Sokoine University of Agriculture

MSc Dissertation

The Effects of Different Grazing Intensities on Soil properties in Miombo Woodlands of Tanzania

Hadija Ahmad Mchelu

May 2024

THE EFFECTS OF DIFFERENT GRAZING INTENSITIES ON SOIL PROPERTIES IN MIOMBO WOODLANDS OF TANZANIA

Dissertation Submitted to Sokoine University of Agriculture in Fulfilment of the Requirements of Masters of Science in Forestry

By

Hadija Ahmad Mchelu

Supervisors

Dr. Charles Joseph Kilawe

Prof. Salim Salim Maliondo

Department of Ecosystems and Conservation

College of Forestry, Wildlife and Tourism

Sokoine University of Agriculture, Morogoro, Tanzania

May 2024

EXTENDED ABSTRACT

This study was conducted at Miombo woodlands in Tanzania to enhance the sustainability of miombo woodlands in response to the increasing grazing pressure in miombo woodlands, driven by agricultural expansion, population growth, and rising demand for livestock products, has led to soil degradation, land scarcity, and socio-economic conflicts among land users. The study aimed to evaluate dynamics of selected soil physical and Soil organic carbon under different grazing intensities for sustainability of Miombo woodlands. The research used a purposive sampling and random sampling design. Grazing intensity was evaluated through two approaches: livestock stocking rates based on official records and a scoring method derived from field observations. Soil organic carbon (SOC) content was determined from topsoil samples collected from 188 plots whereas soil hydraulic conductivity (K_{fs}) and underground Water movement was estimated in 117 of these plots. Statistical analysis was carried out using R® software version 4.4.2, using Linear Mixed-Effects Models (LMM) and Gamma Generalized Linear Mixed-Effects Models (GLMM) with a random intercept. The results showed a slight agreement (k=0.14) between the stocking rate and scoring methods on classification of grazing intensities. Significant positive effects of increasing grazing intensity GI were observed on bulk density (BD) and preferential flow ($P<0.001$), while significant negative effects ($P<0.001$) were observed on SOC, (Kfs), percentage dye cover, and uniform infiltration flow. The mean SOC ranged from 2.38 ± 0.84% under light grazing intensity to 1.42 ± 0.75% under high grazing intensity. Kfs showed a mean range of 100.08-± 65.56 mmhr-1 under light grazing intensity to 27.28 ± 22.99 mmhr-1 under high grazing intensity, while BD ranged from 1.64 ± 0.12 gcm-3 under high grazing intensity to 1.34 ± 0.17 g cm-3 under light grazing intensity. The study recommends developing and implementing proper sustainable livestock management practices made to the specific conditions of Miombo ecosystems. Adhering to sustainable livestock management practices, to mitigate the adverse effects of grazing to ensure the sustainability of Miombo woodlands.

Keywords: Grazing, preferential flow, soil organic carbon, uniform infiltration depth
.

IKISIRI KUU

Utafiti huu ulifanyika katika misitu ya Miombo nchini Tanzania ili kuimarisha uendelevu wa misitu ya miombo ili kukabiliana na ongezeko la shinikizo la malisho katika misitu ya Miombo, linalochangiwa na upanuzi wa kilimo, ongezeko la watu na mahitaji ya mazao ya mifugo, kumesababisha uharibifu wa udongo, uhaba wa ardhi, na migogoro ya kijamii na kiuchumi miongoni mwa watumiaji wa ardhi. Utafiti ulilenga kutathmini mienendo ya udongo, kemikali na mali ya kibayolojia chini ya nguvu tofauti za malisho kwa ajili ya uendelevu wa misitu ya Miombo. Utafiti ulitumia sampuli madhubuti na muundo wa sampuli nasibu. Kiwango cha malisho kilitathminiwa kupitia mbinu mbili: viwango vya ufugaji wa mifugo kulingana na rekodi rasmi na mbinu ya alama inayotokana na uchunguzi wa shambani. Maudhui ya kaboni hai ya udongo (SOC) yalibainishwa kutokana na sampuli za udongo wa juu zilizokusanywa kutoka ploti 188 ambapo Kfs ilikadiriwa katika 117 kati ya ploti hizi. Zaidi ya hayo, utafiti ulichunguza athari za Nguvu Tofauti za Malisho kwenye Upenyezaji wa Udongo na Njia za Maji ya Chini ya Ardhi. Uchanganuzi wa takwimu ulifanywa kwa kutumia programu ya R® toleo la 4.4.2, kwa kutumia Miundo ya Linear ya Athari-Mseto (LMM) na Miundo ya Athari Mchanganyiko ya Gamma (GLMM) kwa kukatiza bila mpangilio. Matokeo yalionyesha makubaliano kidogo ($k=0.14$) kati ya kiwango cha hisa na mbinu za kufunga. Madhara makubwa chanya ya GI ya kiwango cha malisho ($P<0.001$) yalizingatiwa kwenye (BD) na mtiririko wa upendeleo, wakati athari mbaya ($P<0.001$) zilizingatiwa kwenye SOC, upitishaji majimaji ya udongo (Kfs), kiwango cha kupenyeza, kifuniko cha rangi. na mtiririko sare. Wastani wa SOC ulianzia 2.38 ± 0.84% chini ya kiwango cha malisho chepesi hadi 1.42 ± 0.75% chini ya kiwango kikubwa cha malisho. Vile vile, Kfs ilionyesha wastani wa 100.08 ± 65.56 mmhr-1 chini ya kiwango cha malisho chepesi hadi 27.28 ± 22.99 mmhr-1 chini ya kiwango cha juu cha malisho, wakati BD ilianzia 1.64 ± 0.12 gcm-3 chini ya ± 1 cm 1 hadi 1.3 cm. -3 chini ya nguvu nyepesi ya malisho. Viwango vya kufunika kwa rangi ni kati ya

60.43 ±11% katika GI nyepesi hadi 39.68±17% chini ya Kiwango cha juu cha malisho. Thamani ya kina cha mtiririko mmoja ni kati ya Kiwango cha Malisho ya Mwanga 27.70 ±12cm hadi 15.28±9.3cm chini ya Kiwango cha juu cha malisho, Thamani za mtiririko wa upendeleo ni kati ya 38.84±27% chini ya Kiwango cha juu cha malisho hadi 27.68±16% chini ya Kiwango cha malisho chepesi. Kulingana na matokeo, utafiti unapendekeza kuendeleza na kutekeleza mbinu endelevu za usimamizi wa mifugo zinazofanywa kwa hali mahususi za mifumo ikolojia ya Miombo. Zaidi ya hayo, kwa kuzingatia taratibu za usimamizi endelevu wa mifugo, wadau wanaweza kupunguza athari za malisho, kuhakikisha utoaji wa huduma muhimu za mfumo wa ikolojia kutoka misitu ya Miombo.

Maneno muhimu: Malisho, mtiririko wa upendeleo, kaboni hai ya udongo, kina cha kupenyeza sawa

DECLARATION

I, **HADIJA AHMAD MCHELU**, do hereby declare to the Senate of Sokoine University of Agriculture that, this thesis is my original work and that it has neither been submitted nor concurrently submitted for a degree award in any other institution

________________________ __________________

Hadija Ahmad Mchelu Date

(MSc Candidate)

The above declaration is confirmed by

________________________ __________________

Dr. Charles Joseph Kilawe Date

(Supervisor)

________________________ __________________

Prof. Salim Mohamed Maliondo Date

(Supervisor)

LIST OF MANUSCRIPTS

Manuscript 1: Increasing livestock grazing intensity reduces soil organic carbon and infiltration capacity in Miombo woodlands of Tanzania.

Manuscript 2: Effect of different grazing intensities on soil infiltration and underground water movement in Miombo woodland of Tanzania.

COPYRIGHT

ACKNOWLEDGMENT

First and foremost, praises and thanks go to Almighty God for the showers of blessings throughout my study period and its successful completion.

I express my gratitude to my supervisors, Dr. Charles J. Kilawe, Prof. Salim S. Maliondo, Dr. Aida Bargués-Tobella, and Prof.Gert Nyberg for their enthusiastic support and guidance throughout the research project. Their expertise in research methodology, along with their encouragement and mentorship, has been key in shaping my work.

Special thanks go to the Swedish Research Council [grant number 2021-04789_3] for providing funds for this study.

I would like to acknowledge the contributions of Dr. Lufunyo Lulandala during experimental design. Mr. John Shesige, Mr. Iddi Rajab, Mr. Huruma Mbonea, and Mr. John Mahomela, and Mr. Sudi Ramadhani for their contributions to data collection. Dr. Eva Mtengeti and Mr. Walter Msangi from SUA for the soil laboratory analysis for this study. District Councils for Kilombero, Kilosa and Handeni districts and the villagers surrounding village forests in the nine villages of Gole, Madebe, Kwamsundi, Chabima, Ihombwe, Ulaya Mbuyuni, Utengule, Iduindembo, and Miyomboni for their cooperation to carry out our study. Each individual mentioned above has played a great role in the success of this research, and for that, I am truly thankful.

DEDICATION

This work is dedicated to my parents Mr. and Mrs. Mchelu I am filled with joy to be your daughter. Your love and wisdom have shaped me into the person I am today. Thank you for everything. I would like to dedicate this work to all my friends and all those who believes in me through out in this long journey.

TABLE OF CONTENTS

EXTENDED ABSTRACT .... **i**
IKISIRI KUU .... **iii**
DECLARATION .... **v**
LIST OF MANUSCRIPTS .... **vi**
COPYRIGHT .... **vii**
ACKNOWLEDGMENT .... **viii**
DEDICATION .... **ix**
LIST OF TABLES .... **xiii**
LIST OF FIGURES .... **xiv**
LIST OF APPENDICES .... **xv**
LIST OF ABBREVIATIONS AND ACRONYMS .... **xvi**

CHAPTER ONE **1**
1.0 Introduction **1**
1.1 Background information 1
1.2 Problem statement and justification 2
1.2.1 Problem statement 2
1.2.2 Justification of the Study 3
1.3 Research objectives 4
1.3.1 Overall objective 4
1.3.2 Specific objectives 4
1.4 Research Questions 4
1.5 Study Limitations 5
1.6 Dissertation Structure 5
References 6

CHAPTER TWO **9**
Manuscript One 9
2.1 Abstract 10
2.2 Introduction 11
2.3 Methodology 12
2.3.1 Study Area description 12
2.3.2 Sampling design 13
2.3.4 Estimation of grazing intensity 14
2.3.4.1 Stocking rate method 14
2.3.4.2 Scoring method based 14

2.3.5 Soil samples collection 15
2.3.6 Soil Water infiltration measurement and estimation of field-saturated soil hydraulic conductivity 16
2.3.7 Laboratory analysis 16
2.3.8 Statistical analysis 17
2.4 Results 18
2.4.1 Comparison of the scoring and the stocking rate methods to estimate livestock grazing intensity 18
2.4.2 Effect of grazing intensity on soil organic carbon 19
2.4.3 Effect of grazing intensity on field-saturated soil hydraulic conductivity 19
2.4.4 Soil Bulk density across grazing Intensities 20
2.5 Discussion 21
2.6 Conclusions 23
References 25

CHAPTER THREE 32
Manuscript Two 32
3.1 Abstract 33
3.2 Introduction 34
3.3 Materials and Methods 36
3.3.1 Study area description 36
3.3.2 Sampling design 37
3.3.3 Grazing intensities estimation 37
3.3.4 Soil water infiltration measurement 38
3.3.5 Pathways measurement 39
3.4 Data Analysis 40
3.4.1 Soil water pathways analysis 40
3.4.2 Statistical analysis 42
3.5 Results 43
3.5.1 Field-saturated soil hydraulic conductivity across grazing intensity 43
3.5.2 Percentage dye coverage (DC, %) 44
3.5.3 Uniform infiltration depth 44
3.5.4 Preferential flow fraction 44
3.6 Discussions 46
3.7 Conclusions 48
References 49

CHAPTER FOUR 56
General Discussion 56
4.1 Effect of grazing intensities on soil organic carbon (SOC)..... 56
4.2 Effect of grazing intensities on soil physical properties (Kfs, BD and Preferential flow 56

CHAPTER FIVE.. 58
5.0 General conclusion and recommendations 58
5.1 Contribution of the study 58
5.2 Conclusion 58
5.3 Recommendations 59

References 60
APPENDICES 61

LIST OF TABLES

Table 2. 1: Criteria for awarding scores of GI based on the Scoring method... 15
Table 2. 2: Contingency table of frequency for grazing intensity determination using official livestock population and Scoring method... 18

