^2)] \dots\dots\dots\text{Equation 14}$$

where $q(x_i)$ is the individual membership function for the i th soil property x , x is the measured soil parameter, $b_2 = 2.0$, $d_2 = 1.0$

The transformed values were then multiplied by their respective weights (Table 3.4) and aggregated to quantify the state of soil (Q) for each soil using equation 15 (Lenka et al., 2014; Mandal & Sharda, 2011).

$$Q = q_{ir}w_{ir} + q_k w_k + q_{bd}w_{bd} + q_{oc}w_{oc} + q_{pH}w_{pH} \dots\dots\dots\text{Equation 15}$$

where Q is the quantified state of the soil, q_{ir} is the rating for infiltration rate, q_k is the rating for soil erodibility, q_{bd} is the rating for bulk density, q_{oc} is the rating for organic carbon, q_{pH} is the rating for pH, w_{ir} is the weight for infiltration rate, w_k is the weight for soil erodibility, w_{bd} is the weight for bulk density, w_{oc} is the weight for organic carbon, and w_{pH} is the weight for pH

Using the quantified state of the soil (Q) and measured favourable rooting depth/soil depth, soil loss tolerance thresholds (T-values) were calculated based on values from Table 3.5 (Lenka et al., 2014; Mandal & Sharda, 2011).

Table 3.5: Soil Loss Tolerance Thresholds based on soil depth and quantified soil state (Q) (Lenka et al., 2014).

Soil depth (cm)	Annual Soil Loss Tolerance Threshold; T-values ($\text{tha}^{-1}\text{yr}^{-1}$)		
	Group 1; $Q < 0.33$	Group 2; $0.33 < Q < 0.66$	Group 3; $Q > 0.66$
0 – 25	2.5	2.5	7.5
25 – 50	2.5	5.0	7.5
50 – 100	5.0	7.5	10.0
100 – 150	7.5	10.0	12.5
>150	12.5	12.5	12.5

Data analysis

The soil loss tolerance thresholds for different soil types and land uses was analysed using the Kruskal-Wallis’s test, a non-parametric alternative to one-way ANOVA, as the data violated assumptions of normality and homogeneity of variance. The Kruskal-Wallis test accommodates the Dunn’s non-parametric post-hoc test at a 5% significant level which identifies statistically significant pairwise differences between group means. Differences between soil erosion rates and tolerance thresholds were calculated to assess the status of the soils. Multiple regression analysis was carried out to analyse the sensitivity of the parameters used to estimate soil tolerance rates. These statistical analyses were conducted using the R Statistical programming software package version 4.3.2 and Microsoft Excel since they provide extensive quantitative statistical and data manipulation capabilities and are easy to use.

CHAPTER FOUR

RESULTS

4.1 Soil erosion rates in Andosols and Ferralsols under four land uses (annual, perennial, grassland and woodland).

4.1.1 Case study one on Andosols in Kabarole district, Rwenzori highlands (Objective 1)

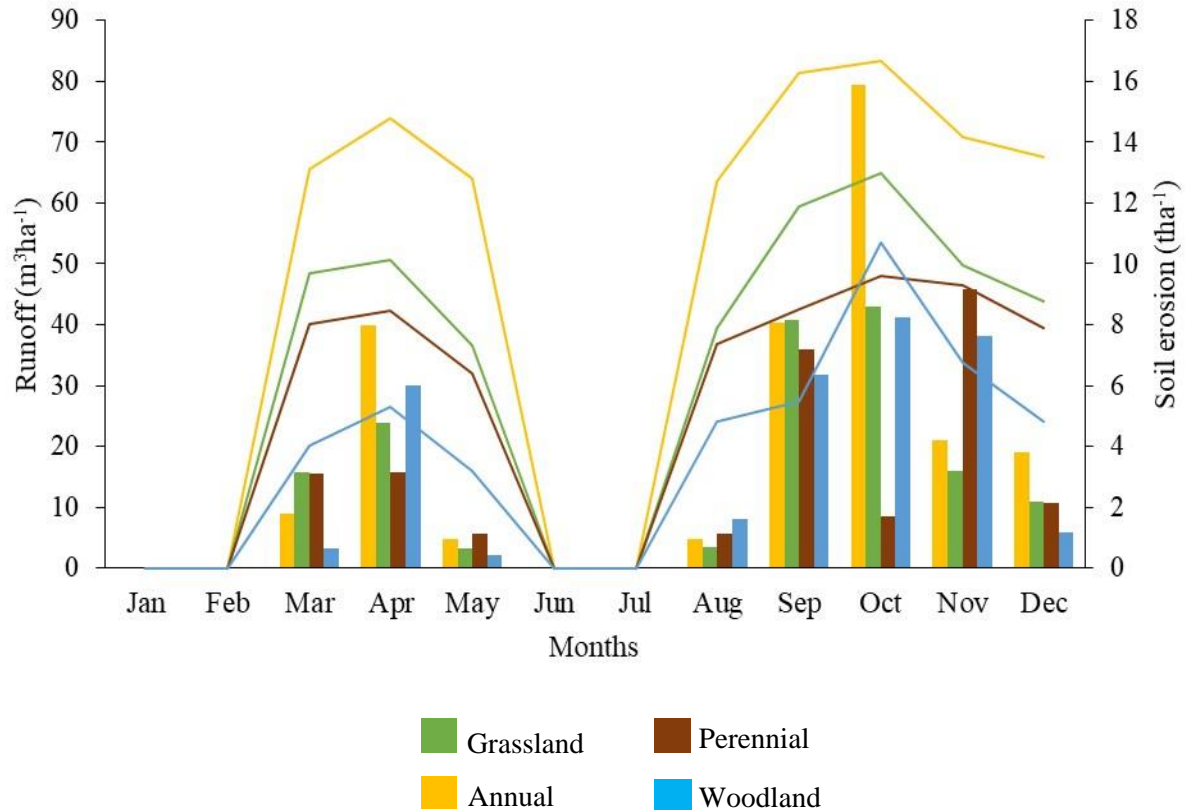
Soil physical and chemical properties: Generally, soils were mainly sandy loam, with high N levels (0.07 – 0.32%), fair amounts of soil organic matter (SOM) ranging from 1.2% - 4.8% and a pH

range of 5.1 – 7.2. The soils were, however, found to have low levels (0.11 – 0.31cmol/kg and 1.0 – 9.8mg/kg) of potassium and phosphorus respectively (Table 4.1).

Table 4.1: Soil test results of samples collected from four land uses under Andosols (Kabarole district).

Plot	Depth	pH (H ₃ O ⁺)	SOM	Available P	Total N	Exchangeable K	Na ⁺	Ca ²⁺	Mg ²⁺	Sand	Clay	Silt	Textural Class	
														cm
Woodlands	1	0-30	6.7	1.9	2.15	0.17	0.27	0.16	5.85	0.71	70	18	12	Sandy Loam
	1	30-60	6.4	1.3	7.7	0.12	0.20	0.14	5.40	0.58	70	22	8	SandyClayLoam
	2	0-30	6.4	3.1	1.1	0.17	0.31	0.16	5.40	0.53	74	16	10	Sandy Loam
	2	30-60	7.2	2.1	9.8	0.13	0.17	0.07	6.75	0.74	74	16	10	Sandy Loam
	3	0-30	6.6	2.1	1.17	0.14	0.31	0.23	4.95	0.63	70	22	8	SandyClayLoam
	3	30-60	6.6	2.1	1.17	0.13	0.14	0.09	5.40	0.54	74	18	8	Sandy Loam
Annual	1	0-30	5.5	1.2	1.17	0.08	0.17	0.14	4.05	0.46	68	20	12	SandyClayLoam
	1 2	30-60	6.1	1.4	1.00	0.13	0.18	0.21	5.25	0.68	66	28	6	SandyClayLoam
	2	0-30	5.4	1.2	1.11	0.07	0.14	0.18	4.20	0.42	68	18	14	Sandy Loam
		30-60	6.1	1.9	1.89	0.32	0.20	0.16	5.70	0.56	60	28	12	SandyClayLoam
	3	0-30	6.1	1.7	1.02	0.11	0.14	0.12	5.70	0.52	70	22	8	SandyClayLoam
	3	30-60	5.6	1.4	1.91	0.08	0.15	0.14	4.05	0.44	70	18	12	Sandy Loam
Grassland	1 1	0-30	6.2	4.8	4.74	0.29	0.29	0.21	5.10	0.66	60	26	14	SandyClayLoam
	2 2	30-60	5.3	3.3	1.49	0.21	0.11	0.16	4.80	0.58	62	24	14	SandyClayLoam
		0-30	6.0	2.9	2.65	0.17	0.25	0.16	5.80	0.63	60	30	10	SandyClayLoam
		30-60	6.1	2.1	5.77	0.13	0.11	0.14	5.10	0.63	64	20	16	SandyClayLoam
	3	0-30	6.4	1.9	8.76	0.12	0.20	0.23	6.00	0.71	60	26	14	SandyClayLoam

	3	30 – 60	6.2	3.1	2.05	0.19	0.18	0.09	5.40	0.60	62	26	12	SandyClayLoam
	1	0 -30	5.4	2.9	8.14	0.18	0.28	0.16	4.2	0.46	64	26	10	SandyClayLoam
Perennial	1	30 – 60	5.1	1.9	2.00	0.12	0.20	0.12	5.3	0.54	70	20	10	SandyClayLoam
	2	0 – 30	5.9	1.9	6.47	0.11	0.29	0.25	5.6	0.70	60	28	12	SandyClayLoam
	2	30 – 60	5.7	1.2	2.48	0.08	0.18	0.23	4.4	0.45	60	24	16	SandyClayLoam
	3	0 – 30	6.1	1.4	1.07	0.08	0.28	0.14	5.6	0.57	64	26	10	SandyClayLoam
	3	30 – 60	5.8	3.3	1.31	0.21	0.25	0.09	5.1	0.66	56	32	12	SandyClayLoam



4.1.2 Runoff and soil erosion rates in Andosols under four land uses (annual, perennial, grassland and woodland) in Kabarole district.

The highest runoff volume was generally observed in the rainy seasons March to May (first rainy season) and September to November (second rainy season). Generally, the lowest runoff volumes were collected from woodlands and the highest from annual land use. Annual land use consistently yielded the highest runoff volumes and erosion rates, with distinct peaks observed in April (first rainy season) and October (second rainy season) (Fig. 4.1).

Figure 4.1: Runoff (bar graph) and soil erosion rates (line graph) of Andosols in annual, woodland, grassland and perennial land uses.

4.1.3 Soil erosion rates of Andosols under four land uses (annual, perennial, woodland and grassland) using runoff plots in Kabarole District.

The one-way ANOVA revealed that there was no significant effect of the land uses on soil erosion rates under Andosols. The mean soil erosion rates in annual land use were higher than the soil erosion rates in woodland, grasslands and perennial land uses in Andosols (Table 4.2). Annual land use had the highest mean soil erosion rate of $(14.21 \pm 2.15) \text{ t ha}^{-1}\text{yr}^{-1}$ due to the tillage practices and soil surface exposure that characterised this land use in the study, whereas woodlands had the lowest mean soil erosion rate of $(7.06 \pm 3.78) \text{ t ha}^{-1}\text{yr}^{-1}$ due to the constant vegetation cover and standing canopy in the land use that intercepts rainfall (Table 4.2).

Table 4.2: The effect of land use on the soil erosion rates under Andosols in Kabarole district

Land Use	Mean \pm SD	Range	Confidence interval
			(95%)
(t ha ⁻¹ yr ⁻¹)			
Annual	14.21 \pm 2.15	12.70 - 16.67	10.59 – 17.84
Grassland	9.92 \pm 2.86	7.32 - 12.98	0.83 – 9.42
Perennial	8.03 \pm 1.61	6.40 - 9.61	1.06 – 11.31
Woodland	7.06 \pm 3.78	3.18- 10.72	2.02– 12.27
p value		0.0501	
LSD		5.13	
CV%		27.76	

LSD = Least Significant Difference; CV (%) = Coefficient of Variation.

4.1.4 Estimated soil erosion rates of Andosols using the Revised Universal Soil Loss Equation in Kabarole district

While using the RUSLE, the one-way ANOVA revealed that there was a significant effect of the land uses on soil erosion rates under Andosols (Table 4.3). Tukey's honestly significant difference (Tukey's HSD) test at a 5% significant level and LSD test revealed that the mean estimated soil erosion rates in annual land use were significantly higher than the soil erosion rates in woodlands, grasslands and perennial land uses in Andosols (Table 4.3). Annual land use had the highest estimated mean soil erosion rate of (78.33 ± 5.36) $\text{tha}^{-1}\text{yr}^{-1}$, whereas grasslands had the lowest estimated mean soil erosion rate of (9.46 ± 1.01) $\text{tha}^{-1}\text{yr}^{-1}$ (Table 4.3).