LIST OF FIGURES

Figure 2. 1: Location of study sites within Handeni, Kilosa and Kilombero districts in Tanzania 13
Figure 2. 2: Boxplots (median, first and third quartile) of the SOC content under various grazing intensities based on Scoring method; dots indicate individual plot-level observations within each grazing intensity; p-values for the pair-wise comparisons (Tukey method) between different levels of GI are indicated............................ 19
Figure 2. 3: Boxplots (median, first and third quartile) of the Kfs across grazing intensities based on Scoring method; dots indicate individual plot-level observations within each grazing intensity; p-values for the pair-wise comparisons (Tukey method) between different levels of GI are indicated. 20
Figure 2. 4: Boxplots (median, first and third quartile) of the BD across grazing intensities based on Scoring method; dots indicate individual plot-level observations within each grazing intensity; p-values for the pair-wise comparisons (Tukey method) between different levels of GI are indicated. 21
Figure 3. 1: A map showing location of study sites within Handeni, Kilosa and Kilombero districts in Tanzania 36
Figure 3.2: Different grazing parameters for assessing grazing intensity in the forests (Picture was taken by Hadija Mchelu).. 38
Figure 3.3: Water infiltration and pathways measurement in the field (Picture was taken by Hadija Mchelu) 40
Figure 3.4: Example of soil profiles and classified soil profiles showing water infiltration pathways across different grazing intensities 43
Figure 3. 5: Boxplots (median, first and third quartile) of the Kfs, DC, Uniform Infiltration depth and Preferential flow across grazing intensities based on Scoring method; n indicate number of observations at each grazing intensity; p-values for the pair-wise comparisons (Tukey method) between different levels of GI are indicated. 45

LIST OF APPENDICES

Appendix 1: Village characteristics found in Handeni district 61
Appendix 2: Village characteristics found in Kilosa district 62
Appendix 3: Village characteristics found in Handeni district 63
Appendix 4: Summary of Linear mixed-effects models and Generalized Linear mixed-effects model explaining variation in Soil Organic Carbon (SOC), Soil Bulk Density (BD) and field-saturated soil hydraulic conductivity (Kfs) 64
Appendix 5: Summary of Linear mixed-effects models and Generalized Linear mixed-effects model explaining variation in field-saturated soil hydraulic conductivity (Kfs), Percentage Dye Coverage (DC%), Uniform infiltration depth, and Preferential Flow 66

LIST OF ABBREVIATIONS AND ACRONYMS

BD	Soil bulk density
CO_2	Carbon dioxide gas
GI	Grazing Intensity
Kf_s	Field-saturated soil hydraulic conductivity
REDD(+)	Reducing Emissions from Deforestation and forest Degradation
SOC	Soil organic carbon
SUA	Sokoine University of Agriculture

CHAPTER ONE

1.0 Introduction

1.1 Background information

Miombo woodland, cover approximately 270 million hectares across southern and eastern Africa, is a complex ecological social economic system crucial for the livelihoods of over 100 million people (Njana *et al.,* 2013; Ryan *et al.,* 2016). In Tanzania alone, it covers about 45 million hectares, comprising 80% of the country's woodland area (Campbell, 1996). Renowned for its crucial roles in ecosystem services and rural livelihoods (Campbell *et al.,* 2007; Chidumayo & Gumbo, 2010), Miombo woodland faces escalating degradation primarily due to human activities such as agricultural expansion (Kilawe *et al.,* 2018), illegal logging, wildfires (Ryan *et al.,* 2011), overgrazing, and charcoal production (Abdallah and Monela, 2007; Chidumayo and Gumbo, 2010). This factor contributes to an increasing scarcity of miombo woodlands (Mugasha *et al.,* 2017) and lowers its productivity in general (Lusambo *et al.,* 2007).

Livestock grazing, a widespread economic activity in Sub-Saharan Africa (Robinson *et al.,* 2011). While contributing substantially to the global economy, grazing practices are highly linked with land degradation (Robinson *et al.,* 2011). Excessive grazing emerges as a significant threat to the remaining Miombo woodland, leading to a 7% of degradation particularly affecting vegetation and soil health (Hosonuma *et al.,* 2012). Livestock grazing in Miombo woodlands is increasing because of by poor livestock grazing practices, growing demands for livestock products, and diminishing grazing resources in alternative vegetation types (Paul *et al.,* 2020). In Tanzania, some of the potential grazing areas, including forests adjacent to pastoralists, have been converted to wildlife protected areas or forest nature reserves (Gizachew *et al.,* 2020) and are thus not available for livestock grazing.
Studies have highlight the detrimental effect of increasing grazing intensities on soil health which leads to reduced soil organic carbon

(SOC) (Navarro-Perea *et al.,* 2023; Wei *et al.,* 2011), reduces soil hydraulic conductivity capacity (Kfs) , and increase soil nutrient loss and erosion (Bargués-Tobella *et al.,* 2024), increases soil compaction (BD) and surface runoff (Lulandala *et al.,* 2022), lowers plant diversity and soil cover (Mtimbanjayo & Sangeda, 2018; Wang *et al.,* 2016) and thus, increases land scarcity to support livestock (Mtimbanjayo and Sangeda, 2018). Intensive grazing reduces the amount of vegetation and slows down plant growth, resulting in a decrease in soil organic carbon levels (Jiang *et al.,* 2020; Wang *et al.,* 2016). Livestock trampling increases soil compression causing soil structure deformation and low soil porosity impeding soil water movements (Bargués-Tobella *et al.,* 2024; Lulandala *et al.,* 2022). Despite its critical implications on soil, the effects of increasing grazing intensity on soil health are unpredictable and yet their quantitative information is under-researched in Miombo woodlands. There is a notable gap on the effect of different grazing intensities on soil properties including SOC, Kfs, and soil underground water ways in Miombo woodlands of Tanzania.

1.2 Problem statement and justification

1.2.1 Problem statement

Overgrazing is among listed factors causing soil degradation (Lupala *et al.,* 2015) as a result increases land scarcity (Zhang *et al.,* 2019). In that context, more pastoralists shift and invade new areas in the Miombo woodland increasing pressure to the remaining woodlands (Mtimbanjayo and Sangeda, 2018), causing conflicts between land users (Benjaminsen *et al.,* 2009). Traditional grazing management systems have been reported to inadequate dealing with rising grazing pressure (Ruvuga *et al.,* 2020). Studies have shown that excessive pressure from grazing increases soil variation, soil erosion, reduces soil permeability, infiltration, SOC, soil productivity, soil quality and plant diversity (Amiri *et al.,* 2008; Mihertu *et al.,* 2021; Wang *et al.,* 2016; Wei *et al.,* 2011; Zhang *et al.,* 2019; Zhao *et al.,* 2007; Zhou *et al.,* 2017). However, little has been done in Miombo woodlands to document the effects of increasing grazing intensities on soil properties. Majority of existing researches in Miombo woodlands have focused on the effect of grazing practices on the vegetations and single biome of Miombo woodland in the country (Lulandala *et al.,* 2022; Mtimbanjayo & Sangeda, 2018; Ruvuga *et al.,* 2020, 2021). As it has been pointed out, livestock grazing is increasing in the Miombo ecosystem and also under-researched area, thus there is a need to clarify the effect of grazing intensity on the soil health of Miombo woodlands of Tanzania for soil and Miombo productivity and ecosystem functioning as whole.

1.2.2 Justification of the Study

Understanding the dynamics of soil properties under different grazing intensities is crucial for proper management of soil and sustainability of Miombo ecosystems. This study explores the effect of different grazing intensities on soil-selected properties (SOC, Kfs, and soil water preferential flow) in Miombo woodlands across diverse climates and landforms covering the whole biome in Tanzania. SOC is good indicator of soil health as it explains soil nutrient level, soil colour, soil structure, soil organic matter, Cation and Anion Exchange Capacity. Soil infiltration capacity determines soil moistures and influence plant growth thus can be used to indicator of soil health. Therefore, this study will assess the impact of grazing intensities on SOC, BD and K_{fs} in Miombo woodlands of Tanzania. Healthier soil is among of the important carbon pools thus its management will contribute to Carbon emissions sequestration, which is fundamental to global climate change mitigation (Bond, 2010; Miles *et al.,* 2009). Soil also acts as a universal water reservoir; with healthier soil, we can provide reliable water access that is the key to UN sustainable Development Goals with Goal no: 6 which aim to ensure availability and sustainable management of water and sanitation for all. Nevertheless, understanding the effect of grazing intensities on soil will contribute to existing scientific knowledge for management strategies and policy processes for solving land conflicts, managing soil and Miombo woodlands, which harbor the largest share of forest vegetation in the country.

1.3 Research objectives

1.3.1 Overall objective

The overall objective of the study was to assess the effect of grazing intensity on soil properties in Miombo Woodland of Tanzania

1.3.2 Specific objectives

The specific objectives of this study were to:

i. To assess the effect of different grazing intensities on Soil Organic Carbon (SOC)
ii. To assess the effect of different grazing intensities on selected soil physical properties (Soil Bulk Density (BD), Soil hydraulic conductivity (Kfs) and underground water movement)

1.4 Research Questions

The study aimed to answer the following questions

1. To assess the effect of different grazing intensities on soil biological properties
   i. How does varying grazing intensity impact organic carbon content of a soil?
   ii. What are the specific changes in SOC under different grazing intensities?

2. To assess the effect of different grazing intensities on soil physical properties
   i. How does varying grazing intensity affect BD, Kfs and underground water movement of soil under Miombo woodlands?
   ii. How are the alterations of soil structure and porosity affects soil water infiltration, underground water movement with varying grazing intensities?
   iii. What are the specific changes in BD, Kfs and underground water movement across grazing intensities?

1.5 Study Limitations

This study focused only the effects of grazing intensities on some of soil properties and therefore, there were no other interactions from factors such as wildfire and trees studied in this work.

1.6 Dissertation Structure

This dissertation follows a structured format, having five main chapters designed in the format of publishable manuscripts. Chapter one provides the introduction, showing the background information of the study. It addresses the problem statement, provides justification for the research, and outlines the study's objectives, research questions, and limitations. Chapter two, presented as Manuscript one, explains the Increasing livestock grazing intensity reduces soil organic carbon and infiltration capacity in Miombo woodlands of Tanzania. Chapter three, presented as Manuscript two, focuses on effect of different grazing intensities on soil infiltration and underground water ways in Miombo woodland of Tanzania. Chapter four provides the general discussion of the study’s findings. Chapter five summarizes the study's key contributions and presents general conclusions drawn from the research findings. Additionally, it offers valuable recommendations.

References

Abdallah, J. M., & Monela, G. G. (2007). Overview of Miombo woodlands in Tanzania. Proceedings of the First MITMIOMBO Project Workshop, Morogoro, Tanzania, 50, 9–23.

Bargués-Tobella, A., Winowiecki, L. A., Sheil, D., & Vågen, T.-G. (2024). Determinants of Soil Field-Saturated Hydraulic Conductivity Across Sub-Saharan Africa: Texture and Beyond. Water Resources Research, 60(1), e2023WR035510.

Bond, I. (2010). REDD+ in dryland forests: Issues and prospects for pro-poor REDD in the miombo woodlands of southern Africa (Issue 21). IIED.

Gizachew, B., Rizzi, J., Shirima, D. D., & Zahabu, E. (2020). Deforestation and connectivity among protected areas of Tanzania. Forests, 11(2), 170.

Hosonuma, N., Herold, M., De Sy, V., De Fries, R. S., Brockhaus, M., Verchot, L., Angelsen, A., & Romijn, E. (2012). An assessment of deforestation and forest degradation drivers in developing countries. Environmental Research Letters, 7(4), 044009.

Jiang, Z.-Y., Hu, Z.-M., Lai, D. Y., Han, D.-R., Wang, M., Liu, M., Zhang, M., & Guo, M.-Y. (2020). Light grazing facilitates carbon accumulation in subsoil in Chinese grasslands: A meta-analysis. Global Change Biology, 26(12), 7186–7197.

Kilawe, C. J., Mertz, O., Birch-Thomsen, T., & Maliondo, S. M. (2018). Transformation of shifting cultivation: Extent, driving forces and impacts on livelihoods in Tanzania. Applied Geography, 94, 84–94.

Lulandala, L., Bargués-Tobella, A., Masao, C. A., Nyberg, G., & Ilstedt, U. (2022). Excessive livestock grazing overrides the positive effects of trees on infiltration capacity and modifies preferential flow in dry miombo woodlands. Land Degradation & Development, 33(4), 581–595.

Mtimbanjayo, J. R., & Sangeda, A. Z. (2018). Ecological effects of cattle grazing on Miombo tree species regeneration and diversity in Central-Eastern Tanzania. Journal of Environmental Research, 2(13), 1–7.

Mugasha, W. A., Eid, T., Bollandsås, O. M., & Mbwambo, L. (2017). Modelling diameter growth, mortality and recruitment of trees in miombo woodlands of Tanzania. Southern Forests: A Journal of Forest Science, 79(1), 51–64

Navarro-Perea, M., Pueyo, Y., Moret, D., Valverde, Á., Igual, J. M., & Alados, C. L. (2023). Plant-soil interactions in response to grazing intensity in a semi-arid ecosystem from NE Spain. Arid Land Research and Management, 37(2), 184–196

Njana, M. A., Kajembe, G. C., & Malimbwi, R. E. (2013). Are miombo woodlands vital to livelihoods of rural households? Evidence from Urumwa and surrounding communities, Tabora, Tanzania. Forests, Trees and Livelihoods, 22(2), 124–140.