Table 4.3: Estimated soil erosion rates of land uses under Andosols in Kabarole district

Land Use	Mean \pm SD	Range	Confidence interval
			(95%)
(t $\text{ha}^{-1}\text{yr}^{-1}$)			
Annual	78.33 ± 5.36^a	72.22 – 82.30	73.87 – 82.78
Grassland	9.46 ± 1.01^c	8.87 – 10.63	62.57 – 75.16
Perennial	37.63 ± 3.82^b	34.47 – 41.87	34.40 – 47.00
Woodland	10.90 ± 0.60^c	10.50 – 11.59	61.13 – 73.72
p value		<0.001	
LSD		6.30	
CV%		9.81	

Means within a column followed by different superscript letters are different from each other as revealed by Tukey's HSD and lsd post-hoc tests, lsd = least significant difference; CV (%) = Coefficient of variation.

4.1.5 Case study two on Ferralsols in Kasese district, Rwenzori highlands (Objective 1) Soil physical and chemical properties: Generally, soils were mainly sandy clay loam, with high N levels

(0.07 – 0.31), fair amounts of soil organic matter (SOM) ranging from 1.0% - 3.8% and a pH range of 4.5 – 7.4. The soils were, however, found to have low levels (0.06 – 0.28cmol/kg and 0.43 – 2.77mg/kg) of potassium and phosphorus, respectively (Table 4.4).

Table 4.4: Soil test of soil samples collected from four land uses under Ferralsols in Kasese district.

Plot	Depth	pH(H_3O^+)	SOM	Available P	Total N	Exchangeable K	Na ⁺	Ca ²⁺	Mg ²⁺	Sand	Clay	Silt	Textural Class	
	cm		%	mg/kg	%		cmol/kg			%				
Woodlands	1	0-30	4.5	1.7	2.22	0.21	0.15	0.09	4.05	0.47	64	24	12	SandyClayLoam
		30-60	6.2	3.3	0.55	0.2	0.10	0.25	5.4	0.63	70	20	10	SandyClayLoam
		0-30	5.7	3.1	1.99	0.19	0.28	0.28	4.35	0.49	64	26	10	SandyClayLoam
		30-60	5.9	1.7	1.37	0.11	0.21	0.12	5.85	0.61	66	26	8	SandyClayLoam
1	0-30	7.4	2.2	1.44	0.13	0.20	0.18	6.15	0.68	64	28	8	SandyClayLoam	
2														
3														
3	30-60	5.4	1.0	0.90	0.07	0.15	0.18	4.05	0.47	64	28	8	SandyClayLoam	
1	0-30	5.7	1.7	1.07	0.09	0.15	0.09	4.7	0.52	64	24	12	SandyClayLoam	
1	30-60	6.1	1.0	0.86	0.07	0.08	0.09	5.6	0.59	64	26	10	SandyClayLoam	
Annual	0-30	5.9	1.9	1.25	0.22	0.13	0.12	4.2	0.5	64	24	12	SandyClayLoam	
	30-60	5.6	1.3	1.25	0.19	0.13	0.12	4.5	0.52	60	28	12	SandyClayLoam	
2	30-60	5.6	1.3	1.25	0.19	0.13	0.12	4.5	0.52					
3	0-30	5.8	3.6	1.44	0.21	0.13	0.14	4.4	0.45	60	24	16	SandyClayLoam	
3	30-60	7.3	1.7	2.15	0.11	0.06	0.16	6.6	0.65	64	26	10	SandyClayLoam	

Grassland	1	0-30	4.8	1.9	2.69	0.12	0.15	0.16	3.75	0.53	70	20	10	SandyClayLoam
		30-60	6.3	1.7	0.47	0.09	0.11	0.09	5.55	0.63	68	20	12	SandyClayLoam
		0-30	6.2	2.4	1.60	0.14	0.27	0.18	5.40	0.61	74	18	8	Sandy Loam
		30-60	6.5	1.4	1.13	0.09	0.11	0.14	6.00	0.56	62	26	12	SandyClayLoam
	1 2													
	2													
	3	0-30	5.8	1.4	1.83	0.19	0.10	0.07	3.90	0.51	66	22	12	SandyClayLoam
	3	30-60	5.8	3.6	0.43	0.21	0.11	0.18	4.20	0.54	62	22	16	SandyClayLoam
Perennial	1	0-30	5.8	3.1	2.07	0.18	0.24	0.18	4.5	0.49	58	28	14	SandyClayLoam
		30-60	5.7	3.8	1.14	0.2	0.11	0.12	5.1	0.53	68	24	8	SandyClayLoam
		0-30	6.8	2.6	2.54	0.16	0.22	0.05	5.3	0.62	64	28	8	SandyClayLoam
		30-60	6.2	1.9	2.77	0.13	0.28	0.23	5.9	0.67	60	26		SandyClayLoam
		1 2											14	
		2												
	3	0-30	6.1	1.7	1.87	0.31	0.25	0.09	5.6	0.57	60	28	12	SandyClayLoam
	3	30-60	6.5	1.9	1.44	0.12	0.11	0.12	5.3	0.61	58	28	14	SandyClayLoam

4.1.6 Runoff and soil erosion rates in Ferralsols under four land uses (annual, perennial, grassland and woodland) in Kasese the Rwenzori highlands of Uganda

High runoff volumes were collected in the first rainy season from January to March (Figure 4.2). Generally, the highest runoff volumes were observed in perennial and annual land uses, whereas the lowest runoff volumes were observed in woodlands (Figure 4.2). Similarly, the highest erosion rates were observed in the first rainy season. Annual land use recorded the highest soil erosion rates with the highest soil erosion rate was recorded in February, whereas woodlands recorded the lowest soil erosion rates (Figure 4.2).

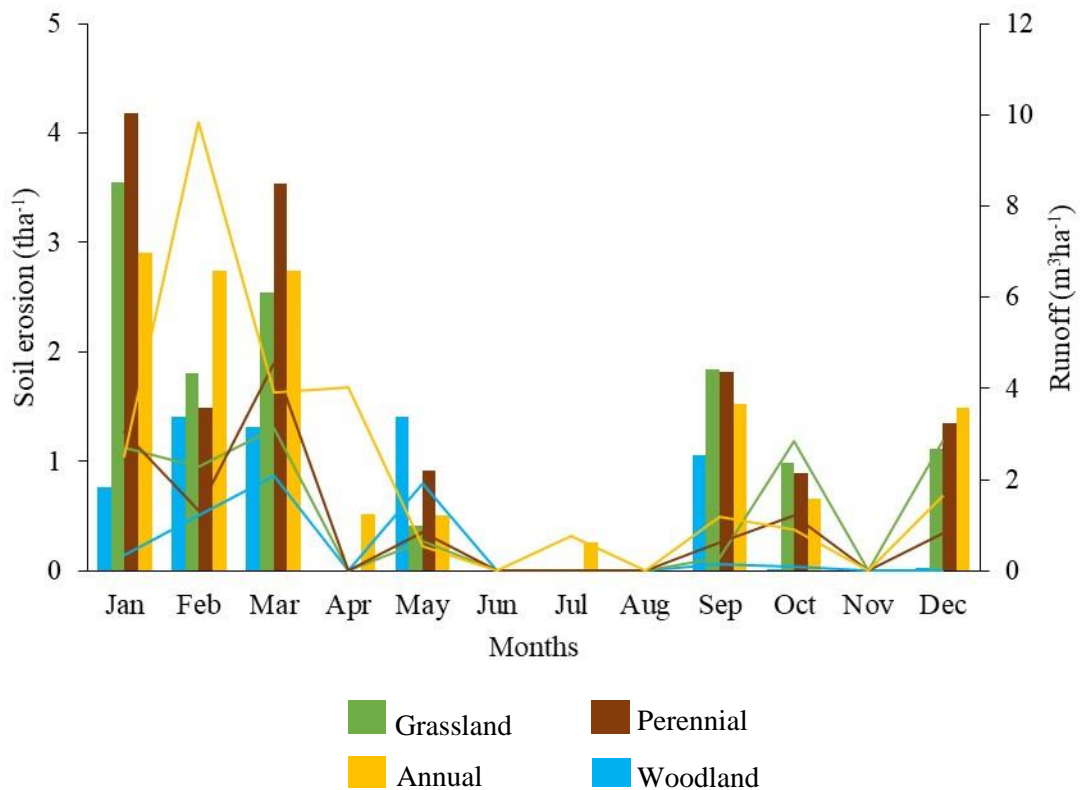


Figure 4.2: Runoff (bar graph) and soil erosion rates (line graph) of Ferralsols in annual, woodland, grassland and perennial land uses.

4.1.7 Soil erosion rates of Ferralsols under four land uses (annual, perennial, woodland and grassland) using runoff plots

The one-way ANOVA revealed that there was no significant effect of land use on soil erosion rates under Ferralsols (Table 4.5). The mean soil erosion rates in annual land use were higher than the soil erosion rates in woodland, grasslands and perennial land uses in Ferralsols (Table 4.5). Annual land use had the highest mean soil erosion rate of $(8.50 \pm 1.26) \text{ tha}^{-1}\text{yr}^{-1}$ due to the till age practices and soil surface exposure that characterised this land use in the study, whereas woodlands had the lowest mean soil erosion rate of $(4.49 \pm 2.05) \text{ tha}^{-1}\text{yr}^{-1}$ due to the constant vegetation cover and standing canopy in the land use that intercepts rainfall (Table 4.5).

Table 4.5: Effect of land use on the soil erosion rates under Ferralsols in the Rwenzori highlands

Land Use	Mean \pm SD	Range Confidence interval (95%)	
		(tha-1yr-1)	
Annual	8.50 ± 1.26	7.45 – 9.90	6.13 – 10.86
Grassland	4.59 ± 1.34	3.18 – 5.85	0.55 – 7.25
Perennial	6.11 ± 2.26	4.49 – 8.69	0.96 – 5.74
Woodland	4.49 ± 2.05	2.16 – 6.01	0.66 – 7.34
P value		0.078	
LSD		3.35	
CV%		30.06	

LSD = Least Significant Difference; CV (%) = Coefficient of Variation.

4.1.8 Estimated soil erosion rates of Ferralsols using the Revised Universal Soil Loss Equation

While using the RUSLE, the one-way ANOVA revealed that there was a significant effect of the land uses on soil erosion rates under Ferralsols (Table 4.6). Tukey's honestly significant difference (Tukey's HSD) test at a 5% significant level and LSD test revealed that the mean estimated soil erosion rates in annual land use were significantly higher than the soil erosion rates in woodlands, grasslands and perennial land uses in Andosols (Table 4.6). Annual land use had the highest estimated mean soil erosion rate of $(40.61 \pm 5.57) \text{ t ha}^{-1}\text{yr}^{-1}$ whereas woodlands had the lowest estimated mean soil erosion rate of $(2.52 \pm 0.26) \text{ t ha}^{-1}\text{yr}^{-1}$ (Table 4.6).

Table 4.6: Estimated soil erosion rates of land uses under Ferralsols in Kasese district

Land Use	Mean \pm SD	Range	Confidence interval
			(95%)
(t ha ⁻¹ yr ⁻¹)			
Annual	40.61 \pm 5.57 ^a	34.22 – 44.43	36.74 – 44.49
Grassland	9.55 \pm 0.20 ^c	9.32 – 9.69	36.54 – 25.58
Perennial	16.19 \pm 1.65 ^b	14.53 – 17.82	18.95 – 29.91
Woodland	2.52 \pm 0.26 ^d	2.30 – 2.81	32.62 – 43.58
p value		<0.001	
LSD		5.48	
CV%		16.91	

Means within a column followed by different superscript letters are different from each other as revealed by Tukey's HSD and lsd post-hoc tests, lsd = least significant difference; CV (%) = Coefficient of variation.

4.2 Soil loss tolerance thresholds of Andosols and Ferralsols under four land uses (annual, perennial, woodland and grassland).

4.2.1 Sensitivity analysis of the parameters used to measure soil loss tolerance thresholds.

Multiple regression analysis was done to test for the sensitivity of the factors (bulk density, soil infiltration rate, soil erodibility, pH, organic carbon and rooting depth) that are used to compute the soil loss tolerance thresholds (Table 4.7). The models revealed that tolerance thresholds are most sensitive to rooting depth, and the linear model including all the parameters and rooting depth explained up to 69% of the T-values attained (Table 4.7). The models, including rooting depth, significantly ($p < 0.05$) influenced the derivation of T-values in this study (Table 4.7). This however, also informs us that other factors that were not used and included in this study can be used to calculate the soil loss tolerance thresholds.

Table 4.7: Sensitivity analysis of the soil properties and rooting depth on soil loss tolerance thresholds.