Paul, B. K., Groot, J. C. J., Birnholz, C. A., Nzogela, B., Notenbaert, A., Woyessa, K., Sommer, R., Nijbroek, R., & Tittonell, P. (2020). Reducing agro-environmental trade-offs through sustainable livestock intensification across smallholder systems in Northern Tanzania. International Journal of Agricultural Sustainability, 18(1), 35–54. https://doi.org/10.1080/14735903.2019.1695348

Robinson, T. P., Thornton, P. K., Francesconi, G. N., Kruska, R. L., Chiozza, F., Notenbaert, A. M. O., Cecchi, G., Herrero, M. T., Epprecht, M., & Fritz, S. (2011). Global livestock production systems. FAO and ILRI.

Ruvuga, P. R., Wredle, E., Mwakaje, A., Selemani, I. S., Sangeda, A. Z., Nyberg, G., & Kronqvist, C. (2020). Indigenous Rangeland and Livestock Management Among Pastoralists and Agro-pastoralists in Miombo Woodlands, Eastern Tanzania. Rangeland Ecology & Management, 73(2), 313–320.

Ruvuga, P. R., Wredle, E., Nyberg, G., Hussein, R. A., Masao, C. A., Selemani, I. S., Sangeda, A. Z., & Kronqvist, C. (2021). Evaluation of rangeland condition in miombo woodlands in eastern Tanzania in relation to season and distance from settlements. Journal of Environmental Management, 290, 112635.

Ryan, C. M., & Williams, M. (2011). How does fire intensity and frequency affect miombo woodland tree populations and biomass? Ecological Applications, 21(1), 48–60.

Ryan, C. M., Pritchard, R., McNicol, I., Owen, M., Fisher, J. A., & Lehmann, C. (2016). Ecosystem services from southern African woodlands and their future under global change. Philosophical Transactions of the Royal Society B: Biological Sciences, 371(1703), 20150312.

Thomas, A. D. (2012). Impact of grazing intensity on seasonal variations in soil organic carbon and soil CO2 efflux in two semiarid grasslands in southern Botswana. Philosophical Transactions of the Royal Society B: Biological Sciences, 367(1606), 3076–3086.

Timberlake, J., Chidumayo, E., & Sawadogo, L. (2010). Distribution and characteristics of African dry forests and woodlands. The Dry Forests and Woodlands of Africa: Managing for Products and Services, 2, 11–41.

Wachiye, S., Pellikka, P., Rinne, J., Heiskanen, J., Abwanda, S., & Merbold, L. (2022). Effects of livestock and wildlife grazing intensity on soil carbon dioxide flux in the savanna grassland of Kenya. Agriculture, Ecosystems & Environment, 325, 107713.

Wang, Z., Johnson, D. A., Rong, Y., & Wang, K. (2016). Grazing effects on soil characteristics and vegetation of grassland in northern China. Solid Earth, 7(1), 55–65.

Wei, L., Hai-Zhou, H., Zhi-Nan, Z., & Gao-Lin, W. (2011). Effects of grazing on the soil properties and C and N storage in relation to biomass allocation in an alpine meadow. Journal of Soil Science and Plant Nutrition, 11(4), 27–39.

CHAPTER TWO

Manuscript One

Increasing Livestock Grazing Intensity Reduces Soil Organic Carbon and Infiltration Capacity in Miombo Woodlands of Tanzania

Hadija Ahmad Mchelu[a*], Charles Joseph Kilawe[a], Aida Bargués-Tobella[b], Thadei Tarcis Rugambwa[a], Ikabongo Mukumbuta[bc], Salim Mohamed Maliondo[a], Gert Nyberg[b]

[a]*Department of Ecosystems and Conservation, Sokoine University of Agriculture, P.O. Box 3010, Chuo Kikuu, Morogoro, Tanzania*

[b]*Department of Forest Ecology and Management, Swedish University of Agricultural Sciences, 901 83, Umeå, Sweden*

[c]*Golden Valley Agricultural Research Trust, P.O Box RW 50834, Lusaka, Zambia*

[*]Corresponding author e-mail: hadija.mchelu@sua.ac.tz

Status: The material contained in this paper has been submitted to the Journal of Environmental Management *[JEMA-D-24-05587]*

2.1 Abstract

The intensity of livestock grazing has been increasing in Miombo woodlands as a result of rising livestock numbers and limited grazing resources in alternative vegetation types. Increasing grazing intensity poses concerns for soil health, but empirical evidence on the impact of livestock grazing intensity on soil degradation in Miombo woodlands remains insufficient. In this study, we investigated the effect of light, medium, and high grazing intensities (GI) on soil organic carbon (SOC) and field-saturated soil hydraulic conductivity (Kfs) across nine Miombo woodlands spanning three districts in Tanzania with diverse climates and landforms. Grazing intensity was assessed using two methods: livestock stocking rates based on official livestock population records, and scoring method based on field observations. SOC content was determined from topsoil samples collected from 188 plots whereas Kfs was estimated in 117 of these plots. There was a slight agreement (40%) between the stocking rate and scoring methods on the classification of grazing intensities. Our results indicate that medium and high grazing intensities substantially reduced SOC content and Kfs compared to light grazing intensity. These findings suggest that Miombo woodland soils can remain healthy under light grazing but could be degraded under medium and high grazing intensities. Consequently, efforts should be directed towards promoting management practices that reduce the number and frequency of livestock grazing in Miombo woodlands, especially in areas designated for water and biodiversity conservation

Keywords: Bulk density; Grazing; Soil health; Soil water; Soil degradation

2.2 Introduction

Miombo woodlands, characterized by trees belonging to the genera Brachystegia, Julbernardia, Isoberlinia, and other legume trees in the family Fabaceae, subfamily Caesalpinioideae (White, 1983), span approximately 270 million square kilometers across Southern Africa, encompassing countries such as Angola, Botswana, Namibia, Zambia, Zimbabwe, Malawi, Mozambique, and Tanzania (White, 1983). In Tanzania, these woodlands constitute around 80% of the total woodland area (Campbell, 1996), providing valuable ecosystem services that are vital for supporting the livelihoods and well-being of the local population and other global benefits (Abdallah & Monela, 2007; Gumbo *et al.,* 2018; Ryan *et al.,* 2016). However, Miombo woodlands face escalating threats from anthropogenic activities such as agriculture expansion (Doggart *et al.,* 2020; Kilawe *et al.,* 2018), wildfires (Ryan and Williams, 2011; Tarimo *et al.,* 2015), charcoal extraction (Lusambo *et al.,* 2007) and overgrazing (Lulandala *et al.,* 2022; Mtimbanjayo and Sangeda, 2018).

The intensity of livestock grazing within Miombo woodlands is increasing rapidly as a result of the rising demand for livestock products alongside diminishing grazing resources in alternative vegetation types (Paul *et al.,* 2020). In Tanzania, several potential grazing areas, including forests adjacent to pastoralists and Miombo woodlands, have been converted to wildlife protected areas or forest nature reserves (Mwambene *et al.,* 2014; Gizachew *et al.,* 2020) and are thus not available for livestock grazing. Previous studies have highlighted the potential negative impacts of high grazing intensities on soil carbon storage (Klumpp *et al.,* 2009; Navarro-Perea *et al.,* 2023; Thomas, 2012; Wachiye *et al.,* 2022), soil infiltration capacity (Lulandala *et al.,* 2022), plant cover, composition and diversity (Andrew, 2021; Mtimbanjayo and Sangeda, 2018; Wang *et al.,* 2016), and soil erosion and nutrient depletion (Wang *et al.,* 2016; Wei *et al.,* 2011). Intensive livestock grazing reduces vegetation cover and growth which in turn reduces SOC (Jiang *et al.,* 2020; Wang *et al.,* 2016). Livestock trampling increases soil compression causing soil structure deformation and low soil porosity impeding soil water movements (Bargués-Tobella *et al.,* 2024).

Despite existing research on the impacts of livestock grazing intensity on vegetation (Andrew, 2021; Mtimbanjayo and Sangeda, 2018; Ruvuga *et al.,* 2020, 2021), a notable gap persists regarding its effect on SOC and infiltration capacity in Miombo woodlands. While Lulandala et al. (2022) demonstrated the detrimental impact of excessive livestock grazing on SOC and water infiltration, their study focused only on one woodland on a transition from Coastal Forest to Miombo woodland. In this study, we conduct a comprehensive assessment of the effect of livestock grazing intensity on SOC and soil infiltration capacity across diverse climates and landforms within Tanzanian Miombo woodlands. Additionally, we compare two grazing intensity assessment methods: the stocking rate method based on official livestock population records in the study villages and scoring method based on field observations. We hypothesize that high grazing intensities will negatively affect SOC and soil infiltration capacity.

2.3 Methodology

2.3.1 Study Area description

The study was conducted across nine villages situated in the Kilosa (Ihombwe, Ulaya mbuyuni and Chabima), Handeni (Madebe, Gole and Kwamsundi) and Kilombero (Miyomboni, Utengule and Iduindembo) Districts of Tanzania (Fig. 2.1). These villages encompass a wide range of Miombo ecosystems, spanning from dry to wet conditions (Table S1 in electronic supplementary materials, ESM). Approximately 50% of the local communities in these areas are pastoralists, with livestock grazing representing the second most important economic activity (Kabuye, 2015). There are three main groups of communities engaged in different livestock management practices in these villages: 1) Farming communities involved in agricultural activities 2) Agro-pastoralist communities practicing both extensive livestock keeping and farming, and 3) Pastoralist communities engaged primarily in extensive livestock keeping.

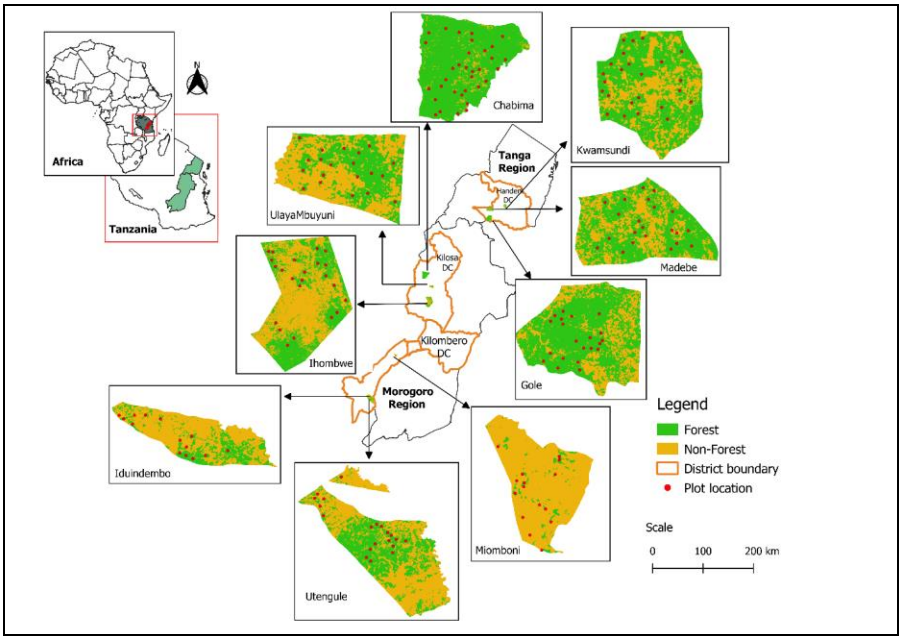

Figure 2. 1: Location of study sites within Handeni, Kilosa and Kilombero districts in Tanzania

2.3.2 Sampling design

The study utilized a two-phase sampling design approach. In the first phase, a purposive sampling design was employed to select three districts in Tanzania based on the presence of Miombo woodlands and grazing activities. The selected districts aimed to represent the Miombo woodlands across a climatic gradient in Tanzania, ranging from dry Miombo (Handeni), intermediate (Kilosa) to wet (Kilombero) Miombo (Table S1, ESM). In the second phase, all villages in the three districts with Miombo and grazing activities were listed, and three villages per district were randomly selected to represent each grazing intensity category, according to the official livestock population records. The area within each village was classified into forest and non-forest strata using a supervised classification in QGIS. Sampling plots (50 m x 20 m) were then randomly distributed within the forest stratum for data collection (Fig. 2.1).

2.3.4 Estimation of grazing intensity

To estimate livestock grazing intensity, we employed two different methods: the stocking rate based on official livestock population records, and scoring methods based on field observations.

2.3.4.1 Stocking rate method

Grazing intensity (GI) was determined as the ratio between the total livestock count registered in the village and the available grazing area in Miombo woodlands within a particular village (equation 1). To determine the available grazing area within the Miombo woodland, we considered the woodland area after deducting 35% to account for unsuitable grazing areas, such as inaccessible areas due to steep slopes and poor resources (Meshesha *et al.,* 2019). The tropical livestock unit (TLU) was adopted to calculate the number of livestock. Livestock numbers were converted to TLU using standard conversion factors: 0.7 TLU for cattle and 0.1TLU for small ruminants (goats/sheep) (FAO, 2019). We established three different grazing intensity (GI) categories based on the stocking rate (SR): Light GI if SR ≤ 0.2TLU/ha/yr, medium GI if 0.3 < SR < 0.4 TLU/ha/yr, and high GI if SR ≥0.5 TLU/ha/yr. These categories were adopted from Kikoti and Mligo, (2015) with some adjustments to fit the environmental conditions of the study area.

$$\boldsymbol{Stocking\ rate(TLU/ha/yr)} = \frac{\boldsymbol{Total\ number\ of\ Livestock\ (TLU)}}{\boldsymbol{Grazing\ Area\ in\ Miombo\ woodland}} \qquad \textbf{(1)}$$

2.3.4.2 Scoring method based

In each plot, we assessed grazing intensity using the scoring method proposed by Lulandala *et al*. (2022), which is based on field observations. This method involves evaluating and scoring three parameters: 1) signs of livestock presence (such as droppings), 2) livestock paths and hoof prints on the soil surface, and 3) proportion of grazed vegetation. Specific criteria for assigning scores are outlined in Table 2.1. The individual scores were aggregated to derive an overall plot score. The plot-level grazing intensity was classified into one of three classes: Light GI (total scores of 1 to 3), Medium GI (total scores of 4 to 6), and High GI (total scores of 7 to 9).

Table 2. 1: Criteria for awarding scores of GI based on the Scoring method

Scores / Parameters	1	2	3
1. Signs of livestock or presence (such as droppings)	i. Very little evidence of the animal presence i.e.; droppings <30% of the plot area	i. Clear evidence of the animal presence i.e.; droppings >30% of the plot area	i. Clear evidence of the animal presence i.e.; droppings >70% of plot area ii. The area is characterized by a smell of urine
2. Livestock paths and hoof prints on the soil surface	ii. The soil is practically appearing undisturbed iii. Very few hoofs print (sometimes can even be counted)	ii. Visible evidence of livestock trailing and hoof prints (can't be individually counted) iii. Parts of soil surface is slightly exposed	iii. Livestock trailing and hoof prints are clearly seen cover more than 70% of plot area iv. Most of soil parts are exposed as a result of livestock activity
3. Proportion of grazed vegetation.	iv. Young plants are slightly disturbed v. Forage plants are slightly consumed (<30%) vi. Poor forage plants are not consumed	iv. Forage plants are used or have stalks left to a maximum of 50% v. Some young plants show damages vi. Poor forage plants are slightly used	v. Most of the good forage plants are used (>70%) and don't have stalks left vi. Sometimes some of the poor forage plants are used vii. Many young plants show damages

Note for Table 2.1: The scoring of each parameter was done independently by assessing percentage coverage at plot level

2.3.5 Soil samples collection

Soil sampling was conducted between November 2022 and April 2023. In each study village, 20-22 sample plots were randomly selected (Table S2, ESM). A rectangular plot measuring 50m x 20m (0.1 ha) was established, with five sub-plots located at the corners and center of each plot. Topsoil (0-10 cm) samples were collected from the center of each sub-plot, combined to form a composite sample and transferred to a clearly labeled plastic bag. Bulk density (BD) samples were obtained from the center sub-plot using a steel soil core ring with 10cm height and 6.4 cm diameter.

2.3.6 Soil Water infiltration measurement and estimation of field-saturated soil hydraulic conductivity

Soil infiltration was measured in 117 plots randomly selected among the 188 (Appendix 4). Water infiltration was measured following the methodology outlined in Bargués-Tobella *et al.* (2024). At the center of each plot, a single ring infiltrometer with an inner diameter of 30 cm and a height of 30 cm was inserted 5 cm into the soil. Pre-wetting was conducted for 15 minutes by filling the ring with water to a level of at least 15 cm and allowing it to infiltrate. Subsequently, the ring was filled with water up to 20 cm, and the water level was recorded after 5 minutes. After reading the water level, the ring was immediately refilled to the start level. This process was repeated at intervals of 5 minutes for the first half-hour, 10 minutes for the second half-hour, and finally every 20 minutes for the second hour of the infiltration experiment. Infiltration rates were calculated for each interval by subtracting the final water level from the initial one and dividing it by the time interval. Topsoil field-saturated hydraulic conductivity (K_{fs}) was estimated from the infiltration rates using the procedure described by Bargués-Tobella *et al*. (2024).

2.3.7 Laboratory analysis

Soil samples were analyzed at the Soil Laboratory of the Department of Ecosystems and Conservation at Sokoine University of Agriculture in Morogoro, Tanzania. Soil samples were air-dried and sieved through a 2mm wire mesh to remove roots, stones, and gravel. SOC was analyzed by the Walkley-Black wet oxidation method (Nelson and Sommers, 2015). Soil texture was analyzed by the Bouyoucos hydrometer method (Gee and Bauder, 2018). Bulk density was determined from the undisturbed soil samples as the ratio of oven dry mass of the soil to the volume of the soils (Blake, 1965). Samples from the field were oven-dried at 105℃ for 24 hours and weighted after cooling in a desiccator for BD determination.

2.3.8 Statistical analysis

The degree of agreement between the two methods used to estimate livestock grazing intensity, the stocking rate and scoring methods, was determined using the weighted Cogen's Kappa (k). The following levels of agreement recommended by Watson and Petrie, (2010) were adopted for judging the extent of the agreement between the two methods: Poor, if $k < 0.00$; slight, if $0.00 \leq k \leq 0.20$; fair, if $0.21 \leq k \leq 0.40$; moderate, if $0.41 \leq k \leq 0.60$; substantial if $0.61 \leq k \leq 0.80$, and almost perfect if $k > 0.80$ (Watson and Petrie, 2010).

Linear mixed-effects models (LMM) with a random intercept were used to assess the effect of grazing intensity on SOC and BD. A gamma generalized linear mixed-effects model (GLMM) with a log-link function and a random intercept was used to test the effect of grazing intensity on K_{fs}. We adopted a GLMM in the case of K_{fs} because this data showed a Gamma-like distribution. In both LMMs and the GLMM, the grazing intensity was treated as a fixed factor, while villages nested within districts were considered random effects. The LMMs were fitted using the function "*lmer*" within the "lme4" package (Bates *et al.,* 2009), while the GLMM was fitted using the function "*glmmTMB*" in the "*glmmTMB*" package (Bolker, 2016). The guidelines by Zuur *et al*. (2013) were followed to check that model assumptions for LMMs and Gamma GLMMs were not violated. The function "*check model*" in the "*performance*" package (Lüdecke *et al.,* 2021) was used to visually assess the lack of heteroscedasticity, non-linear patterns and the normality of random effects and of residuals.

Overall model performance was evaluated using marginal and conditional R^2 (Nakagawa *et al.,* 2017), as well as Interclass Correlation Coefficient (ICC) (Hox *et al.,* 2017), which were computed using the "performance" package. Marginal R^2 quantifies the variance explained by the fixed effects only, while conditional R^2 considers variance explained by both the fixed and random effects (Nakagawa *et al.,* 2017). We also performed post-hoc pairwise comparisons between the different levels of grazing intensity using the function *"emmeans*" from the "*emmeans*" package (Lenth and Lenth, 2018). This function compares the means using the Tukey method to test differences between the different levels of grazing intensity. All statistical analyses were conducted using R version 4.4.2 (R Core Team, 2023).

2.4 Results

2.4.1 Comparison of the scoring and the stocking rate methods to estimate livestock grazing intensity

The weighted Cohen's kappa analysis indicated a slight agreement between the stocking rate and scoring methods, yielding a coefficient of k=0.14. Out of the total 188 observations, there were 76 instances of observed agreements, accounting for 40% of the total (Table 2.2). Interestingly, a relatively higher level of agreement between the two methods was observed in plots classified as having high GI compared to those having light or medium GI.

Table 2. 2: Contingency table of frequency for grazing intensity determination using official livestock population and Scoring method

	Scoring method				
	Grazing Intensity	**Light GI**	**Medium GI**	**High GI**	**Total**
Stocking rate Based on number of livestock population	Light GI	14	10	18	42
	Medium GI	27	13	26	66
	High GI	13	18	49	80
	Total	54	41	93	188

2.4.2 Effect of grazing intensity on soil organic carbon

Results from the LMM indicated a significant negative effect of grazing intensity on SOC (Figure 2.2, Appendix 4). Tukey's pairwise comparisons showed that mean SOC was significantly ($p < 0.05$) higher under light GI (2.38 ± 0.84 %) compared to medium GI (1.85± 0.74%) high GI (1.42 ± 0.75%). However, there was no significant difference between SOC levels under medium GI and high GI ($p>0.05$) (Fig. 2.2).

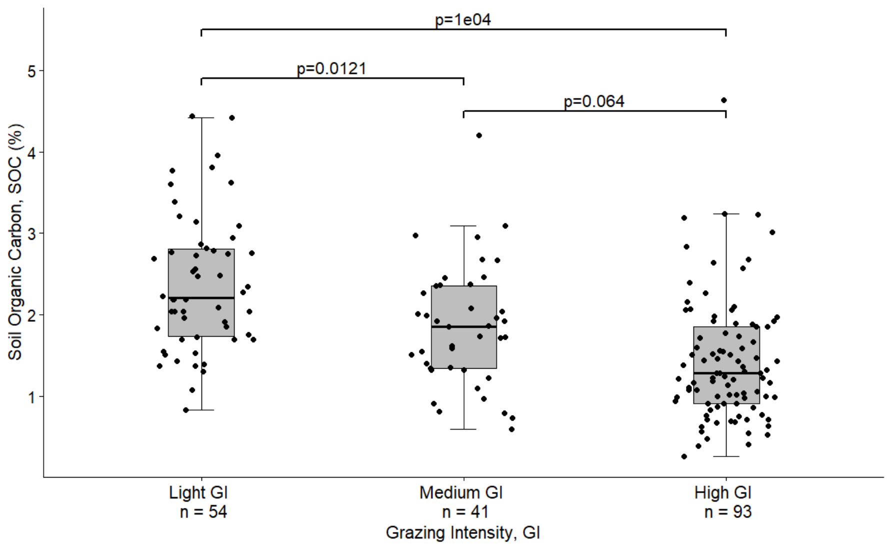

Figure 2. 2: Boxplots (median, first and third quartile) of the SOC content under various grazing intensities based on Scoring method; dots indicate individual plot-level observations within each grazing intensity; p-values for the pair-wise comparisons (Tukey method) between different levels of GI are indicated.

2.4.3 Effect of grazing intensity on field-saturated soil hydraulic conductivity

Results from the GLMM revealed a significant negative effect of grazing intensity on the K_{fs} (Figure 2.3, Appendix 4). Tukey's pairwise comparisons indicated that the mean Kfs was significantly ($P < 0.05$) higher under light GI (100.08 ± 65.56 mmhr-1) compared to medium (62.73 ± 54.88 mmhr-1) and high GI (27.28 ± 22.99 mmhr-1). A significant difference in K_{fs} was also observed between medium GI and high GI with p<0.05.

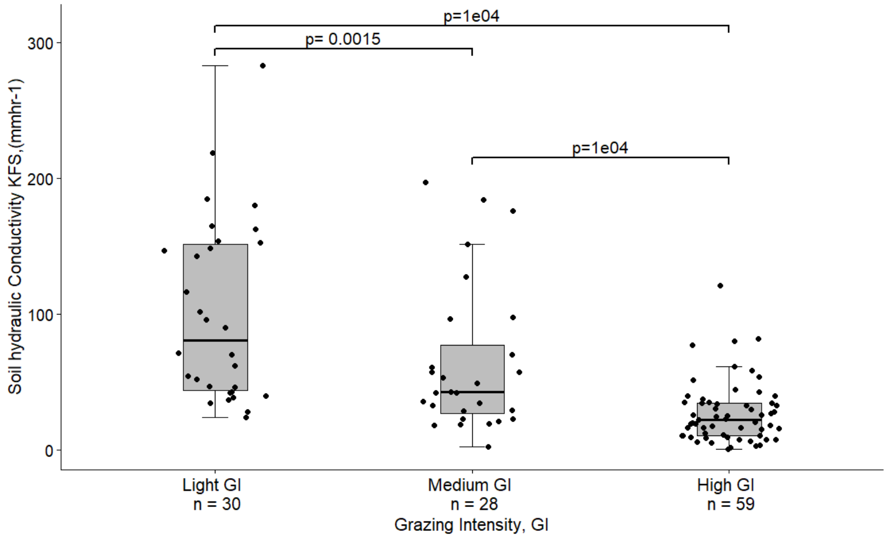

Figure 2. 3: Boxplots (median, first and third quartile) of the K_{fs} across grazing intensities based on Scoring method; dots indicate individual plot-level observations within each grazing intensity; p-values for the pair-wise comparisons (Tukey method) between different levels of GI are indicated.

2.4.4 Soil Bulk density across grazing Intensities

Results from the LMM indicated a significant positive effect of grazing intensity on BD (Figure 2.4, Appendix 4). Tukey's pairwise comparisons indicate that mean BD was significantly ($p < 0.05$) higher under high GI (1.64 ± 0.12 gcm-3) than under light GI (1.34 ± 0.17 g cm-3) and medium GI (1.45 ± 0.12 gcm-3). A significant difference in BD was also observed between medium GI and high GI with p<0.05.