Model	F-statistic	P value	Multiple R ²	Adjusted R ²
Model 1	1.145	0.352	0.12	0.015
Model 2	14.71	7.02e-09	0.683	0.637
Model 3	10.38	3.43e-08	0.76	0.687

Where; Model 1 only uses soil properties (bulk density, infiltration rate, soil erodibility, pH and organic carbon), Model 2 only uses rooting depth and Model 3 uses both soil properties (bulk density, infiltration rate, soil erodibility, pH and organic carbon) and rooting depth.

4.2.2 Case study one on Andosols in Kabarole district, Rwenzori highlands (Objective 2). The Kruskal-Wallis's test revealed that there was a significant effect ($p < 0.05$) of the land uses on soil loss tolerance thresholds under Andosols (Table 4.8). The Dunn's post-hoc test revealed that woodlands and grasslands had the significantly highest tolerance thresholds in Andosols (Table 4.8). Descriptive statistics to understand the risk of degradation the land uses have if the erosion rates exceed the soil loss tolerance thresholds were done. Annual land use was found to have erosion rates that exceed the tolerance thresholds; therefore, these soils are at risk of loss of productivity (Table 4.8). Even though woodlands, grasslands, and perennial land uses were found to have erosion rates less than the tolerance thresholds, their sustainability cannot be guaranteed due to the small margin of exceedance that is observed (Table 4.8).

Table 4.8: Soil loss tolerance thresholds of Andosols under four land uses.

	Land Use	Tolerance threshold	Erosion rates	Risk of degradation
		Mean \pm s.d	Mean \pm s.d	
		(tha ⁻¹ yr ⁻¹)		
Annual	8.33 \pm 1.29 ^a	14.21 \pm 2.15		Yes
Grassland	11.67 \pm 1.29 ^b	9.92 \pm 2.86		No
Perennial	8.75 \pm 1.37 ^{ac}	8.03 \pm 1.61		No
Woodland	11.25 \pm 1.37 ^{bc}	7.06 \pm 3.78		No

Kruskal-Wallis's test; p-value = 0.0034 **

Means within a column followed by different superscript letters are different from each other as revealed by Dunn's post-hoc test, s.d = Standard Deviation

4.2.3 Case study two on Ferralsols in Kasese district, Rwenzori highlands (Objective 2).

The Kruskal-Wallis's test indicated a significant difference ($p < 0.05$) among land use types under Ferralsols (Table 4.9). However, Dunn's post hoc test did not find any specific pairwise comparisons to be statistically significant. Grasslands were found to have the highest tolerance thresholds in Ferralsols of $8.75 \pm 1.37 \text{ t ha}^{-1} \text{ yr}^{-1}$ (Table 4.9). Descriptive statistics used to assess the risk of degradation and loss of productivity revealed that annual land use had soil erosion rates exceeding the tolerance thresholds (Table 4.9). Although soil erosion rates in annual land use were the only ones exceeding the tolerance thresholds, the risk of the grasslands, woodlands and perennial land uses to lose productivity is close due to the very small margin left for the erosion rates to exceed the tolerance thresholds (Table 4.9).

Table 4.9: Soil loss tolerance thresholds of Ferralsols under four land uses.

Land Use	Tolerance threshold	Erosion rates	
	Risk of degradation		
	Mean \pm s.d	Mean \pm s.d	
	($\text{t ha}^{-1} \text{ yr}^{-1}$)		
Annual	$6.67 \pm 1.29^{\text{ab}}$	8.50 ± 1.26	Yes
Grassland	$8.75 \pm 1.37^{\text{a}}$	4.59 ± 1.34	No
Perennial	$6.25 \pm 1.37^{\text{b}}$	6.11 ± 2.26	No
Woodland	$8.33 \pm 1.29^{\text{ab}}$	4.49 ± 2.05	No

Kruskal-Wallis test; p -value = 0.0189 *

Means within a column followed by different superscript letters are different from each other as revealed by Dunn's post-hoc test, s.d = standard deviation **CHAPTER FIVE**

DISCUSSION

5.1 Soil erosion rates of Andosols and Ferralsols under woodlands, grasslands, perennial and annual land uses

The highest soil erosion rates measured in this study using runoff plots occurred in annual land use on Andosols ($14.21 \text{ t ha}^{-1} \text{ yr}^{-1}$). In contrast, the lowest measured rates were observed in woodlands

on Ferralsols ($4.49 \text{ t ha}^{-1} \text{ yr}^{-1}$). When expressed over the active six-month period of the two annual rainy seasons, these observed rates equate to approximately $31 \text{ kg acre}^{-1} \text{ day}^{-1}$ and $9.8 \text{ kg acre}^{-1} \text{ day}^{-1}$ for annuals on Andosols and woodlands on Ferralsols, respectively. While using the Revised Universal Soil Loss Equation (RUSLE), soil loss rates estimated were substantially highest for annuals on Andosols ($78.33 \text{ t ha}^{-1} \text{ yr}^{-1}$) and lowest for woodlands on Ferralsols ($2.52 \text{ t ha}^{-1} \text{ yr}^{-1}$). Projected over the six-month rainy season in a year, these RUSLE estimates correspond to approximately $173.1 \text{ kg acre}^{-1} \text{ day}^{-1}$ and $5.6 \text{ kg acre}^{-1} \text{ day}^{-1}$, respectively. The disparity between observed soil loss from runoff plots and estimations from the Revised Universal Soil Loss Equation (RUSLE) highlights the inherent challenges in scaling empirical models to site-specific field measurements.

A national-scale soil erosion risk assessment for Uganda by Karamage et al. (2017) utilised the RUSLE model to identify critical erosion hotspots. Their study estimated a national mean soil loss of $3.2 \text{ t ha}^{-1} \text{ yr}^{-1}$ across erosion-prone landscapes. Regionally, they reported an overall mean soil loss of $37.5 \text{ t ha}^{-1} \text{ yr}^{-1}$ for Kasese (mean slope: 19.9%) and $6.4 \text{ t ha}^{-1} \text{ yr}^{-1}$ for Kabarole (mean slope: 18.6%). However, these rates are generalised averages across all land uses and soil types within the specified districts (Karamage et al., 2017). Consequently, while valuable for national prioritisation, such aggregated estimates do not elucidate the specific erosion threats associated with discrete land use and soil type combinations, which is a key refinement provided by this study.

When comparing land-use categories, Karamage et al. (2017) reported mean erosion rates of 2.4, 1.2, 5.3, and $2.7 \text{ t ha}^{-1} \text{ yr}^{-1}$ for annual land use, perennial land use, grasslands, and woodlands, respectively. Karamage et al. (2017) estimated erosion rates for woodlands align closely with the RUSLE-derived estimate for woodlands on Ferralsols in this study ($2.52 \text{ t ha}^{-1} \text{ yr}^{-1}$). However, their estimates for other land uses (annual, perennial and grasslands) are lower than the corresponding RUSLE estimates generated in this study.

Within this study, observed erosion rates in perennial land use (bananas) under Ferralsols and Andosols while using runoff plots were 6.11 and $8.03 \text{ t ha}^{-1} \text{ yr}^{-1}$ respectively. This finding contrasts

with the work of Semalulu et al. (2012), who reported a much higher observed rate of $38.5 \text{ tha}^{-1}\text{yr}^{-1}$ for bananas using Gerlach troughs on runoff plots. Notably, the rate reported by Semalulu et al. (2012) is similar to the RUSLE-modelled estimate for perennial land use (banana) on Andosols in this study ($37.63 \text{ tha}^{-1}\text{yr}^{-1}$). This discrepancy between observed rates in similar land uses suggests that localised factors such as specific management practices, topography, or measurement methodology, can cause substantial variation in observed data.

The high erosion rates observed in the annual land use compared to woodlands, grasslands and perennials under Andosols and Ferralsols can be attributed to the land management practices that are associated with annual land use (Mohammed et al., 2020; Negash et al., 2021; Nunes et al., 2011). The frequent and rigorous tillage practices in annual land use loosen soil particles and expose the soil surface to erosive agents increasing soil erodibility which results into increased erosion rates (Arifin et al., 2022; Quinton & Fiener, 2024). Tilling of land breaks up soil agglomerates, reduces inter-particle cementation and destroys the soil structure by making the soil particles smaller, lighter, disintegrated and easier to erode (Yuan & Fan, 2024). Higher soil erosion rates in annual land use are therefore mainly attributed to its associated management and tillage practices (Mohammed et al., 2020; Nasir Ahmad et al., 2024).

Woodlands had the lowest soil erosion rates in both Andosols and Ferralsols, similarly grasslands and perennials in the two soil types had lower erosion rates. This can be attributed to the vegetative cover and management. Woodlands and perennials usually have all-year-round vegetation cover that provides constant soil cover and protection from erosion agents unlike annual land use. Annual land use only had stable vegetation cover during specific periods (May – July and November –

January) after the maize crops have matured, therefore the soil in the annual land use was exposed to erosive agents at the beginning of the two rainy seasons (March – April and September – October) before crop maturity. Presence of constant stable vegetation cover intercepts rainfall and shields the soil surface and soil particles from intense and direct raindrops. Additionally, vegetation cover increases water infiltration through interception, thus lowering the soil erosion rates (Nunes et al., 2011; Quinton & Fiener, 2024).

The presence of constant vegetation cover in woodlands also manifests with high soil organic matter content which enhances stability of soil aggregates and reduces soil erosion rates (Mohammed et al., 2020). Wei et al. (2024) and Quinton & Fiener (2024) also mention that presence of vegetation supports root growth whose exudates and root hairs improve soil particle

aggregation and stability. This study showed that different land uses on the same soil type resulted in varying soil erosion rates, highlighting the impact of land use on erosion (Meng et al., 2021).

The higher soil erosion rates experienced in Andosols with annual land use than those in Ferralsols with annual land use could be attributed to the differences in soil properties. Andosols are characterised by a loose and very friable structure; this weakens the soil's structural stability and makes the soils more susceptible to erosion (Lu et al., 2024). Andosols also have a high organic matter content, which improves the soil's water-holding capacity; this property enables the soils to retain water for a very long period of time. Since these soils are located in tropical highlands that receive high amounts of rainfall and have a high water retention capacity, they can easily reach saturation. Saturation of these soils inhibits percolation of water which results into runoff and erosion. Additionally, saturation leads to soil particle destabilization and ease with which soil particles are detached and eroded (Arifin et al., 2022; Li et al., 2024). Rodriguez et al. (2002) also noted that the organic soil surface of Andosols tends to be hydrophobic, resulting into reduced water entry and increased runoff and soil erosion.

The lower erosion rates of Ferralsols with grassland than those of Andosols with grassland could similarly be attributed to the differences in soil properties. Ferralsols are characterised by a stable soil structure which is resistant to physical breakdown and erosion (Gan et al., 2024; Stanchi et al., 2015). Additionally, Ferralsols are characterised by high water permeability and low water storage which encourages water movement through the profile without easily getting saturated to cause runoff and erosion (WRB, 2014).

5.2 Soil erosion tolerance thresholds of Ferralsols and Andosols under woodlands, grasslands, perennial and annual land uses

Grasslands and woodlands in Andosols and Ferralsols had the highest soil loss tolerance thresholds as compared to perennial and annual land uses. In Andosols, the highest tolerance thresholds were measured in grasslands > woodlands > perennial > annual land uses, whereas in Ferralsols, the highest soil loss tolerance thresholds were measured in grasslands > woodlands > annual > perennial land uses. The higher tolerance thresholds measured in grasslands and woodlands

indicate that these land uses are more resilient to erosion damage than perennial and annual land uses (Di Stefano et al., 2023; Di Stefano & Ferro, 2016).

Woodlands and grasslands had significantly higher tolerance thresholds due to their deep rooting depths, which greatly influences the tolerance thresholds. The capacity of grasslands and woodlands to enhance soil erosion resistance threshold can also be attributed to the land uses' characteristics, which include: extensive root systems, high organic matter content, effective vegetation canopy, and minimal or no tillage operations (Di Stefano et al., 2023; Gray et al., 2023). The lower tolerance thresholds measured in annual and perennial land uses in Andosols and Ferralsols can be attributed to the shallow rooting depths, which are the most sensitive factor affecting the soil loss tolerance thresholds.

Andosols and Ferralsols with annual land use had soil erosion rates exceeding their tolerance thresholds. These soils are considered to be degraded and less productive, since the erosion limit that will maintain stable and sustainable production has been surpassed. The influence of land use on soil loss tolerance thresholds can be supported by evidence of land uses such as grassland and woodland in the two soil types, having soil erosion rates lower than their tolerance thresholds. Andosols and Ferralsols used annually need sustainable management practices to decrease soil erosion rates and keep them below the erosion tolerable limits (Carollo et al., 2023). Although grasslands and woodlands on Andosols and Ferralsols are experiencing soil erosion below tolerance thresholds that are technically acceptable, the rates are alarmingly close to the limits. This narrow margin means the soil is not truly safe and is highly vulnerable to any increase in erosion, and therefore, the soil are at substantial risk.