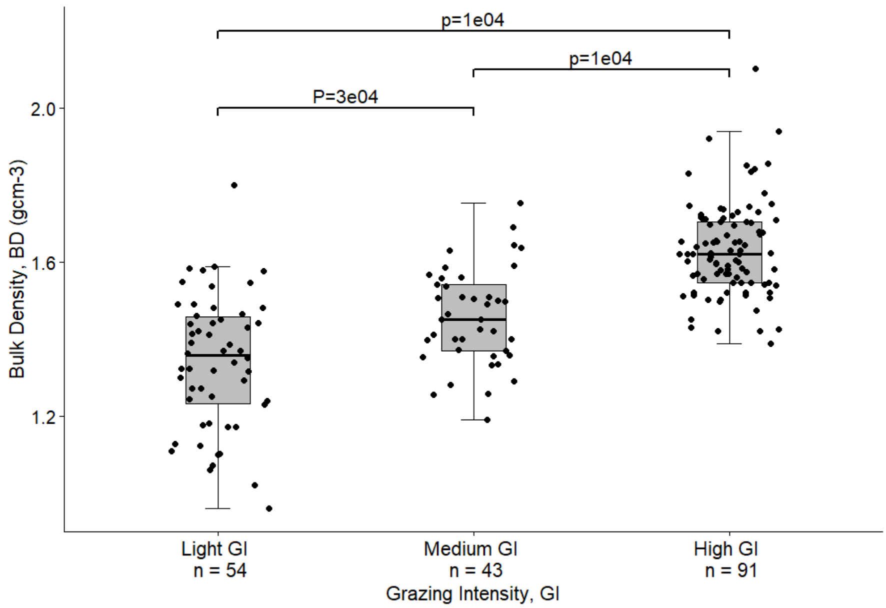

Figure 2. 4: Boxplots (median, first and third quartile) of the BD across grazing intensities based on Scoring method; dots indicate individual plot-level observations within each grazing intensity; p-values for the pair-wise comparisons (Tukey method) between different levels of GI are indicated.

2.5 Discussion

The study revealed only a moderate (40%) level of agreement between the individual scoring and stocking rate methods for assessing livestock grazing intensities. The scoring method, based on field observations, was deemed more realistic and reliable, which is consistent with previous findings (Lulandala *et al.,* 2022; Mathewos *et al.,* 2023). The observed discrepancy between the two methods may arise from the inherent challenges in maintaining accurate official livestock records, particularly in areas with pastoralist communities where animals migrate seasonally. This mobility underscores the challenge of managing grazing in forested areas like Miombo woodlands, highlighting the strength of the scoring method in such contexts.

Our results indicate a significant decline in soil infiltration capacity and SOC content, alongside a significant increase in bulk density under medium and high grazing intensities as compared to light grazing intensity. These findings agree with our hypothesis and previous studies conducted in Miombo woodlands (Lulandala *et al.,* 2022) and in other vegetation types and land uses (Bargués-Tobella *et al.,* 2024; Falk *et al.,* 2024; Jiang *et al.,* 2020; Navarro-Perea *et al.,* 2023). Medium and high grazing intensity reduces plant biomass deposition and decomposition, leading to lower SOC levels (Wang *et al.,* 2016). Livestock trampling reduces soil vegetation cover and expose the soil surface to erosion agents such as wind and water which ultimately lowers SOC at upper soil layers (Klumpp *et al.,* 2009). In addition, excessive trampling and reduced SOC content can deteriorate soil structure (Zhao *et al.,* 2007), including reduced soil aggregate stability and soil porosity (Klumpp *et al.,* 2009), which in turn decreases soil infiltration capacity (Bargués-Tobella *et al.,* 2024). Reduced soil infiltration capacity might increase water insecurity through increased surface runoff, soil erosion, flooding, and reduced groundwater recharge (Bargués Tobella *et al.,* 2014).

Furthermore, we observed higher SOC and infiltration capacity in lightly grazed areas compared to medium and high grazed areas. SOC levels in lightly grazed areas were twice as high as those in heavily grazed areas. This finding is consistent with previous studies in Miombo woodlands (Lulandala *et al.,* 2022) and underscores the critical role of vegetation cover in enhancing soil organic matter. Plant roots enhance soil aggregation and stability, creating macropores that facilitate water flow in the soil (Mair *et al.,* 2022; Malmer and Nyberg, 2008). Thus, reducing livestock grazing intensity may promote vegetation growth and subsequently enhance soil hydrological functioning and soil carbon storage (BarguésTobella *et al.,* 2014; Lulandala *et al.,* 2022).

The alteration of soil properties due to livestock grazing may also influence plant composition and species distribution (Mathewos *et al.,* 2023; Navarro-Percea *et al.,* 2023). Grazing may affect soil nutrient status by altering the C:N ratio of plant tissue (Navarro-Perea *et al.,* 2023). Changes in soil nutrient levels can influence plant life forms, density, and diversity, potentially leading to an increase in invasive species and non-palatable species (Kikoti and Mligo, 2015), thus reducing pasture availability and quality which possess more threat to the remaining Miombo woodlands. Proper livestock management strategies and practices may mitigate these effects and enhance soil carbon storage.

2.6 Conclusions

Findings from this study highlight the detrimental impact of overstocking and excessive livestock grazing in Miombo woodlands on SOC and soil infiltration capacity. High grazing intensity increases soil compaction, with negative impacts on soil carbon storage and soil hydrological functioning. Collectively, these grazing effects have the potential to disrupt soil function, including nutrient release, thereby diminishing soil productivity and posing significant threats to the remaining Miombo woodlands. To address these challenges, it is essential to develop and implement proper sustainable livestock management practices tailored to the specific conditions of Miombo ecosystems. Responsible management authorities and pastoralists alike are encouraged to adopt strategies and approaches that prioritize the long-term health and resilience of Miombo woodlands. By adhering to sustainable livestock management practices, stakeholders can mitigate the adverse effects of grazing, ensuring the provision of vital ecosystem services from Miombo woodlands.

Data availability statement: The data that support the findings of this study are available on request from the corresponding author.

Acknowledgments

The authors are grateful to the management of the Sokoine University of Agriculture for their support (Supervisors and learning facilities) during the studying period. We are greatly appreciating the district council i.e; Kilombero, Kilosa and Handeni and the villagers and landowners surrounding village forests in the nine villages of Gole, Madebe, Kwamsundi, Chabima, Ihombwe, Ulaya Mbuyuni, Utengule, Iduindembo, and Miyomboni for giving their permission to carry out our study. We thank Dr. Eva Mtengeti and Mr. Walter Msangi from SUA for the soil laboratory analysis for this study. Authors are also grateful to Mr. John Shesige, Mr. Iddi Rajab, Mr. Huruma Mbonea, and Mr. John Mahomela for assisting data collection. We also wish to thank Dr. Lufunyo Lulandala for his help during the preparation phase of the experiment

Funding: This work was supported by the Swedish Research Council [grant numbers 2021-04789_3]

Author contributions:

Hadija Mchelu: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Validation; Visualization, Writing - original draft; and Writing - review & editing

Charles Joseph Kilawe: Conceptualization; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Supervision; and Writing - review & editing

Aida Bargués-Tobella: Formal analysis; Methodology; Supervision; Validation; Visualization and Writing - review & editing

Thadei Tarcis Rugambwa: Data curation; Investigation; Methodology; Validation; Visualization, review & editing

Ikabongo Mukumbuta: Methodology; Supervision; Validation; Visualization and Writing - review & editing

Salim Mohamed Maliondo: Data curation; Methodology; Supervision; Validation; Visualization and Writing - review & editing

Gert Nyberg Conceptualization; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Supervision; Validation and Writing - review & editing

References

Abdallah, J. M., & Monela, G. G. (2007). Overview of Miombo woodlands in Tanzania. Proceedings of the First MITMIOMBO Project Workshop, Morogoro, Tanzania, 50, 9–23.

Abdel-Magid, A. H., Schuman, G. E., & Hart, R. H. (1987). Soil bulk density and water infiltration as affected by grazing systems. Rangeland Ecology & Management/Journal of Range Management Archives, 40(4), 307–309.

Andrew, S. (2021). Effects of plant species diversity and biomass on grazing patch selection by semi free-ranging cattle. Tanzania Journal of Science, 47(1), 282–295.

Bargués Tobella, A., Reese, H., Almaw, A., Bayala, J., Malmer, A., Laudon, H., & Ilstedt, U. (2014). The effect of trees on preferential flow and soil infiltrability in an agroforestry parkland in semiarid Burkina Faso. Water Resources Research, 50(4), 3342–3354.

Bargués-Tobella, A., Hasselquist, N. J., Bazié, H. R., Bayala, J., Laudon, H., & Ilstedt, U. (2020). Trees in African drylands can promote deep soil and groundwater recharge in a future climate with more intense rainfall. Land Degradation & Development, 31(1), 81–95.

Bargués-Tobella, A., Winowiecki, L. A., Sheil, D., & Vågen, T.-G. (2024). Determinants of Soil Field-Saturated Hydraulic Conductivity Across Sub-Saharan Africa: Texture and Beyond. Water Resources Research, 60(1), e2023WR035510.

Bates, D., Maechler, M., Bolker, B., Walker, S., Christensen, R. H. B., Singmann, H., Dai, B., Scheipl, F., Grothendieck, G., & Green, P. (2009). Package 'lme4.' URL Http://Lme4. r-Forge. r-Project. Org.

Blake, G. R. (1965). Bulk density. Methods of Soil Analysis: Part 1 Physical and Mineralogical Properties, Including Statistics of Measurement and Sampling, 9, 374–390.

Bolker, B. (2016). Getting started with the glmmTMB package. Vienna, Austria: R Foundation for Statistical Computing. Software.

Campbell, B. M. (1996). The Miombo in transition: Woodlands and welfare in Africa. Cifor.

Doggart, N., Morgan-Brown, T., Lyimo, E., Mbilinyi, B., Meshack, C. K., Sallu, S. M., & Spracklen, D. V. (2020). Agriculture is the main driver of deforestation in Tanzania. Environmental Research Letters, 15(3), 034028.

Easton, Z. M. (2021). Soil and soil water relationships.

Falk, D., Winowiecki, L. A., Vågen, T.-G., Lohbeck, M., Ilstedt, U., Muriuki, J., Mwaniki, A., & Tobella, A. B. (2024). Drivers of field-saturated soil hydraulic conductivity: Implications for restoring degraded tropical landscapes. Science of the Total Environment, 907, 168038.

FAO, I. (2019). Animal Feed Action Plan. Published by the Food and Agriculture Organization of the United Nations and the Intergovernmental Authority on Development Rome, 2019. https://icpald.org/wp-content/uploads/2020/02/Animal-Feed-Action-Plan-4.pdf

Gee, G. W., & Bauder, J. W. (2018). Particle-size Analysis. In A. Klute (Ed.), SSSA Book Series (pp. 383–411). Soil Science Society of America, American Society of Agronomy. https://doi.org/10.2136/sssabookser5.1.2ed.c15

Gerke, H. H., & Van Genuchten, M. T. (1993). A dual-porosity model for simulating the preferential movement of water and solutes in structured porous media. Water Resources Research, 29(2), 305–319.

Gizachew, B., Rizzi, J., Shirima, D. D., & Zahabu, E. (2020). Deforestation and connectivity among protected areas of Tanzania. Forests, 11(2), 170.

Gumbo, D. J., Dumas-Johansen, M., Muir, G., Boerstler, F., & Zuzhang, X. (2018). Sustainable management of Miombo woodlands: Food security, nutrition and wood energy. FAO.

Hox, J., Moerbeek, M., & Van de Schoot, R. (2017). Multilevel analysis: Techniques and applications. Routledge.

Ilstedt, U., Bargués Tobella, A., Bazié, H. R., Bayala, J., Verbeeten, E., Nyberg, G., Sanou, J., Benegas, L., Murdiyarso, D., & Laudon, H. (2016). Intermediate tree cover can maximize groundwater recharge in the seasonally dry tropics. Scientific Reports, 6(1), 21930.

Jiang, Z.-Y., Hu, Z.-M., Lai, D. Y., Han, D.-R., Wang, M., Liu, M., Zhang, M., & Guo, M.-Y. (2020). Light grazing facilitates carbon accumulation in subsoil in Chinese grasslands: A meta-analysis. Global Change Biology, 26(12), 7186–7197.

Kabuye, A. M. (2015). The impact of migrant livestock keepers on the Natives and natural resources of Kilombero Valley, in Tanzania: A case of Kilombero district. Mzumbe University.

Kikoti, I. A., & Mligo, C. (2015). Impacts of livestock grazing on plant species composition in montane forests on the northern slope of Mount Kilimanjaro, Tanzania. International Journal of Biodiversity Science, Ecosystem Services & Management, 11(2), 114–127.

Kilawe, C. J., Mertz, O., Birch-Thomsen, T., & Maliondo, S. M. (2018). Transformation of shifting cultivation: Extent, driving forces and impacts on livelihoods in Tanzania. Applied Geography, 94, 84–94.

Klumpp, K., Fontaine, S., Attard, E., Le Roux, X., Gleixner, G., & Soussana, J.-F. (2009). Grazing triggers soil carbon loss by altering plant roots and their control on soil microbial community. Journal of Ecology, 97(5), 876–885.

Lange, B., Lüescher, P., & Germann, P. F. (2009). Significance of tree roots for preferential infiltration in stagnic soils. Hydrology and Earth System Sciences, 13(10), 1809–1821.

Lenth, R., & Lenth, M. R. (2018). Package 'lsmeans.' The American Statistician, 34(4), 216–221.

Lüdecke, D., Ben-Shachar, M. S., Patil, I., Waggoner, P., & Makowski, D. (2021). performance: An R package for assessment, comparison and testing of statistical models. Journal of Open Source Software, 6(60). https://pure.mpg.de/rest/items/item_3316363/component/file_3316364/content

Lulandala, L., Bargués-Tobella, A., Masao, C. A., Nyberg, G., & Ilstedt, U. (2022). Excessive livestock grazing overrides the positive effects of trees on infiltration capacity and modifies preferential flow in dry miombo woodlands. Land Degradation & Development, 33(4), 581–595.

Lulandala, L., Bargués-Tobella, A., Masao, C. A., Nyberg, G., & Ilstedt, U. (2022b). Excessive livestock grazing overrides the positive effects of trees on infiltration capacity and modifies preferential flow in dry miombo woodlands. Land Degradation & Development, 33(4), 581–595.

Lusambo, L. P., Monela, G. C., & Katani, J. (2007). Socio-economic analysis of land use factors causing degradation and deforestation of miombo woodlands in Kilosa District, Tanzania. Tanzania Journal of Forestry and Nature Conservation, 76(1), 28–39.

Mair, A., Dupuy, L. X., & Ptashnyk, M. (2022). Model for water infiltration in vegetated soil with preferential flow oriented by plant roots. Plant and Soil, 478(1–2), 709–729.

Malmer, A., & Nyberg, G. (2008). Forest and water relations in miombo woodlands: Need for understanding of complex stand management. Research and Development for Sustainable Management of Semiarid/Miombo/Woodlands in East Africa. Working Papers of the Finnish Forest Research Institute, 98, 70–86.

Mathewos, M., Sisay, A., & Berhanu, Y. (2023). Grazing intensity effects on rangeland condition and tree diversity in Afar, northeastern Ethiopia. Heliyon.

Meshesha, D. T., Moahmmed, M., & Yosuf, D. (2019). Estimating carrying capacity and stocking rates of rangelands in Harshin District, Eastern Somali Region, Ethiopia. Ecology and Evolution, 9(23), 13309–13319.

Mtimbanjayo, J. R., & Sangeda, A. Z. (2018). Ecological effects of cattle grazing on Miombo tree species regeneration and diversity in Central-Eastern Tanzania. Journal of Environmental Research, 2(13), 1–7.

Nakagawa, S., Johnson, P. C. D., & Schielzeth, H. (2017). The coefficient of determination R 2 and intra-class correlation coefficient from generalized linear mixed-effects models revisited and expanded. Journal of The Royal Society Interface, 14(134), 20170213. https://doi.org/10.1098/rsif.2017.0213

Navarro-Perea, M., Pueyo, Y., Moret, D., Valverde, Á., Igual, J. M., & Alados, C. L. (2023). Plant-soil interactions in response to grazing intensity in a semi-arid ecosystem from NE Spain. Arid Land Research and Management, 37(2), 184–196.

Nelson, D. W., & Sommers, L. E. (2015). Total Carbon, Organic Carbon, and Organic Matter. In A. L. Page (Ed.), Agronomy Monographs (pp. 539–579). American Society of Agronomy, Soil Science Society of America. https://doi.org/10.2134/agronmonogr9.2.2ed.c29

Paul, B. K., Groot, J. C. J., Birnholz, C. A., Nzogela, B., Notenbaert, A., Woyessa, K., Sommer, R., Nijbroek, R., & Tittonell, P. (2020). Reducing agro-environmental trade-offs through sustainable livestock intensification across smallholder systems in Northern Tanzania. International Journal of Agricultural Sustainability, 18(1), 35–54. https://doi.org/10.1080/14735903.2019.1695348

Robinson, T. P., Thornton, P. K., Francesconi, G. N., Kruska, R. L., Chiozza, F., Notenbaert, A. M. O., Cecchi, G., Herrero, M. T., Epprecht, M., & Fritz, S. (2011). Global livestock production systems. FAO and ILRI.

Ruvuga, P. (2021). Rangeland and livestock management practices for improved herder livelihoods in miombo woodland. Acta Universitatis Agriculturae Sueciae, 2021: 35.

Ruvuga, P. R., Wredle, E., Mwakaje, A., Selemani, I. S., Sangeda, A. Z., Nyberg, G., & Kronqvist, C. (2020). Indigenous Rangeland and Livestock Management Among Pastoralists and Agro-pastoralists in Miombo Woodlands, Eastern Tanzania. Rangeland Ecology & Management, 73(2), 313–320.

Ruvuga, P. R., Wredle, E., Nyberg, G., Hussein, R. A., Masao, C. A., Selemani, I. S., Sangeda, A. Z., & Kronqvist, C. (2021).

Evaluation of rangeland condition in miombo woodlands in eastern Tanzania in relation to season and distance from settlements. Journal of Environmental Management, 290, 112635.

Ryan, C. M., Pritchard, R., McNicol, I., Owen, M., Fisher, J. A., & Lehmann, C. (2016). Ecosystem services from southern African woodlands and their future under global change. Philosophical Transactions of the Royal Society B: Biological Sciences, 371(1703), 20150312.

Ryan, C. M., & Williams, M. (2011). How does fire intensity and frequency affect miombo woodland tree populations and biomass? Ecological Applications, 21(1), 48–60.

Tarimo, B., Dick, Ø. B., Gobakken, T., & Totland, Ø. (2015). Spatial distribution of temporal dynamics in anthropogenic fires in miombo savanna woodlands of Tanzania. Carbon Balance and Management, 10(1), 1–15.

Thomas, A. D. (2012). Impact of grazing intensity on seasonal variations in soil organic carbon and soil CO2 efflux in two semiarid grasslands in southern Botswana. Philosophical Transactions of the Royal Society B: Biological Sciences, 367(1606), 3076–3086.

Thornton, P. K. (2010). Livestock production: Recent trends, future prospects. Philosophical Transactions of the Royal Society B: Biological Sciences, 365(1554), 2853–2867.

Timberlake, J., Chidumayo, E., & Sawadogo, L. (2010). Distribution and characteristics of African dry forests and woodlands. The Dry Forests and Woodlands of Africa: Managing for Products and Services, 2, 11–41.

Vågen, T. G., Winowiecki, L. A., Desta, L. T., & Tondoh, J. E. (2013). The land degradation surveillance framework (LDSF). Field Guide, 4.

Van Schaik, N. (2009). Spatial variability of infiltration patterns related to site characteristics in a semi-arid watershed. Catena, 78(1), 36–47.

Wachiye, S., Pellikka, P., Rinne, J., Heiskanen, J., Abwanda, S., & Merbold, L. (2022). Effects of livestock and wildlife grazing intensity on soil carbon dioxide flux in the savanna grassland of Kenya. Agriculture, Ecosystems & Environment, 325, 107713.

Wang, Z., Johnson, D. A., Rong, Y., & Wang, K. (2016). Grazing effects on soil characteristics and vegetation of grassland in northern China. Solid Earth, 7(1), 55–65.

Watson, P. F., & Petrie, A. (2010). Method agreement analysis: A review of correct methodology. Theriogenology, 73(9), 1167–1179.

Wei, L., Hai-Zhou, H., Zhi-Nan, Z., & Gao-Lin, W. (2011). Effects of grazing on the soil properties and C and N storage in relation to biomass allocation in an alpine meadow. Journal of Soil Science and Plant Nutrition, 11(4), 27–39.

White, F. (1983). The vegetation of Africa. (Vol. 20).

Zuur, A. F., Hilbe, J. M., & Ieno, E. N. (2013). A beginner's guide to GLM and GLMM with R. A frequentist and Bayesian. Newburgh, United Kingdom: Highland Statistics Ltd.

CHAPTER THREE

Manuscript Two

Effect of different grazing intensities on soil infiltration and underground water movement in Miombo woodlands of Tanzania

Hadija Ahmad Mchelu[a]*, Charles Joseph Kilawe[a], Aida Bargués-Tobella[b], Salim Mohamed Maliondo[a], Gert Nyberg[b]

[a]Department of Ecosystems and Conservation, Sokoine University of Agriculture, P.O. Box 3010, Chuo Kikuu, Morogoro, Tanzania

[b]Department of Forest Ecology and Management, Swedish University of Agricultural Sciences, 901 83, Umeå, Sweden

*Corresponding author e-mail: hadija.mchelu@sua.ac.tz

Status: Preparation to submit

3.1 Abstract

Livestock practices are common practiced in dryland areas in Africa. It is listed among factors causing soil degradation increasing risks for water scarcity and threats to the remaining dryland areas. Despite this, little has been documented on the effect of increasing grazing intensity on soil water infiltration and movement in the Miombo woodlands of Tanzania. This study, assessed the effect of light, medium, and high grazing intensities (GI) on field-saturated soil hydraulic conductivity (Kfs) and water movement including dye coverage (DC), uniform flow depth and preferential flow fraction across different soil profiles found in nine Miombo woodlands of Tanzania. Grazing intensity was assessed using scoring field method. The Kfs and water movement parameters were studied across 117 different soil profiles. Results has found that, the soil infiltration capacity, DC and uniform flow depth decreases significantly with increasing grazing intensities ($p<0.001$), while preferential flow fraction increases significantly with increased grazing intensities ($p<0.001$). The soil infiltrability capacity is declining and continue to degrade under high grazing intensity. To reverse this, responsible management authorities should reduce the number of livestock to allowable carrying capacity and adopt other proper grazing management practices to reduce pressure in Miombo woodlands.

Keywords: Overgrazing, uniform infiltration, uniform flow depth, preferential flow, soil compaction

3.2 Introduction

Livestock grazing is among major adopted economic activity in many dryland areas in Sub-Saharan Africa countries (Robinson *et al.,* 2011). Globally, livestock grazing contributes to about 30% of the global economy with meat and milk become the leading products in the market (Robinson *et al.,* 2011). It is also a common practice in many Miombo woodlands in Africa (Mtimbanjayo & Sangeda, 2018; Ruvuga, 2021). Miombo woodland is an African dryland forest ecosystem dominated by Brachystegia species, either alone or in association with Julbernardia and Isoberlinia species (Timberlake *et al.,* 2010). It covers close to 2.7 million km2 across southern Africa (Angola, Democratic Republic of the Congo, Malawi, Mozambique, Tanzania, Zambia and Zimbabwe) (Campbell, 1996). They are characterized by limited water sources (Timberlake *et al.,* 2010). Nevertheless, it sustains the livelihoods for more than 100 million rural poor and 50 million urban people globally (Gumbo *et al.,* 2018). In Tanzania, it is a dominant woodland supplying a diverse ecosystem services and products to the surrounding communities (Abdallah and Monela, 2007). However, human-induced activities such as charcoal production, wildfires (Tarimo *et al.,* 2015), shifting cultivation (Kilawe *et al.,* 2018) and overgrazing are increasingly putting Miombo woodlands at risk (Lulandala *et al.,* 2022a) .

Overgrazing is listed among prime factor leading to land degradation, posing a major threat to dryland regions across Sub-Saharan Africa (Robinson *et al.,* 2011). The intensity of livestock grazing has been increasing in Miombo woodlands due to combined factors such as poor livestock management practices, limited grazing area, scarcity of pastures, diminished pasture quality with growing demands for livestock products (Paul *et al.,* 2020; Robinson *et al.,* 2011; Thornton, 2010). This activity is directly linked with detrimental effects on soil such as soil health depletion, decreased soil infiltrability and increased surface runoff (Lulandala *et al.,* 2022). Overgrazing increases soil compaction which blocks soil water passages and channels lowering soil infiltration capacity (Abdel-Magid *et al.,* 1987).

The soil infiltration capacity influences the quantity, quality, location, and timing of water supplies to reach the stream channel (Mair *et al.,* 2022). It supports number of ecosystem services, including primary soil productivity and water cycling, water purification and regulation, soil moisture conservation and erosion control (Malmer & Nyberg, 2008). The higher soil infiltration capacity the more water can enter the soil surface and become available for both soil, plants and groundwater recharge (Bargués Tobella *et al.,* 2014). Thus, reducing infiltration capacity eventually affects ecosystem functioning, increase in risks for water scarcity, groundwater recharge, surface runoff, soil erosion, loss of soil fertility, and low soil productivity.