CHAPTER SIX

CONCLUSIONS, RECOMMENDATIONS AND LIMITATIONS

6.1 Conclusions

Annual land use type registered the highest soil erosion rates as high as $14.21 \text{ tha}^{-1}\text{yr}^{-1}$, this renders Andosols and Ferralsols vulnerable due to the land management practices and soil exposure which result from limited vegetation cover. Woodlands, perennials and grasslands provide more effective

erosion control than annual land use due to constant soil cover, which intercepts erosion agents such as rain. Therefore, land use has a dominant control over soil erosion rates.

The Andosol under grasslands also registered the highest soil tolerance rates of $11.67 \text{ tha}^{-1}\text{yr}^{-1}$ compared to the lowest tolerance thresholds of $6.25 \text{ tha}^{-1}\text{yr}^{-1}$ registered in Ferralsols with perennial land use. Annual cropping consistently leads to loss of productivity due to high unsustainable soil erosion rates that exceed tolerance thresholds in both Andosols and Ferralsols. Even though grasslands and woodlands in Andosols and Ferralsols are more resilient to erosion stress than annual land use, the erosion rates of these land uses are dangerously close to tolerance thresholds, indicating that these soils are not truly safe and are vulnerable to any future intensification and climatic pressures.

6.2 Recommendations

There is a critical need to implement sustainable land management practices in annually cultivated areas in Andosols and Ferralsols to curb severe degradation and to proactively manage the wellvegetated land uses (perennials, grasslands and woodlands) to prevent further soil loss and future threshold exceedance. Tillage practices and soil exposure in annual land use should also be minimised to reduce soil erosion rates.

Further research and studies should be done on the soil erosion tolerance thresholds of different soil types while looking at improvement of the currently developed models in order to tailor them to the tropical environment context.

6.3 Limitations of the study

The data collection was conducted over a single year. However, soil erosion is influenced by interannual climatic variability, such as fluctuations in rainfall intensity and distribution, therefore, a longer-term study is required to capture these variations and their influence on erosion rates and runoff.

The study assumed uniform management practices within each land-use category across both soil types, as farmers were provided with the same guidelines. However, on-farm implementation can vary due to individual farmer preferences, decisions, skill and local conditions. This potential variability may introduce unaccounted-for errors into the data when comparing erosion responses between soil types.

Practical constraints prevented the study from being conducted on a uniform slope. Instead, the research was carried out across a narrow range of slopes to cater for the already existing land uses and soil types used for the study. Since slope gradient is a primary factor controlling erosion, this variation could confound the direct comparison of erosion rates between different land use and soil type combinations.

REFERENCES

- Abdalla, K., Mutema, M., & Hill, T. (2020). Soil and organic carbon losses from varying land uses: a global meta-analysis. *Geographical Research*, 58(2), 167–185. <https://doi.org/10.1111/1745-5871.12389>
- Abrha, H., Abraha, B., & Yaebio, G. (2018). Effect of Land Uses and Physical Soil and Water Conservation Practices on Runoff and Soil Loss in Western Tigray, Ethiopia. *Asian Journal of Research in Agriculture and Forestry*, 2(1), 1–5. <https://doi.org/10.9734/ajraf/2018/44208>
- Ahaneku, I. E., Ezinna, K. C., Orji, F. N., Alaneme, G. U., & Chukwudi, E. E. (2024). Spatial distribution of soil erodibility factors in erosion-prone areas in Umuahia, Southeast, Nigeria. *Journal of Engineering Research (Kuwait)*. <https://doi.org/10.1016/j.jer.2024.04.002>
- Ahmed, I. A., Talukdar, S., Baig, M. R. I., Shahfahad, Ramana, G. V., & Rahman, A. (2024). Quantifying soil erosion and influential factors in Guwahati's urban watershed using statistical analysis, machine and deep learning. *Remote Sensing Applications: Society and Environment*, 33(December 2022). <https://doi.org/10.1016/j.rsase.2023.101088>

- Akinnawo, S. O. (2023). Eutrophication: Causes, consequences, physical, chemical and biological techniques for mitigation strategies. In *Environmental Challenges* (Vol. 12). Elsevier B.V. <https://doi.org/10.1016/j.envc.2023.100733>
- Arifin, M., Devnita, R., Anda, M., Goenadi, D. H., & Nugraha, A. (2022). Characteristics of Andisols Developed from Andesitic and Basaltic Volcanic Ash in Different Agro-Climatic Zones. *Soil Systems*, 6(4). <https://doi.org/10.3390/soilsystems6040078>
- Asempah, M., Shisanya, C. A., & Schütt, B. (2024). Modeling of soil erosion risk in a typical tropical savannah landscape. *Scientific African*, 23. <https://doi.org/10.1016/j.sciaf.2023.e02042>
- Bamutaze, Y. (2011). Patterns of water erosion and sediment loading on Mt. Elgon, Eastern Uganda. Ph.D., Makerere University, Kampala.
- Bayata, A. (2024). *Soil Degradation : Contributing Factors and Extensive Impacts on Agricultural Practices and Ecological Systems- Systematic Review*. 13(June), 16–34. <https://doi.org/10.15640/ijhs.v13a2>
- Bellocchi, G., & Diodato, N. (2020). Rainfall erosivity in soil erosion processes. *Water (Switzerland)*, 12(3). <https://doi.org/10.3390/w12030722>
- Bhattacharyya, P., Bhatt, V. K., & Mandal, D. (2008). Soil loss tolerance limits for planning of soil conservation measures in Shivalik-Himalayan region of India. *Catena*, 73(1), 117–124. <https://doi.org/10.1016/j.catena.2007.10.001>
- Bhuyan, P. K., Meher, J., & Mohanty, L. (2024). Soil erosion estimation using RUSLE: a case study of Bannidhi sub basin. *ISH Journal of Hydraulic Engineering*, 30(2), 273–280. <https://doi.org/10.1080/09715010.2024.2301721>
- Boix-Fayos, C., Martínez-Mena, M., Arnau-Rosalén, E., Calvo-Cases, A., Castillo, V., & Albaladejo, J. (2006). Measuring soil erosion by field plots: Understanding the sources of variation. *Earth-Science Reviews*, 78(3–4), 267–285. <https://doi.org/10.1016/j.earscirev.2006.05.005>

- Borrelli, P., Alewell, C., Alvarez, P., Anache, J. A. A., Baartman, J., Ballabio, C., Bezak, N., Biddoccu, M., Cerdà, A., Chalise, D., Chen, S., Chen, W., De Girolamo, A. M., Gessesse, G. D., Deumlich, D., Diodato, N., Efthimiou, N., Erpul, G., Fiener, P., ... Panagos, P. (2021). Soil erosion modelling: A global review and statistical analysis. In *Science of the Total Environment* (Vol. 780). Elsevier B.V. <https://doi.org/10.1016/j.scitotenv.2021.146494>
- Borrelli, P., Robinson, D. A., Fleischer, L. R., Lugato, E., Ballabio, C., Alewell, C., Meusburger, K., Modugno, S., Schütt, B., Ferro, V., Bagarello, V., Oost, K. Van, Montanarella, L., & Panagos, P. (2017). An assessment of the global impact of 21st century land use change on soil erosion. *Nature Communications*, 8(1). <https://doi.org/10.1038/s41467-017-02142-7>
- Bryan, R. B. (2000). Soil erodibility and processes of water erosion on hillslope. *Geomorphology*, 32(3–4), 385–415. [https://doi.org/10.1016/S0169-555X\(99\)00105-1](https://doi.org/10.1016/S0169-555X(99)00105-1)
- Carollo, F. G., Di Stefano, C., Nicosia, A., Palmeri, V., Pampalone, V., & Ferro, V. (2023). A new strategy to assure compliance with soil loss tolerance at a regional scale. *Catena*, 223(December 2022). <https://doi.org/10.1016/j.catena.2023.106945>
- Chalise, D., Kumar, L., Sharma, R., & Kristiansen, P. (2020). Assessing the impacts of tillage and mulch on soil erosion and corn yield. *Agronomy*, 10(1). <https://doi.org/10.3390/agronomy10010063>
- Chandel, S., & Hadda, M. S. (2018). Soil loss tolerance assessment under different land uses in submontane Punjab. *Journal of Soil and Water Conservation*, 17(4), 303. <https://doi.org/10.5958/2455-7145.2018.00046.2>
- Chorny, S. (2022). Soil loss tolerance for agricultural land of the Right-Bank Steppe of Ukraine. *Soil Science Annual*, 73(4). <https://doi.org/10.37501/SOILSA/156066>
- David, W., P. (1988). Soil and Water Conservation Planning: Policy Issues and Recommendations, J. Philipp. Dev., 15, 47–84

- Descroix, L., Viramontes, D., Vauclin ', M., Gonzalez Barrios, J. L., Esteves, M., Vauclin, M., Gonzalez Barrios, J. L., & Esteves, M. (2001). Influence of soil surface features and vegetation on runoff and erosion in the western Sierra Madre (Durango, Northwest Mexico). *Catena*, 43(2), 115–135. [https://doi.org/10.1016/S0341-8162\(00\)00124-7](https://doi.org/10.1016/S0341-8162(00)00124-7)
- Detamo Aga, K. (2020). Soil erodibility and soil susceptibility to erosion by water in Shonkola mountainous area of Soro district, Ethiopia. *Journal of Mountain Research*, 15(1). <https://doi.org/10.51220/jmr.v15i1.1>
- Di Stefano, C., & Ferro, V. (2016). Establishing soil loss tolerance: An overview. *Journal of Agricultural Engineering*, 47(3), 127–133. <https://doi.org/10.4081/jae.2016.560>
- Di Stefano, C., Nicosia, A., Pampalone, V., & Ferro, V. (2023). Soil loss tolerance in the context of the European Green Deal. *Heliyon*, 9(1). <https://doi.org/10.1016/j.heliyon.2023.e12869>
- Duan, X., Shi, X., Li, Y., Rong, L., & Fen, D. (2017). A new method to calculate soil loss tolerance for sustainable soil productivity in farmland. *Agronomy for Sustainable Development*, 37(1). <https://doi.org/10.1007/s13593-016-0409-3>
- Duressa, A. A., Feyissa, T. A., Tukura, N. G., Gudeta, B. G., Fekadu Gechelu, G., & Bibi, T. S. (2024). Identification of soil erosion-prone areas for effective mitigation measures using a combined approach of morphometric analysis and geographical information system. *Results in Engineering*, 21. <https://doi.org/10.1016/j.rineng.2023.101712>
- Ekesa, B., Rao, J., Cadilhon, J., Ayebare, P., Bashaasha, B., & Muyanja , C Muchunguzi, P. (2015). *A situational analysis of agricultural production and marketing, and natural resource management systems in the central region of Uganda*.
- Ekwue, E. I., & Harrilal, A. (2010). Effect of soil type, peat, slope, compaction effort and their interactions on infiltration, runoff and raindrop erosion of some Trinidadian soils. *Biosystems Engineering*, 105(1), 112–118. <https://doi.org/10.1016/j.biosystemseng.2009.10.001>

- El Mazi, M., Hmamouchi, M., Saber, E. R., Bouchantouf, S., & Houari, A. (2022). Deforestation effects on soil properties and erosion: a case study in the central Rif, Morocco. *Eurasian Journal of Soil Science*, 11(4), 275–283. <https://doi.org/10.18393/ejss.1098600>
- Evangelista, S. J., Field, D. J., McBratney, A. B., Minasny, B., Ng, W., Padarian, J., Román Dobarco, M., & Wadoux, A. M. J. C. (2023). A proposal for the assessment of soil security: Soil functions, soil services and threats to soil. *Soil Security*, 10. <https://doi.org/10.1016/j.soisec.2023.100086>
- FAO. (2006). *Guidelines for soil description. Rome, Italy*. (Issue January). Food and Agriculture Organization of the United Nations.
- FAO. (2024). *Geospatial information for sustainable food systems*. <https://www.fao.org/geospatial/our-work/what-we-do/land-cover-and-land-use/en/>
- FAO, Food and Agriculture Organisation of the U. N. (2002). *Second expert meeting on harmonizing forest-related definitions for use by various stakeholders*. <https://www.fao.org/4/y4171e/y4171e00.htm#TopOfPage>
- Gan, F., Shi, H., Gou, J., Zhang, L., Dai, Q., & Yan, Y. (2024). Responses of soil aggregate stability and soil erosion resistance to different bedrock strata dip and land use types in the karst trough valley of Southwest China. *International Soil and Water Conservation Research*, 12(3), 684–696. <https://doi.org/10.1016/j.iswcr.2023.09.002>
- Gao, J., Jiang, Y., Wang, H., & Zuo, L. (2020). Identification of dominant factors affecting soil erosion and water yield within ecological red line areas. *Remote Sensing*, 12(3). <https://doi.org/10.3390/rs12030399>
- Gray, J. M., Leys, J. F., Yang, X., & Zhang, M. (2023). Monitoring of sustainable land management using remotely sensed vegetation cover and variable tolerable soil erosion targets across New South Wales, Australia. *Soil Use and Management*, 39(2), 849–866. <https://doi.org/10.1111/sum.12876>