Studies have reported that, poor livestock management activities such as increasing livestock grazing reduces plant diversity, accelerates species invasion and overrides the soil infiltration capacity (Bargués-Tobella *et al.,* 2024; Lulandala *et al.,* 2022). However, little is documented on how different grazing intensities affects the soil infiltrability and underground water movements in Miombo woodlands. While these studies focused on intermediate dry Miombo, a notable gap still exist on covering a diverse biome of Miombo woodlands in Tanzania. In this study, we aim to conducted a comprehensive investigation on the effect of different grazing intensities on soil infiltration capacity and underground water movement in Tanzanian Miombo woodlands across diverse climates and landforms. We assessed grazing intensities using scoring method based on field observations. We hypothesize that high grazing intensities will negatively affect soil infiltration capacity and modifies underground water pathways.

3.3 Materials and Methods

3.3.1 Study area description

The data for this study were collected from nine villages found in three districts Kilosa (Ihombwe, Ulaya mbuyuni and Chabima), Handeni (Madebe, Gole and Kwamsundi) and Kilombero (Miyomboni, Utengule and Iduindembo) located in Tanzania (Figure 3.1). Miombo woodlands founds in these villages represents the whole biome in the country spanning form dry (Handeni), intermediate (Kilosa) to wet (Kilombero) Miombo (Appendix 1,2,3, Electronic Supplementary Material). More than 45% of these villages is covered by Miombo woodlands. After agriculture, livestock grazing is second economic activity (Kabuye, 2015). People in these villages can be grouped into three groups based on the livestock management practices i.e.; 1) Pastoralist communities engaged primarily in extensive livestock keeping 2) Agro-pastoralist communities practicing both extensive livestock keeping and farming, and 3) Farming communities involved in agricultural activities.

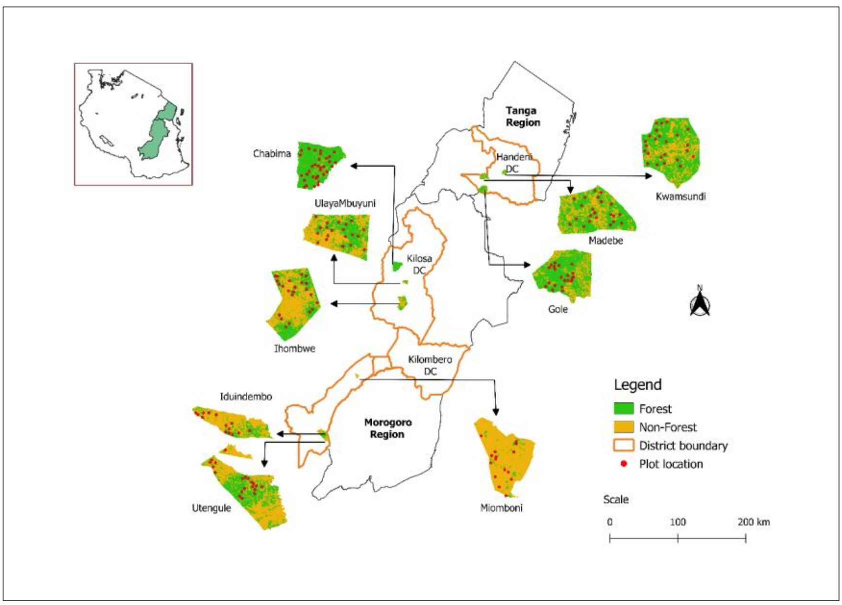

Figure 3. 1: A map showing location of study sites within Handeni, Kilosa and Kilombero districts in Tanzania

3.3.2 Sampling design

A two-phase sampling design was used in the study. A purposive sampling design was used at first stage to select the three districts in Tanzania based on the presence of Miombo woodlands and grazing activities. The selected districts represent the whole Miombo gradient in Tanzania. In the second phase, all villages in the district with Miombo and grazing activities were listed, only three villages were selected randomly based on the number of livestock registered in the village. After selection of the study sites plots were established in the woodlands using a stratified random sampling technique. The area in each village were divided into strata using a supervised classification system in QGIS. The area was divided into two strata i.e.; forest and non-forest comprises of grassland, agricultural fields, and settlement. At least 15 sampling plots (50m x 20m) were randomly distributed within the forest stratum for data collection (Figure 3.1).

3.3.3 Grazing intensities estimation

Scoring method based on the field observation was used to estimate different grazing intensities. The method has also been used by Lulandala *et al.* (2022); Mathewos *et al.* (2023). The assessment of field parameters was done at plot level (Figure 3.2). This method involves evaluation and scoring of three grazing parameters 1) signs of livestock presence (droppings), 2) grazed vegetation level, and 3) animal paths and hoof print on the soil surface. For each parameter, a value between 0 and 3 was assigned separately according to its severity (where 0 = no sign observed, 1=few signs, 2= clearly observations, and 3 = most severe condition observed). The individual scores were aggregated to derive an overall plot score. The plot-level grazing intensity was classified into one of three classes: Light GI (total scores of 1 to 3), Medium GI (total scores of 4 to 6), and High GI (total scores of 7 to 9).

Figure 3.2: **Different grazing parameters for assessing grazing intensity in the forests (Picture was taken by Hadija Mchelu)**

3.3.4 Soil water infiltration measurement

Infiltration measurement was done following the Land Degradation Surveillance Framework (LDSF) as described in (Vågen *et al.,* 2013). At center of each plot a single ring infiltrometer with an inner diameter of about 30 cm and a height of 30cm was used Figure 3.3a. At each point, 5 cm of the ring was inserted into the soil and pre-wetting was done by filling water to at least 15cm level of the ring and allowing it to infiltrate for 15 minutes. After, the ring was filled with water up to 20 cm level and the water level within the ring was recorded after 5 minutes, and the ring was immediately refilled to the initial start level (20 cm). This procedure was repeated every 5 minutes during the first half-hour, every 10 minutes during the second half-hour for a minimum period of 1hour, then 20 minutes for the second hour of the infiltration experiment. For each time interval, infiltration capacity rates were calculated by subtracting the final water level from the initial one and dividing it by the time interval. Topsoil field-saturated hydraulic conductivity (K_{fs}) was estimated from the infiltration rates using the procedure described by Bargués-Tobella *et al.,* (2024).

3.3.5 Pathways measurement

Soil water pathways were measured after infiltration using a brilliant blue FCF (C.I.42090) dissolved in about 14.1 L of water. A 48g of 200mm of FCF was added into the ring infiltrometer (20cm equivalent to 14.1L) and allowed to soak completely. After complete infiltration of the dye solution, the infiltration ring was removed (Fig. 3.3b), and carefully dug a 0.50 m wide by 2 m long and 0.5 m deep pit (Fig. 3.3c) to cut across the dye-stained surface and expose a vertical stained soil profile (3.3d). The exposed soil profile was leveled carefully to avoid smearing before taking photo. A Nikon D5200 camera with a 35 mm focal length and a graded frame with inner dimensions of 0.3*0.5 m was used to take pictures of the stained soil profiles. The camera was placed 1.5 m from the center of the photo frame (Fig. 3.3e). Photos were taken in daylight and sometimes under an umbrella to avoid direct radiation causing too much reflection (Fig. 3.3f).

Figure 3.3: **Water infiltration and pathways measurement in the field (Picture was taken by Hadija Mchelu)**

3.4 Data Analysis

3.4.1 Soil water pathways analysis

Soil profile photos were analyzed using QGIS- 3.28.9 'Firenze' version software. At first, photos were pre-processed to correct for geometric distortion, and then individual pixels were classified into dye-stained and non-stained classes using supervised image classification in QGIS (Fig. 3.4). After completing the classification, we created a shapefile and divided it into grids comprising 100 rectangular polygons of 15 cm2 (3*5 cm). Then the stained and non-stained area within each of these rectangular were calculated using majority rule by zonal statistics. From this, the profile was regarded as uniform if the dye-stained area is ≥80% and nonuniform if the stained area is ≤ 80%. These figures were used to calculate the different indices of preferential flow. From the classified images and corresponding dye coverage curves, the following preferential flow indices were calculated;

i. Percentage dye coverage (DC, %)- is the percentage ratio of the dye-stained area to the total profile area under consideration. The lower the DC the higher degree of preferential flow

$$DC = 100 * \left(\frac{D}{D+ND}\right) \quad (3)$$

Where; DC (%) is the percentage dye coverage, D is the dye coverage area(cm^2) and ND is the non-stained area.

ii. Uniform infiltration depth (UniFr, cm) (Van Schaik, 2009); the depth at which the dye coverage decreases below 80%; this represents the depth of the uniform infiltration front where the infiltration process is dominated by the uniform flow. Below this depth, it is assumed that the flow is preferential. Soils showing high preferential patterns will therefore have low values of this parameter.

iii. Preferential flow fraction (Van Schaik, 2009): defined as the fraction of the total infiltration that flows through preferential flow paths, is calculated as

$$PF_{fr} = 100 * \left(1 - \frac{UnFr*Wp}{Tsa}\right) \quad (4)$$

Where Wp is the width of the profile(cm) and Tsa is the Total stained area (cm^2)

3.4.2 Statistical analysis

All statistical analyses were conducted using R version 4.4.2 (R Core Team, 2023). A gamma generalized linear mixed-effects model (GLMM) with a log-link function and a random intercept was used to test K_{fs}, while Linear mixed-effect model (LMM) was used to test DC (%), UniFr, and Preferential flow fraction across grazing intensity. The GLMM was used because of the Gamma distribution of the dataset. In GLMM, the grazing intensity was treated as a fixed factor, while villages nested within districts were considered random effects. The function "*glmmTMB*" in the "*glmmTMB*" package was used to fit GLMM (Bolker, 2016). The guidelines by Zuur *et al.,* (2013) was used to check that model assumptions for Gamma GLMMs were not violated. The "*check model*" function in the "*performance*" package (Lüdecke *et al.,* 2021) used to assess visually the lack of heteroscedasticity, non-linear patterns and the normality of random effects and of residuals. The marginal and conditional R^2 (Nakagawa *et al.,* 2017), and Interclass Correlation Coefficient (ICC) (Hox *et al.,* 2017), which were computed using the "performance" package were used to assess the overall model performance. Marginal R^2 indicates the variance described by the fixed effects only, and conditional R^2 considers variance by both the fixed and random effects (Nakagawa *et al.,* 2017). A post-hoc pairwise comparisons between the different levels of grazing intensity was done using the function *"emmeans*" from the "*emmeans*" package (Lenth and Lenth, 2018). This function compares the means using the Tukey method to test differences between the different levels of grazing intensity.

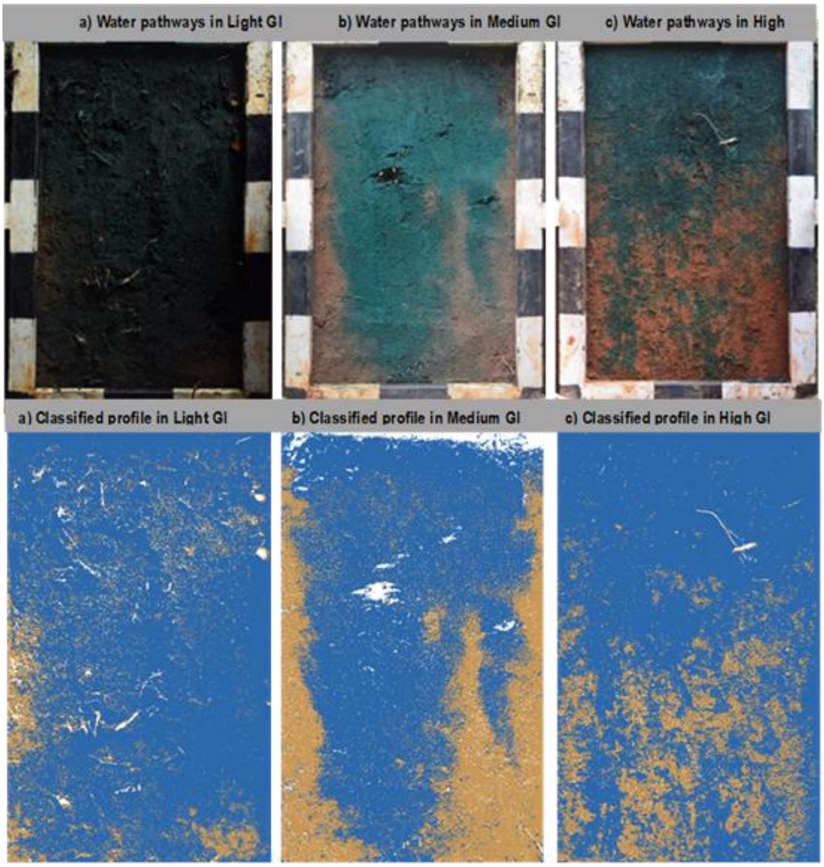

Figure 3.4: **Example of soil profiles and classified soil profiles showing water infiltration pathways across different grazing intensities**

3.5 Results

3.5.1 Field-saturated soil hydraulic conductivity across grazing intensity

Results have shown that, there is significant negative effect of high grazing intensity on the K_{fs} (Appendix 5). A pairwise comparisons between grazing intensities have shown that the mean Kfs was significantly ($P < 0.05$) higher under light grazed areas (100.08 ± 65.56 mmhr-1) compared to medium (62.73 ± 54.88 mmhr-1)

(Figure 3.5a) and high grazed areas (27.28 ± 22.99 mmhr-1). A significant difference in K_{fs} was also observed between medium GI and high GI with $p<0.05$.