- Gupta, S., Borrelli, P., Panagos, P., & Alewell, C. (2024). An advanced global soil erodibility (K) assessment including the effects of saturated hydraulic conductivity. *Science of the Total Environment*, 908. <https://doi.org/10.1016/j.scitotenv.2023.168249>
- Hacisalihoğlu, S., Kalay, H. Z., Sariyildiz, T., Oktan, E., Hacisalihoğlu, S., Kalay, H. Z., Sariyildiz, T., & Oktan, E. (2006). Quantitative determination of soil loss and runoff in different land use types and slope classes in a semi-arid area in Turkey. *Fresenius Environmental Bulletin*, 15(10), 1299–1306.
- Isabirye, M., Mwesige, D., Ssali, H., Magunda, M., & Lwasa, J. (2004). Soil resource information and linkages to agricultural production. *Uganda Journal of Agricultural Sciences*, 9(1), 215–221. <https://www.ajol.info/index.php/uja>
- IUSS Working Group WRB. (2014). World reference base for soil resources 2014. International soil classification system for naming soils and creating legends for soil maps. In *World Soil Resources Reports No. 106*. <https://doi.org/10.1017/S0014479706394902>
- Jacobs, L., Dewitte, O., Poesen, J., Delvaux, D., Thiery, W., & Kervyn, M. (2016). The Rwenzori Mountains, a landslide-prone region? *Landslides*, 13(3), 519–536. <https://doi.org/10.1007/s10346-015-0582-5>
- Ji, C., Cao, Y., Li, X., Pei, X., Sun, B., Yang, X., & Zhou, W. (2024). A review of the satellite remote sensing techniques for assessment of runoff and sediment in soil erosion. *Journal of Hydrology and Hydromechanics*, 72(2), 252–267. <https://doi.org/10.2478/johh-2024-0009>
- Jiang, B., Bamutaze, Y., and Pilesjo, P. (2014). Climate change and land degradation in Africa: a case study in the Mount Elgon region, Uganda. *Geo-spatial Information Science* 17, 39-53.
- Kairis, O., Karavitis, C., Salvati, L., Kounalaki, A., & Kosmas, K. (2015). Exploring the Impact of Overgrazing on Soil Erosion and Land Degradation in a Dry Mediterranean Agro-Forest Landscape (Crete, Greece). *Arid Land Research and Management*, 29(3), 360–374. <https://doi.org/10.1080/15324982.2014.968691>

- Karamage, F., Zhang, C., Liu, T., Maganda, A., & Isabwe, A. (2017). Soil erosion risk assessment in Uganda. *Forests*, 8(2). <https://doi.org/10.3390/f8020052>
- Khodadadi, M., Alewell, C., Mirzaei, M., Ehssan-Malahat, E., Asadzadeh, F., Strauss, P., & Meusburger, K. (2021). Deforestation effects on soil erosion rates and soil physicochemical properties in Iran: a case study of using fallout radionuclides in a Chernobyl contaminated area. In *SOIL Discussions* (Issue January). <https://doi.org/10.5194/soil-2021-2>
- Kimiaghalam, N., Clark, S. P., & Ahmari, H. (2014). An experimental study on the effects of physical, mechanical, and electrochemical properties of natural cohesive soils on critical shear stress and erosion rate. *International Journal of Sediment Research*, 31(1), 1–15. <https://doi.org/10.1016/j.ijsrc.2015.01.001>
- Kopittke, P. M., Berhe, A. A., Carrillo, Y., Cavagnaro, T. R., Chen, D., Chen, Q. L., Román Dobarco, M., Dijkstra, F. A., Field, D. J., Grundy, M. J., He, J. Z., Hoyle, F. C., Kögel-Knabner, I., Lam, S. K., Marschner, P., Martinez, C., McBratney, A. B., McDonald-Madden, E., Menzies, N. W., ... Minasny, B. (2022). Ensuring planetary survival: the centrality of organic carbon in balancing the multifunctional nature of soils. In *Critical Reviews in Environmental Science and Technology* (Vol. 52, Issue 23, pp. 4308–4324). Taylor and Francis Ltd. <https://doi.org/10.1080/10643389.2021.2024484>
- Kuhwald, M., Busche, F., Saggau, P., & Duttmann, R. (2022). Is soil loss due to crop harvesting the most disregarded soil erosion process? A review of harvest erosion. In *Soil and Tillage Research* (Vol. 215). Elsevier B.V. <https://doi.org/10.1016/j.still.2021.105213>
- Kumar Mishra, P., & Mishra, P. K. (2017). Assessment of Run-off and Soil Loss under different Land-use Practices in a Himalayan Watershed, India. *American Research Journal of Humanities and Social Sciences*, 3(1), 1–10. <https://doi.org/10.21694/2378-7031.17002>
- Kusiima, S. K., Egeru, A., Namaalwa, J., Byakagaba, P., Nfitumukiza, D., & Mukwaya, P. (2022). Anthropogenic induced land use/cover change dynamics of Budongo-Bugoma landscape in the Albertine region, Uganda. *Egyptian Journal of Remote Sensing and Space Science*, 25(3), 639–649. <https://doi.org/10.1016/j.ejrs.2022.05.001>

- Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science*, *304*(5677), 1623–1627. <https://doi.org/10.1126/science.1097396>
- Lal, R. (2019). Promoting “4 Per Thousand” and “Adapting African Agriculture” by south-south cooperation: Conservation agriculture and sustainable intensification. *Soil and Tillage Research* *188*, 27-34.
- Lara, M., Enrique, S., Anderson, C. T. A., Montserrat, L., Enrique, C. ., Anderson, A., Lara, M., Enrique, S., & Anderson, C. T. A. (2013). *Baseline report Rwenzori region case study , Aframaison project baseline report* (Issue June).
- Lenka, K. N., Mandal, D., Sudhishri, S., Lenka, N. K., Mandal, D., Sudhishri, S., Kumar Lenka, N., Mandal, D., & Sudhishri, S. (2014). Permissible soil loss limits for different physiographic regions of West Bengal. *Current Science*, *107*(4), 665–670.
- Li, C., Shi, W., & Huang, M. (2023). Effects of Crop Rotation and Topography on Soil Erosion and Nutrient Loss under Natural Rainfall Conditions on the Chinese Loess Plateau. *Land*, *12*(2). <https://doi.org/10.3390/land12020265>
- Li, D., Chen, X., Tan, W., Tao, T., Ma, L., Kong, L., & Zhu, P. (2024). Response of erosion rate to hydrodynamic parameters in sheet and rill erosion process on saturated soil slopes. *Soil and Tillage Research*, *237*(2). <https://doi.org/10.1016/j.still.2023.105996>
- Li, L., Du, S., Wu, L., & Liu, G. (2009). An overview of soil loss tolerance. In *Catena* (Vol. 78, Issue 2, pp. 93–99). <https://doi.org/10.1016/j.catena.2009.03.007>
- Lobb, D. A. (2008). Soil Movement by Tillage and Other Agricultural Activities. *Encyclopedia of Ecology, Five-Volume Set, 1–5*, 3295–3303. <https://doi.org/10.1016/B978-008045405-4.00832-6>
- Lu, Y., Gu, K., Shi, B., & Zhou, Q. (2024). Does biochar mitigate rainfall-induced soil erosion? A review and meta-analysis. *Biogeotechnics*, *2*(3). <https://doi.org/10.1016/j.bgtech.2024.100096>

- Lufafa, A., Tenywa, M., Isabirye, M., Majaliwa, M., and Woomer, P. (2003). Prediction of soil erosion in a Lake Victoria basin catchment using a GIS-based Universal Soil Loss model. *Agricultural systems* 76, 883-894
- Luliro, N. D., Tenywa, J. S., and Majaliwa, J. G. M. (2013). "Adaptation of RUSLE to Model Erosion Risk in a Watershed with Terrain Heterogeneity."
- Ma, S., Wang, L. J., Wang, H. Y., Zhao, Y. G., & Jiang, J. (2023). Impacts of land use/land cover and soil property changes on soil erosion in the black soil region, China. *Journal of Environmental Management*, 328. <https://doi.org/10.1016/j.jenvman.2022.117024>
- Majaliwa, J. G. (2005). Soil erosion from major agricultural land use types and associated pollution loading in selected Lake Victoria micro-catchments. Ph.D., Makerere University, Kampala.
- Mandal, D., & Sharda, V. N. (2011). Assessment of permissible soil loss in India employing a quantitative bio-physical model. *Current Science*, 100(3), 383–390. <http://www.statlab.iastate.edu/soils/>
- Mbabazi, A., Asiiimwe, A., & Mwesigye, A. (2023). Assessment of the Level of Access to University Education by Students from Rural Secondary Schools: A Case Study of Kasese District in Uganda. *Journal of Education*, 9(1), 17 – 32
- McDowell, R. W., & Hamilton, D. P. (2013). Nutrients and eutrophication. In *Marine and Freshwater Research* (Vol. 64, Issue 5, pp. 75–100). Springer Nature Switzerland. <https://doi.org/10.1071/MF13059>
- Meng, X., Zhu, Y., Yin, M., & Liu, D. (2021). The impact of land use and rainfall patterns on the soil loss of the hillslope. *Scientific Reports*, 11(1). <https://doi.org/10.1038/s41598-021-95819-5>
- Mohammad, A. G., & Adam, M. A. (2010). The impact of vegetative cover type on runoff and soil erosion under different land uses. *Catena*, 81(2), 97–103. <https://doi.org/10.1016/j.catena.2010.01.008>

- Mohammed, S., Abdo, H. G., Szabo, S., Pham, Q. B., Holb, I. J., Linh, N. T. T., Anh, D. T., Alsafadi, K., Mokhtar, A., Kbibo, I., Ibrahim, J., & Rodrigo-Comino, J. (2020). Estimating human impacts on soil erosion considering different hillslope inclinations and land uses in the coastal region of syria. *Water (Switzerland)*, *12*(10). <https://doi.org/10.3390/w12102786>
- Morgan, R., P., C. (2005). Soil Erosion and Conservation, National Soil Resources Institute, Cranfield University, <https://doi.org/10.1002/9781118351475.ch22>
- Muhumuza, M., & Byarugaba, D. (2009). Impact of land use on the ecology of uncultivated plant species in the Rwenzori mountain range, mid western Uganda. *African Journal of Ecology*, *47*(4), 614–621. <https://doi.org/10.1111/j.1365-2028.2009.01033.x>
- Musis, G. ., Harrop, B., & Luzinda, J. (1960). *The soils of the Western Province of Uganda*. <https://esdac.jrc.ec.europa.eu/content/soils-western-province-uganda>
- Nahib, I., Wahyudin, Y., Amhar, F., Ambarwulan, W., Nugroho, N. P., Pranoto, B., Cahyana, D., Ramadhani, F., Suwedi, N., Darmawan, M., Turmudi, T., Suryanta, J., & Karolinoerita, V. (2024). Analysis of Factors Influencing Spatial Distribution of Soil Erosion under Diverse Subwatershed Based on Geospatial Perspective: A Case Study at Citarum Watershed, West Java, Indonesia. *Scientifica*, *2024*. <https://doi.org/10.1155/2024/7251691>
- Nakakaawa, C. A., Vedeld, P. O., & Aune, J. B. (2011). Spatial and temporal land use and carbon stock changes in Uganda: Implications for a future REDD strategy. *Mitigation and Adaptation Strategies for Global Change*, *16*(1), 25–62. <https://doi.org/10.1007/s11027-010-9251-0>
- Nasir Ahmad, N. S. B., Mustafa, F. B., & Muhammad Yusoff, S. Y. (2024). Spatial prediction of soil erosion risk using knowledge-driven method in Malaysia’s Steepland Agriculture Forested Valley. *Environment, Development and Sustainability*, *26*(6), 15333–15359. <https://doi.org/10.1007/s10668-023-03251-8>
- Nearing, M. A., Xie, Y., Liu, B., & Ye, Y. (2017). Natural and anthropogenic rates of soil erosion.

International Soil and Water Conservation Research, 5(2), 77–84.
<https://doi.org/10.1016/j.iswcr.2017.04.001>

Negash, D. A., Moisa, M. B., Merga, B. B., Sedeta, F., & Gemedo, D. O. (2021). Soil erosion risk assessment for prioritization of sub-watershed: the case of Chogo Watershed, Horo Guduru Wollega, Ethiopia. *Environmental Earth Sciences*, 80(17), 1–11.
<https://doi.org/10.1007/s12665-021-09901-2>

NRCS/USDA, S. S. S.-. (2014). Keys to soil taxonomy. *Soil Conservation Service*, 12, 1–360.
http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_051546.pdf

Nunes, A. N., de Almeida, A. C., & Coelho, C. O. A. (2011). Impacts of land use and cover type on runoff and soil erosion in a marginal area of Portugal. *Applied Geography*, 31(2), 687–699. <https://doi.org/10.1016/j.apgeog.2010.12.006>

Nyakaisiki, K., Mugume, I., Ngailo, T., & Nakabugo, R. (2019). The Use of Indigenous Knowledge in Predicting Changes in Seasonal Rainfall by Smallholder Farmers of Ruteete Subcounty, Kabarole District. *Journal of Geoscience and Environment Protection*, 7, 13 – 22

Obiahu, O. H., & Elias, E. (2020). Effect of land use land cover changes on the rate of soil erosion in the Upper Eyiohia river catchment of Afikpo North Area, Nigeria. *Environmental Challenges*, 1. <https://doi.org/10.1016/j.envc.2020.100002>

Okalebo, J. R., Gathua, K. W., & Paul, L. W. (2002). Laboratory Methods of Soil and Plant Analysis: A Working Manual The Second Edition. In *TSBF-CIAT and SACRED Africa, Kenya: Vol. SECOND EDI.*

Ostovari, Y., Moosavi, A. A., & Pourghasemi, H. R. (2020). Soil loss tolerance in calcareous soils of a semiarid region: evaluation, prediction, and influential parameters. *Land Degradation and Development*, 31(15), 2156–2167. <https://doi.org/10.1002/ldr.3597>

Ouyang, W., Wu, Y., Hao, Z., Zhang, Q., Bu, Q., & Gao, X. (2018). Combined impacts of land use and soil property changes on soil erosion in a mollisol area under long-term agricultural

development. *Science of the Total Environment*, 613–614, 798–809.
<https://doi.org/10.1016/j.scitotenv.2017.09.173>

Pereira, P., Bogunovic, I., Muñoz-Rojas, M., & Brevik, E. C. (2018). Soil ecosystem services, sustainability, valuation and management. In *Current Opinion in Environmental Science and Health* (Vol. 5, pp. 7–13). Elsevier B.V. <https://doi.org/10.1016/j.coesh.2017.12.003>

Pretorius, J. R., & Cooks, J. (1989). Soil loss tolerance limits: an environmental management tool. *GeoJournal*, 19(1), 67–75. <https://doi.org/10.1007/BF00620551>

Qu, L., Zhu, X., Liang, Y., Qiu, D., Zhang, Q., & Liang, Y. (2023). Spatial variation of soil properties and evaluation of the risk of soil erodibility on a river alluvial and marine sedimentary plain in eastern China. *Journal of Soils and Sediments*, 23(5), 2106–2119. <https://doi.org/10.1007/s11368-023-03460-8>

Quinton, J. N., & Fiener, P. (2024). Soil erosion on arable land: An unresolved global environmental threat. In *Progress in Physical Geography* (Vol. 48, Issue 1, pp. 136–161). SAGE Publications Ltd. <https://doi.org/10.1177/03091333231216595>

Rawat, J. S., Joshi, R. C., & Mesia, M. (2012). Estimation of erosivity index and soil loss under different land uses in the tropical foothills of Eastern Himalaya (India). *Tropical Ecology*, 54(1), 47–58

Renard, K., Foster, G., Weesies, G., McCool, D., & Yoder, D. (1997). Predicting soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE), Agricultural Handbook No. 703, 65–100, <https://doi.org/10.1201/9780203739358-5>

Rodriguez, R. A., Guerra, J. A., Gorrin, S. P., Arbelo, C. D., Mora, J. L., Rodríguez Rodríguez, A., Guerra, J. A., Gorrín, S. P., Arbelo, C. D., & Mora, J. L. (2002). Aggregates Stability and Water Erosion in Andosols of the Canary Islands. *Land Degradation and Development*, 13(6), 515–523. <https://doi.org/10.1002/ldr.543>

- Roller, S., Wittmann, H., Kastowski, M., & Hinderer, M. (2012). Erosion of the Rwenzori Mountains, East African Rift, from in situ-produced cosmogenic ^{10}Be . *Journal of Geophysical Research: Earth Surface*, *117*(3). <https://doi.org/10.1029/2011JF002117>
- Rosinger, C., Bodner, G., Forer, V., Sandén, H., Weninger, T., Zeiser, A., Mentler, A., & Keiblinger, K. M. (2025). Changes in microbial physiology and carbon-use efficiency upon improving soil habitat conditions in conservation farming systems. *Agriculture, Ecosystems and Environment*, *377*(August 2024). <https://doi.org/10.1016/j.agee.2024.109246>
- Rugendo, M. K., Gichimu, B. M., Mugwe, J. N., Mucheru-Muna, M., & Mugendi, D. N. (2023). Surface runoff and soil erosion from Nitisols and Ferralsols as influenced by different soil organic carbon levels under simulated rainfall conditions. *Heliyon*, *9*(7). <https://doi.org/10.1016/j.heliyon.2023.e17684>
- Sartori, M., Ferrari, E., M'Barek, R., Philippidis, G., Boysen-Urban, K., Borrelli, P., Montanarella, L., & Panagos, P. (2024). Remaining Loyal to Our Soil: A Prospective Integrated Assessment of Soil Erosion on Global Food Security. *Ecological Economics*, *219*(December 2023). <https://doi.org/10.1016/j.ecolecon.2023.108103>
- Semalulu, O., & Kaizzi, K. C. (2013). Overview of the status of soil resource in Uganda, and the needs and priorities for its sustainable management. *Regional Conference on the Eastern and Southern Africa Soil Partnership*. <http://www.fao.org/globalsoilpartnership>
- Semalulu, O., Kimaro, D., Kasenge, V., Isabirye, M. & Makhosi, P. (2012). Soil and nutrient losses in banana-based cropping systems of the mount Elgon hillsides of Uganda: economic implications. *International Journal of Agricultural Science*, *2*, 256–262
- Setyawan, C., Lee, C. Y., & Prawitasari, M. (2019). Investigating spatial contribution of land use types and land slope classes on soil erosion distribution under tropical environment. *Natural Hazards*, *98*(2), 697–718. <https://doi.org/10.1007/s11069-019-03725-x>
- Sholagberu, A., T., Ul Mustafa, M., R., Wan Yusof, K., & Ahmad, M., H. (2016). Evaluation of rainfall-runoff erosivity factor for Cameron highlands, Pahang, Malaysia, *J. Ecol. Eng.*, *17*, 1–8, <https://doi.org/10.12911/22998993/63338>

- Skidmore, E. (1982). Soil loss tolerance. *In Determinants of Soil Loss Tolerance*, 87 – 94. <https://doi.org/10.2134/asaspecpub45.c8>
- Ssewankambo, G., Kabenge, I., Nakawuka, P., Wanyama, J., Zziwa, A., Bamutaze, Y., Gwapedza, D., Palmer, C. T., Tanner, J., Mantel, S., & Tessema, B. (2023). Assessing soil erosion risk in a peri-urban catchment of the Lake Victoria basin. *Modeling Earth Systems and Environment*, 9(2), 1633–1649. <https://doi.org/10.1007/s40808-022-01565-6>
- Stanchi, S., Falsone, G., & Bonifacio, E. (2015). Soil aggregation, erodibility, and erosion rates in mountain soils (NW Alps, Italy). *Solid Earth*, 6(2), 403–414. <https://doi.org/10.5194/se-6-403-2015>
- Telo da Gama, J. (2023). The Role of Soils in Sustainability, Climate Change, and Ecosystem Services: Challenges and Opportunities. In *Ecologies* (Vol. 4, Issue 3, pp. 552–567). Multidisciplinary Digital Publishing Institute (MDPI). <https://doi.org/10.3390/ecologies4030036>
- Tibasiima, T. K., Bwambale, B., Ekyaligonza, D. M., Dietrich, P., Jumba, F., Kagorora, J. P. K., & Freyer, B. (2023). Re-assembling land degradation: toward a nature-society-inclusive soil erosion management strategy. A case of the Rwenzori region, Uganda. *Frontiers in Sustainable Food Systems*, 7. <https://doi.org/10.3389/fsufs.2023.1146222>
- UNESCO. (2025). *Rwenzori Mountains National Park*. World Heritage Convention. <https://whc.unesco.org/en/list/684/>
- USDA-NRCS, National Soil Survey Handbook, United States Department of Agriculture – Natural Resource Conservation Service, US Government Printing Office, Washington DC, 430-VI, 1999.
- Vaezi, A. R., Ahmadi, M., & Cerdà, A. (2017). Contribution of raindrop impact to the change of soil physical properties and water erosion under semi-arid rainfalls. *Science of the Total Environment*, 583, 382–392. <https://doi.org/10.1016/j.scitotenv.2017.01.078>

- Verheijen, F. G. A., Jones, R. J. A., Rickson, R. J., & Smith, C. J. (2009). Tolerable versus actual soil erosion rates in Europe. In *Earth-Science Reviews* (Vol. 94, Issues 1–4, pp. 23–38). <https://doi.org/10.1016/j.earscirev.2009.02.003>
- Wang, G., Fang, Q., Teng, Y., & Yu, J. (2016). Determination of the factors governing soil erodibility using hyperspectral visible and near-infrared reflectance spectroscopy. *International Journal of Applied Earth Observation and Geoinformation*, 53, 48–63. <https://doi.org/10.1016/j.jag.2016.08.006>
- Wang, R., Zhang, S., Yang, J., Pu, L., Yang, C., Yu, L., Chang, L., & Bu, K. (2016). Integrated Use of GCM, RS, and GIS for the Assessment of Hillslope and Gully Erosion in the Mushi River Sub-Catchment, Northeast China. *Sustainability*, 8(4), 317. <https://doi.org/10.3390/su8040317>
- Wei, S., Zhang, K., Liu, C., Cen, Y., & Xia, J. (2024). Effects of different vegetation components on soil erosion and response to rainfall intensity under simulated rainfall. *Catena*, 235. <https://doi.org/10.1016/j.catena.2023.107652>
- Williams, R., J. & Renard, K., G. (1983). EPIC – a new method for assessing erosions effect on soil productivity, *J. Soil Water Conserv.*, 38, 381–383
- WRB. (2014). World reference base for soil resources 2014, IUSS Working Group. International soil classification system for naming soils and creating legends for soil maps. In *World Soil Resources Reports No. 106*. <https://doi.org/10.1017/S0014479706394902>
- WRB. (2022). World reference base for soil resources. International soil classification system for naming soils and creating legends for soil maps 4th edition. In International Union of Soil Sciences (IUSS), Vienna, Austria.
- Yao, C., Zhang, Q., Wang, C., Ren, J., Li, H., Wang, H., & Wu, F. (2023). Response of sediment transport capacity to soil properties and hydraulic parameters in the typical agricultural regions of the Loess Plateau. *Science of the Total Environment*, 879. <https://doi.org/10.1016/j.scitotenv.2023.163090>

Yao, X., Yu, J., Jiang, H., Sun, W., & Li, Z. (2016). Roles of soil erodibility, rainfall erosivity and land use in affecting soil erosion at the basin scale. *Agricultural Water Management*, 174, 82–92. <https://doi.org/10.1016/j.agwat.2016.04.001>

Yuan, C., & Fan, H. (2024). Response mechanism of black soil structure to compound erosion forces in sloping farmland, Northeast China. *Soil and Tillage Research*, 240(March). <https://doi.org/10.1016/j.still.2024.106103>

Zhai, L., Sun, L., & Zhang, Y. (2024). Development Trends in Soil Erosion Fields Based on the Quantitative Evaluation of Innovation Subjects and Innovation Content from 1991 to 2020. In *Sustainability (Switzerland)* (Vol. 16, Issue 2). Multidisciplinary Digital Publishing Institute (MDPI). <https://doi.org/10.3390/su16020795>

Zi, R., Zhao, L., Fang, Q., Qian, X., Fang, F., & Fan, C. (2023). Path analysis of the effects of hydraulic conditions, soil properties and plant roots on the soil detachment capacity of karst hillslopes. *Catena*, 228. <https://doi.org/10.1016/j.catena.2023.107177>

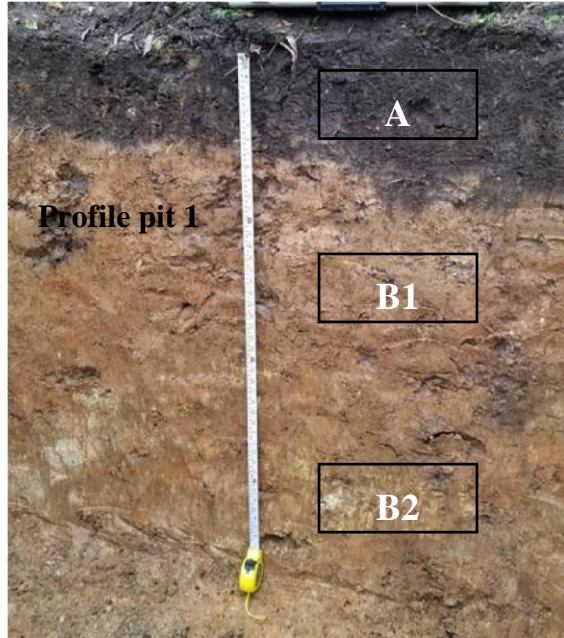
APPENDICES

APPENDIX 1.1: Soil profile description and classification

GENERAL SITE INFORMATION			
Authors: Angella Namatovu		Date: 13-Dec-2021	
Profile number: 1		Soil description status: Routine profile description	
Location, District: Kabarole	Sub-county: Ka rangura	Parish/Village: Kaisamba	
GPS, Latitude (degree/ UTM): 00.66970N	Longitude(degree/UTM): 030.16900E	Elevation (m): 1833m	
Soil Temperature regime: Isothermic			
Soil moisture regime: Ustic			

Topography: Steep land		Position: Upper slope	
Slope form: Straight			
Termitaria (per ha): 0		Rock outcrop (Abundance): None	
Water erosion: Sheet erosion			
Coverage of mulch (%): 30			
Soil drainage class: Weakly drained		Land use: Non-irrigated perennial cultivation	
Human influence: Vegetation slightly disturbed			
Vegetation		Shrub cover %: 0	
		Grass%: 0	
Ground cover (%): 30	Grazing: No	Crop cultivation: Yes	
Crops at the site:	Bananas		
SOIL PROFILE DESCRIPTION			
PROFILE NUMBER: 1			
Horizon	1	2	3
Horizon name	A	B	B
Horizon depth (cm)	0-21	21-74	74-120
Horizon distinctness	Clear	Gradual	Gradual
Topography	Smooth	Irregular	Irregular
Moisture status	Moist	Moist	Moist
Moist color code	2.5YR 2.5/2	7.5YR 5/6	5YR 6/8
Moist color	Very dusky red	Strong brown	Reddish yellow
Mottles			
Abundance	None	None	None
Size	-	-	-
Color code	-	-	-
Color	-	-	-

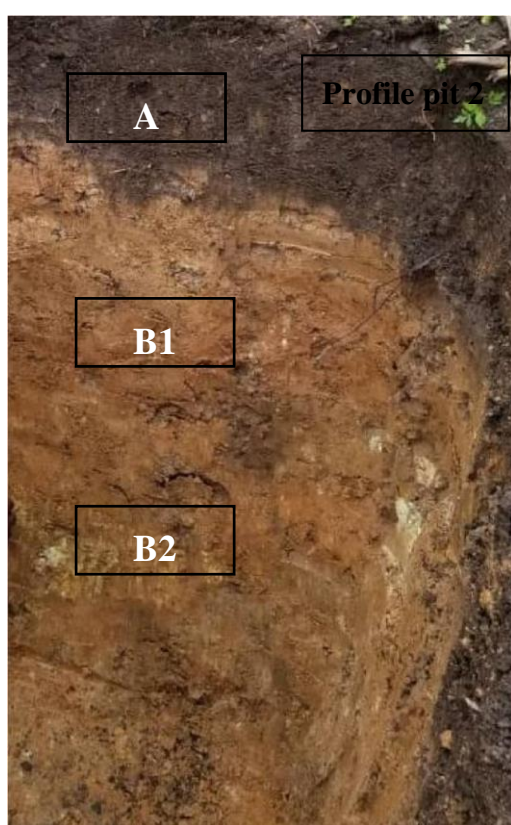
Soil Texture			
Texture code	Sandy Clay Loam	Sandy Clay Loam	Sandy Loam
Soil Structure			
Development	Weak	Moderate	Moderate
Size	Fine	Medium	Medium
Type	Granular	Blocky sub-angular	Blocky sub-angular
Consistence			
Dry	Slightly hard	Hard	Hard
Moist	Very friable	Firm	Firm
Stickiness (Wet)	Sticky	Slightly sticky	Slightly sticky
Plasticity (wet)	Slightly plastic	Plastic	Plastic
Pores			
Size	Fine	Very fine	Very fine
Abundance	Common	Few	Few
Roots			
Abundance	Common	Very few	None
Size	Medium	Fine	-
WRB diagnostic horizon	Melanic	Cambic	Cambic
Diagnostic properties	Andic	Lithic discontinuity	Lithic discontinuity
Diagnostic material	Organic	Mineral	Mineral
Prefix qualifier	1	1	1
Suffix qualifier			
Provisional reference soil group	Andosols		



GENERAL SITE INFORMATION			
Authors: Angella Namatovu		Date: 13-Dec-2021	
Profile number: 2		Soil description status: Routine profile description	
Location, District: Kabarole	Sub-county: Karangur a	Parish/Village: Kaisamba	
GPS, Latitude (degree/ UTM): 00.67250 N	Longitude(degree/UT M): 030.17280E	Elevation (m): 1727m	
Soil Temperature regime: Isother mic			
Soil moisture regime: Ustic			
Topography: Steep land		Position: Upper slope	
Slope form: Straight			
Termitaria (per ha): 0		Rock outcrop (Abundance): None	
Water erosion: Sheet erosion			
Coverage of mulch (%): 0			
Soil drainage class: Weakly drain ed		Land use: Natural grassland	
Human influence: Vegetation slig htly disturbed			
Vegetation		Shrub cover %: 0	
		Grass%: 100	
Ground cover (%): 95	Grazing: Yes	Crop cultivation: No	
Crops at the site:	Native grasses		
SOIL PROFILE DESCRIPTIO N			
PROFILE NUMBER: 2			
Horizon	1	2	3
Horizon name	A	B	B
Horizon depth (cm)	0-39	39-83	83-127
Horizon distinctness	Clear	Gradual	Diffuse
Topography	Smooth	Irregular	Irregular

Moisture status	Moist	Moist	Moist
Moist color code	5YR 2.5/2	7.5YR 8/6	10YR 7/3
Moist color	Dark reddish brown	Reddish yellow	Very pale brown
Mottles			
Abundance	None	None	None
Size	-	-	-
Color code	-	-	-
Color	-	-	-
Soil Texture			
Texture code	Sandy Loam	Sandy Clay Loam	Sandy Clay Loam
Soil Structure			
Development	Moderate	Strong	Strong
Size	Medium	Coarse	Coarse
Type	Blocky sub-angular	Blocky sub-angular	Blocky sub-angular
Consistence			
Dry	Slightly hard	Hard	Hard
Moist	Friable	Firm	Firm
Stickiness (Wet)	Sticky	Sticky	Sticky
Plasticity (wet)	Slightly plastic	Plastic	Plastic
Pores			
Size	Fine	Very fine	Very fine
Abundance	Common	Few	Few
Roots			
Abundance	Many	Few	Few
Size	Fine	Fine	Very fine
WRB diagnostic horizon	Melanic	Cambic	Cambic

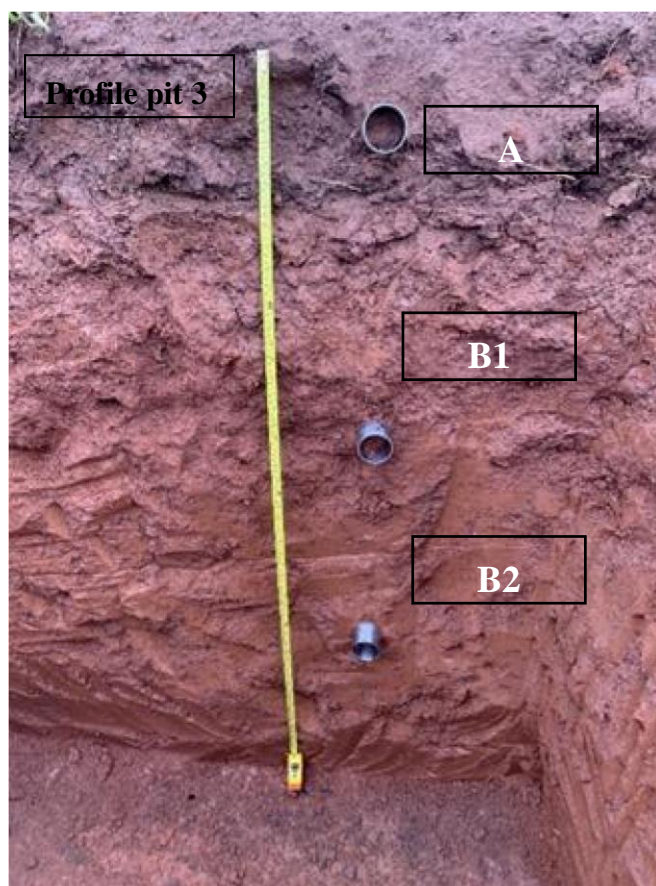
Diagnostic properties	Andic	Lithic discontinuity	Lithic discontinuity
Diagnostic material	Organic	Mineral	Mineral
Prefix qualifier	1	1	1
Suffix qualifier			
Provisional reference soil group	Andosols		



GENERAL SITE INFORMATION			
Authors: Angella Namatovu		Date: 15-Dec-2021	
Profile number: 3		Soil description status: Routine profile description	
Location, District: Kasese	Sub-county: Ki lembe	Parish/Village: Kathulu	
GPS, Latitude (degree/ UTM): 00.22030 N	Longitude(degree/UTM): 029.99250E	Elevation (m): 1538m	

Soil Temperature regime: Isothermic			
Soil moisture regime: Ustic			
Topography: Steep land		Position: Upper slope	
Slope form: Straight			
Termitaria (per ha): 0		Rock outcrop (Abundance): None	
Water erosion: Sheet erosion			
Coverage of mulch (%): 10			
Soil drainage class: Well drained		Land use: Rainfed annual cultivation	
Human influence: Vegetation strongly disturbed			
Vegetation		Shrub cover %: 0	
		Grass%: 0	
Ground cover (%): 30	Grazing: No	Crop cultivation: Yes	
Crops at the site:	Maize		
SOIL PROFILE DESCRIPTION			
PROFILE NUMBER: 3			
Horizon	1	2	3
Horizon name	A	B	B
Horizon depth (cm)	0-15	15-50	50-120
Horizon distinctness	Clear	Gradual	Diffuse
Topography	Wavy	Irregular	Irregular
Moisture status	Moist	Moist	Moist
Moist color code	7.5YR 3/4	7.5YR 4/6	7.5YR 6/8
Moist color	Dark brown	Strong brown	Reddish yellow
Mottles			
Abundance	None	None	None
Size	-	-	-

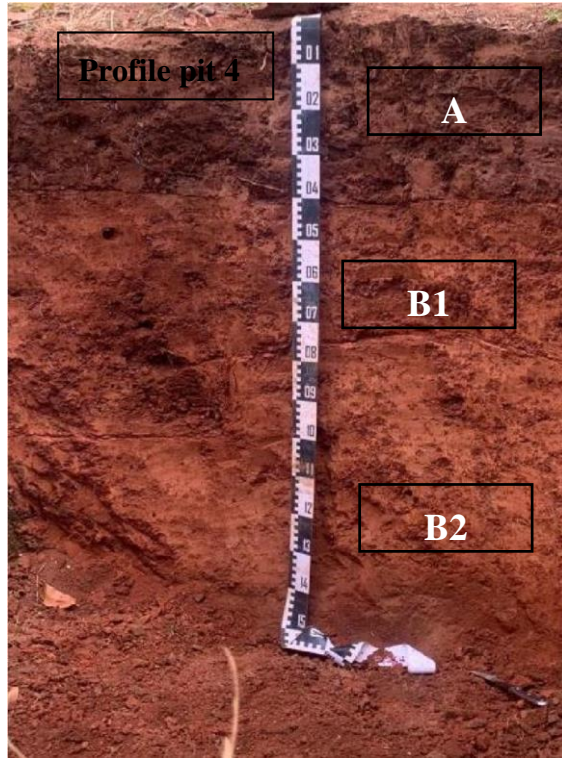
Color code	-	-	-
Color	-	-	-
Soil Texture			
Texture code	Sandy Clay Loam	Sandy Clay Loam	Sandy Loam
Soil Structure			
Development	Moderate	Moderate	Moderate
Size	Medium	Medium	Coarse
Type	Granular	Blocky sub-angular	Blocky sub-angular
Consistence			
Dry	Hard	Hard	Very hard
Moist	Firm	Firm	Firm
Stickiness (Wet)	Sticky	Sticky	Slightly sticky
Plasticity (wet)	Very plastic	Very plastic	Plastic
Pores			
Size	Very fine	Very fine	Very fine
Abundance	Many	Few	Few
Roots			
Abundance	Common	Common	Very few
Size	Medium	Fine	Fine
WRB diagnostic horizon	Ferralic	Ferralic	Ferralic
Diagnostic properties			
Diagnostic material	Mineral	Mineral	Mineral
Prefix qualifier	1	1	1
Suffix qualifier			
Provisional reference soil group	Ferralsol		



GENERAL SITE INFORMATION			
Authors: Angella Namatovu		Date: 15-Dec-2021	
Profile number: 4		Soil description status: Routine profile description	
Location, District: Kasese	Sub-county: Kilemb e	Parish/Village: Kathulu	
GPS, Latitude (degree/ UTM): 00.22240 N	Longitude(degree/U TM): 029.99330E	Elevation (m): 1554m	
Soil Temperature regime: Isothermi c			
Soil moisture regime: Ustic			
Topography: Steep land		Position: Upper slope	
Slope form: Straight			

Termitaria (per ha): 0		Rock outcrop (Abundance): None	
Water erosion: Sheet erosion			
Coverage of mulch (%): 10			
Soil drainage class: Well drained		Land use: Natural grassland	
Human influence: Vegetation mode rarely disturbed			
Vegetation		Shrub cover %: 0	
		Grass%: 100	
Ground cover (%): 70	Grazing: Yes	Crop cultivation: No	
Crops at the site:	Native grasses		
SOIL PROFILE DESCRIPTION			
PROFILE NUMBER: 4			
Horizon	1	2	3
Horizon name	A	B	B
Horizon depth (cm)	0-40	40-80	80-150
Horizon distinctness	Clear	Clear	Diffuse
Topography	Smooth	Wavy	Irregular
Moisture status	Moist	Moist	Moist
Moist color code	5YR 3/3	2.5YR 4/8	2.5YR 5/8
Moist color	Dark Red Brown	Red	Red
Mottles			
Abundance	None	None	None
Size	-	-	-
Color code	-	-	-
Color	-	-	-
Soil Texture			
Texture code	Sandy Clay Loam	Sandy Loam	Sandy Clay Loam

Soil Structure			
Development	Moderate	Moderate	Moderate
Size	Medium	Medium	Medium
Type	Granular	Blocky sub-angular	Blocky sub-angular
Consistence			
Dry	Slightly hard	Slightly hard	Hard
Moist	Friable	Firm	Firm
Stickiness (Wet)	Sticky	Sticky	Slightly sticky
Plasticity (wet)	Very plastic	Plastic	Plastic
Pores			
Size	Very fine	Very fine	Very fine
Abundance	Many	Common	Few
Roots			
Abundance	Common	Common	Very few
Size	Fine	Fine	Fine
WRB diagnostic horizon	Ferralic	Ferralic	Ferralic
Diagnostic properties			
Diagnostic material	Mineral	Mineral	Mineral
Prefix qualifier	1	1	1
Suffix qualifier			
Provisional reference soil group	Ferralsol		



APPENDIX 1.2: Favourable rooting depths of two soil types (Andosols and Ferralsols) under four land use types (annual, grassland, perennial and woodland) in the Rwenzori highlands of Uganda.

Soil type	Land use	Depth (cm)
Andosols	Annual	0 – 65
	Perennial	0 – 74
	Grassland	0 – 127
	Woodland	0 – 150
Ferralsols	Annual	0 – 50
	Perennial	0 – 50
	Grassland	0 – 100
	Woodland	0 – 133

Appendix 1.3: Multiple regression analysis of the parameters used to estimate the soil loss tolerance thresholds

T-values ~ pH + IR + BD + OC + K

Co-efficients	Estimate	Std. Error	t-value	Pr(> t)
Intercept	-48.20	44.49	-1.08	0.285
pH	0.20	0.59	0.34	0.738
Infiltration rate	-0.31	0.45	-0.69	0.491
Bulk density	38.71	31.71	1.22	0.223
Organic carbon	0.76	0.44	1.74	0.089
Soil erodibility	1.53	3.81	0.40	0.689
Multiple R-squared: 0.12, Adjusted R-squared: 0.0152				
F-statistic: 1.145, p-value: 0.352				

T-values ~ Rooting depth

Co-efficients	Estimate	Std. Error	t-value	Pr(> t)
Intercept	8.75	0.54	16.25	<2e-16 ***
Depth 0-127	2.92	0.76	3.83	0.0004 ***
Depth 0-133	-0.42	0.76	-0.55	0.587
Depth 0-150	2.50	0.76	3.28	0.002 **
Depth 0-50	-2.29	0.66	-3.47	0.001 **
Depth 0-65	-0.42	0.76	-0.55	0.587
Depth 0-74	0.00	0.76	0.00	1.000
Multiple R-squared: 0.683, Adjusted R-squared: 0.64				
F-statistic: 14.71, p-value: 7.02e-09				

T-values ~ pH + IR + BD + OC + K + Rooting depth

Co-efficients	Estimate	Std. Error	t-value	Pr(> t)
Intercept	-33.51	30.02	-1.12	0.272
pH	-0.33	0.39	-0.86	0.398
Infiltration rate	-0.60	0.28	-2.12	0.041 *
Bulk density	31.79	21.09	1.51	0.141
Organic carbon	0.57	0.25	2.26	0.030 *
Soil erodibility	2.02	2.16	0.94	0.355
Depth 0-127	2.70	0.77	3.51	0.001 **
Depth 0-133	-1.09	0.77	-1.42	0.165
Depth 0-150	3.12	0.81	3.85	0.0005 ***

Depth 0-50	-2.53	0.69	-3.68	0.0008 ***
Depth 0-65	-0.56	0.71	-0.79	0.434
Depth 0-74	-0.15	0.80	-0.19	0.847

Multiple R-squared: 0.76, Adjusted R-squared: 0.69

F-statistic: 10.38, p-value: 3.43e-08

Appendix 1.4. Rainfall amount as observed from rainfall stations in Kasese and Kabarole from Dec 2021 to Nov 2022

Station	Kasese											
	2021 Dec	2022 Jan	2022 Feb	2022 Mar	2022 Apr	2022 May	2022 Jun	2022 Jul	2022 Aug	2022 Sept	2022 Oct	2022 Nov
Days	Rainfall (mm)											
1	0	0	0	7.5	0	2.2	7.3	0	6	14.4	0.8	2
2	0.7	0	0	17	3.5	0	0.6	0	0	11.7	0	0.4
3	0	0	0	0	5.4	0.2	0	0	1	0	4.9	4.8
4	10.6	0	0	0.1	0.2	0.3	0	0	1.2	0	1.1	3.5
5	4.7	0	0	0	0	0	0	0	0	0	0	0.4
6	0	0	0	0.1	15	3	0	0	0	95.8	15.3	1.2
7	5.7	0.9	0	0	0.1	0	10	0	0	0.3	1.4	0
8	0	0	0	0	1.1	0	0	0	0	0	4	0.9
9	0	0	19.5	0	0.1	0	0	0	0	7.8	5.6	33.6
10	0	0	0	0	13.1	1	0	0	0	0	0	0
11	7.5	0	0	0	6	1.4	0	0	0	0.5	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0.8	0	0	0	0	0.9	4.3	1.4	19.7
14	0	0	0	0	2.2	0	0	0	0	0.4	0	0.8
15	0	1.9	0	0	21.8	0	0	0	5.7	0.6	5.7	5.2
16	0	0	0	0	0	0	0	0	0	0.3	49.2	1.9
17	0	16.7	0	0	0	0.5	1.7	0	17.5	0	0	16.3
18	0	14.2	0	0	24.7	0	0	0	1.1	3.1	6.8	3

19	27.7	0	0	0	0	0	1.1	0	22	0	0.3	0
20	7.5	0	0.8	0	0	0	0.3	0	0	0	17.3	1.8
21	6.4	0	0	3.7	0	0	0	0	0	0.5	9.1	1
22	0	0	0	7.1	20.6	3.2	0	0	0	1.8	0	16.4
23	0	0	0	0	44.2	0	0	0	0	0	0	1.6
24	3.8	0	7.4	2.4	0.1	0	0	0	0	0	0	0
25	6.8	0	0	1.5	0.1	1.4	0	0	0	0	0	1
26	6.4	0	0	1.8	0	4.1	0	0	0	0	0	0
27	0	0	0	0	16.7	0	0	0	0	0	2.1	0.4
28	0	0	4.4	16.8	45.3	1.1	0	0	0	8.5	2.3	0
29	0	0		2.7	2.5	0.8	0	0.1	11.1	0	0	0.5
30	0.1	0		0.2	0	8	0	11.1	26.4	0	0	3
31	7.1	0		0		0.7		0	5.2		0	
TOTAL	95	33.7	32.1	61.7	222.7	27.9	21	11.2	98.1	150	127.3	119.4

Station	Kabarole											
	2021 Dec	2022 Jan	2022 Feb	2022 Mar	2022 Apr	2022 May	2022 Jun	2022 Jul	2022 Aug	2022 Sept	2022 Oct	2022 Nov
Days	Rainfall (mm)											
1	4.1	0	0.1	0	0	15.1	18.6	0	13.4	0	47.7	5.4
2	0.1	0.4	0	0.7	12.1	0	0	0	0	4.4	33.2	0
3	0	0	0	0	14.3	0	0	0	0	1.3	0.8	29
4	0	0	0	0	0	0	0	0	0	0	3.6	0
5	0	0	0	0	0	0	0	0	0	0	1	1
6	0	0	0	0	1.5	0	0	0	0	16.3	0	12
7	0	0	0	1.3	0	0	0	0	0	0	0	8.2
8	0	0	0	14.2	0	18.2	0	0	0	0	0	10.6

9	0	0	0.1	3.3	0	0	4.5	0	0	16.8	27.3	0.6
10	0	0	0	0	4.8	5	0.1	0	0	0	0	7.9
11	1.2	0	0	4.3	3.9	2.4	0	0	0	1.6	25.5	4.2
12	0	0	0	0	0	0	0	0	8.7	3.6	8.9	0
13	0	0	0	0	0.1	18.8	0.4	0	0.8	0.4	8.1	2.2
14	7.5	0	0	0	23.6	1.2	4.4	0	0	2.8	0	10.8
15	0	0.6	0.1	0	6.1	0.2	0	0	0	20.5	5.1	10.2
16	0	9.7	0	0	4.4	0	0	0	0.2	3.2	4.4	0
17	0	14.8	0	0	0.2	26.8	0	0	0	3.6	6	12.3
18	0.8	8.7	0	13.1	65.4	7.4	1.2	6.2	0	0	0	14.6
19	8	0	0	0	4.8	0	23.8	0	43	0	2.9	15.9
20	0	0	0.7	0	1	0	17.2	0	0.4	0	0	3.3
21	2.4	0	0	4.4	0	0	0	0	0.4	47.7	13.2	5.3
22	0.5	0	0	5.1	15.8	3.2	0	0	0.7	33.2	0	4.3
23	53.8	0	0	0	1.2	0	0	0	0	0.8	0	0
24	0	0	0	0	20.6	22.3	0	0	0	3.6	0.2	16
25	1.3	0	17.5	0.1	0.9	4.8	14	0	0	1	1.9	5.1
26	7.4	0	0	16.3	6.8	5.2	0	0	3	0	0	4.3
27	2.8	0	0.4	3.9	11.6	2.5	0	0.9	20.9	0	42	0
28	0	0	5.8	11.6	26.7	9.3	0	0	0	27.3	7.2	16
29	0	0		9.6	0	0	0	4.4	0	0	27.8	5.1
30	0	0		0	0	11.2	0	12.2	34.1	5.2	6.1	4.3
31	0	0		0		0		0.2	0.5		0	
TOTAL	89.9	34.2	24.7	87.9	225.8	153.6	84.2	23.9	126.1	193.3	272.9	208.6

Appendix 1.5: ANOVA on the effects of land uses on soil erosion rates under Andosols in the Rwenzori highlands using runoff plots

	d.f.	Sum Sq.	Mean Sq.	F-value	p-value
Land Use	3	90.31	30.10	4.06	0.0501

Residuals	8	59.28	7.41
Total	11		

Where d.f. is degree of freedom.

Appendix 1.6: ANOVA on the effects of land uses on soil erosion rates under Ferralsols in the Rwenzori highlands using runoff plots

	d.f.	Sum Sq.	Mean Sq.	F-value	p-value
Land Use	3	31.46	10.49	3.31	0.078
Residuals	8	25.34	3.17		
Total	11				

Where d.f. is degree of freedom.

Appendix 1.7: ANOVA on the effects of land uses on soil erosion rates under Andosols in the Rwenzori highlands using the RUSLE

	d.f.	Sum Sq.	Mean Sq.	F-value	p-value
Land Use	3	9341.1	3113.70	278.48	1.984e-08***
Residuals	8	89.4	11.18		
Total	11				

Where d.f. is degree of freedom.

Appendix 1.8: ANOVA on the effects of land uses on soil erosion rates under Ferralsols in the Rwenzori highlands using the RUSLE

	d.f.	Sum Sq.	Mean Sq.	F-value	p-value
Land Use	3	2469.89	823.30	97.172	1.239e-06***
Residuals	8	67.78	8.47		
Total	11				

Where d.f. is degree of freedom.