3.5.2 Percentage dye coverage (DC, %)

LMM results showed a decline in the dye coverage with increased grazing intensities ($p<0.001$). A significant difference between Light GI and High GI (Figure 3.5b, Appendix 5). The highest average dye coverage was observed under Light GI (71.43 ±17%), followed by medium GI with average dye coverage of (60.43 ±11%) and lowest mean dye coverage was observed under high GI (39.68±17%). A pairwise comparison indicated a significant change in dye coverage across the grazing intensities.

3.5.3 Uniform infiltration depth

LMM results showed that, the uniform infiltration depth decreases with increasing grazing intensity ($p<0.001$) (Appendix 5). A Turkey pairwise comparison observed a significant difference between Light GI and High GI, and between medium GI and high GI while no significant variation was observed between medium GI and light GI with $P>0.05$ (Figure 3.5c). The highest average uniform flow depth was observed under Light GI (27.70 ±12cm), followed by medium GI with average dye coverage of (23.83 ±7.5cm) and lowest mean dye coverage was observed under high GI (15.28±9.3cm).

3.5.4 Preferential flow fraction

The study found that, the degree of preferential flow fraction significant increase with increasing grazing intensities (Appendix 5). The highest preferential flow fraction was observed in high GI (38.84±27%) followed by medium GI with average dye coverage of (28.83±23%) and lowest mean preferential flow was observed under light GI (27.68±16%). A pairwise comparison shows that, there is significant different between light GI and high GI and between medium GI and high GI while there is no statistical variation between light GI and medium GI (Figure 3.5d).

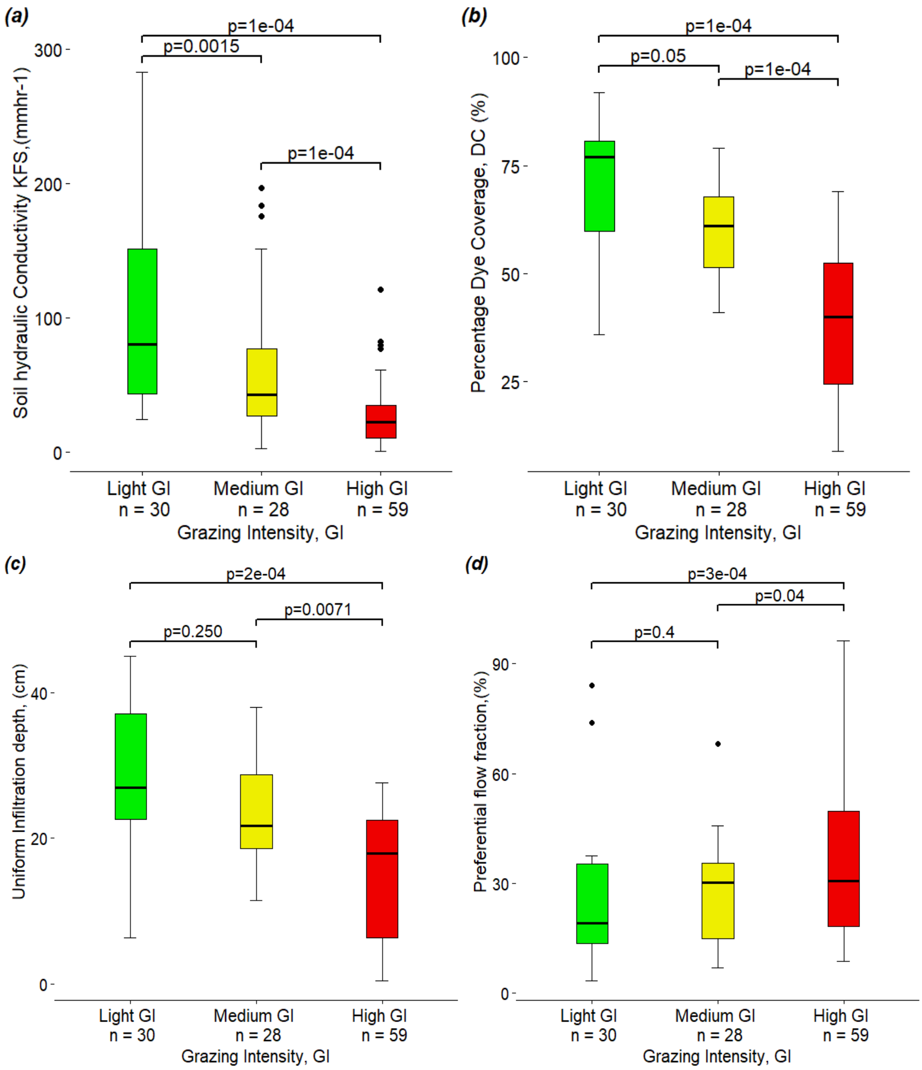

Figure 3. 5: Boxplots (median, first and third quartile) of the K_{fs}, DC, Uniform Infiltration depth and Preferential flow across grazing intensities based on Scoring method; n indicate number of observations at each grazing intensity; p-values for the pair-wise comparisons (Tukey method) between different levels of GI are indicated.

3.6 Discussions

The study found that increasing grazing significantly lowers K_{fs}. This study has accepted the alternative hypothesis which stated that "high grazing intensities will negatively affect soil infiltration capacity and thus modifies underground water pathways". These findings are similar to other researches, showing that soil infiltration capacity decreases with increasing grazing intensity across different landscapes (Bargués-Tobella *et al.,* 2024; Lulandala *et al.,* 2022). Soil infiltration capacity was reduced as the result of increasing soil compaction due to animal trampling. Livestock movements creates pressure on soil surface which compress soil particles increasing soil bulk density and thus lowers soil infiltrability (Abdel-Magid *et al.,* 1987).

Soil infiltration is a function of soil porosity and texture, with increased soil compaction soil texture is disrupted, pore sizes and connectivity are reduced as a results soil water movement becomes slow (Abdel-Magid *et al.,* 1987). In addition, livestock trampling can lead removal of plant cover and diversity (Andrew, 2021; Mathewos *et al.,* 2023), reduced soil organic carbon (SOC) (Jiang *et al.,* 2020; Thomas, 2012)and biomass (Andrew, 2021; Wei *et al.,* 2011), and thus contribute to low infiltrability under high grazing areas. Vegetations offers soil coverage and roots which acts as sponges to better retain soil moisture and recharge groundwater (Bargués Tobella *et al.,* 2014; Ilstedt *et al.,* 2016; Malmer & Nyberg, 2008). Despite soil properties and the role of vegetation on soil Kf_s, studies have shown that, high livestock grazing intensity and other anthropogenic activities such as wildfires can suppress the role of woody vegetation on Kfs (Bargués-Tobella *et al.,* 2024b; Lulandala *et al.,* 2022a). However, this study did not consider the multiple interaction between vegetation and grazing intensity due to the limited resources.

The study has found a decline trend of dye coverage and uniform flow, meanwhile there was a notable increasing trend of preferential flow with increased grazing intensities. These findings, are similar to the one reported by Lulandala *et al.* (2022). High dye coverage and uniform flow in low grazed areas indicates that the area is characterized by evenly distribution of pore spaces and thus water can easily pass through the soil profile (Gerke & Van Genuchten, 1993). In addition to that, areas with light grazing intensity are less compacted and eroded thus the top soil proportion is intact with high level of organic matters which improves uniform water absorption and movement within the soil. On the other hand, due to increased soil compaction and erosion on the topsoil layer in high grazed areas uniform flow is reduced and vice versa preferential flow is increasing (Gerke & Van Genuchten, 1993).

Increasing soil compaction modifies water ways and accelerates preferential flow of water within the soil. Studies have shown that preferential flow contributes to groundwater recharge, because of the non-uniformity distribution of soil pores water molecules will only path through the loose channels reaching deep soils. Trees because of deep prolonged roots can be also be responsible for enhancing preferential flow through macropores formed by their roots (Bargués Tobella *et al.,* 2014; Bargués-Tobella *et al.,* 2020; Lange *et al.,* 2009). Not only root length but also root size and connectivity increases preferential flow and this is reason why there is deeper and wider preferential flow under woody perennials compared to annual crops and pastures (Bargués-Tobella *et al.,* 2020) .

Soil fauna such as earthworms, ground dwellers and termites' activities especially in Miombo woodlands and other isolated areas are found to improves soil infiltrability and soil water storage and drainage (Easton, 2021). In tropical dryland Africa reduced soil infiltration capacity due to increasing grazing intensity increases water scarcity, surface runoff, top soil erosion which in turn reduces soil nutrient release, increase top soil water stagnant, excessive soil evaporation and mostly lowers soil productivity posing more threats to other remained productive areas in Miombo woodlands of Tanzania. Thus, it is crucial to reduce number of livestock to stocking rate and include vegetation in grazing areas to regulates soil water movement.

3.7 Conclusions

The Study highlight the importance of managing livestock grazing in Miombo woodlands of Tanzania to prevent the degradation of soil hydrological functioning. High grazing intensities lowers soil’s ability to stores and regulates water. Adequate management practices including seasonal and rotational grazing, tree and grass planting in grazing areas to be done to reduce pressure of livestock in Miombo woodlands and improves soil hydrological functions. Furthermore, the study does not consider interaction of other forest variables such as trees diversity, structure and distribution on hydrological function. Therefore, this and other potentially relevant interactions should be investigated in future studies in Miombo woodlands.

Data availability statement: The data that support the findings of this study are available on request from the corresponding author.

References

Abdallah, J. M., & Monela, G. G. (2007). Overview of Miombo woodlands in Tanzania. Proceedings of the First MITMIOMBO Project Workshop, Morogoro, Tanzania, 50, 9–23.

Abdel-Magid, A. H., Schuman, G. E., & Hart, R. H. (1987). Soil bulk density and water infiltration as affected by grazing systems. Rangeland Ecology & Management/Journal of Range Management Archives, 40(4), 307–309.

Andrew, S. (2021). Effects of plant species diversity and biomass on grazing patch selection by semi free-ranging cattle. Tanzania Journal of Science, 47(1), 282–295.

Bargués Tobella, A., Reese, H., Almaw, A., Bayala, J., Malmer, A., Laudon, H., & Ilstedt, U. (2014). The effect of trees on preferential flow and soil infiltrability in an agroforestry parkland in semiarid Burkina Faso. Water Resources Research, 50(4), 3342–3354.

Bargués-Tobella, A., Hasselquist, N. J., Bazié, H. R., Bayala, J., Laudon, H., & Ilstedt, U. (2020). Trees in African drylands can promote deep soil and groundwater recharge in a future climate with more intense rainfall. Land Degradation & Development, 31(1), 81–95.

Bargués-Tobella, A., Winowiecki, L. A., Sheil, D., & Vågen, T.-G. (2024). Determinants of Soil Field-Saturated Hydraulic Conductivity Across Sub-Saharan Africa: Texture and Beyond. Water Resources Research, 60(1), e2023WR035510. https://doi.org/10.1029/2023WR035510

Bates, D., Maechler, M., Bolker, B., Walker, S., Christensen, R. H. B., Singmann, H., Dai, B., Scheipl, F., Grothendieck, G., & Green, P. (2009). Package 'lme4.' URL Http://Lme4. r-Forge. r-Project. Org.

Blake, G. R. (1965). Bulk density. Methods of Soil Analysis: Part 1 Physical and Mineralogical Properties, Including Statistics of Measurement and Sampling, 9, 374–390.

Bolker, B. (2016). Getting started with the glmmTMB package. Vienna, Austria: R Foundation for Statistical Computing. Software.

Campbell, B. M. (1996). The Miombo in transition: Woodlands and welfare in Africa. Cifor.

Doggart, N., Morgan-Brown, T., Lyimo, E., Mbilinyi, B., Meshack, C. K., Sallu, S. M., & Spracklen, D. V. (2020). Agriculture is the main driver of deforestation in Tanzania. Environmental Research Letters, 15(3), 034028.

Easton, Z. M. (2021). Soil and soil water relationships.

Falk, D., Winowiecki, L. A., Vågen, T.-G., Lohbeck, M., Ilstedt, U., Muriuki, J., Mwaniki, A., & Tobella, A. B. (2024). Drivers of field-saturated soil hydraulic conductivity: Implications for restoring degraded tropical landscapes. Science of the Total Environment, 907, 168038.

FAO, I. (2019). Animal Feed Action Plan. Published by the Food and Agriculture Organization of the United Nations and the Intergovernmental Authority on Development Rome, 2019. https://icpald.org/wp-content/uploads/2020/02/Animal-Feed-Action-Plan-4.pdf

Gee, G. W., & Bauder, J. W. (2018). Particle-size Analysis. In A. Klute (Ed.), SSSA Book Series (pp. 383–411). Soil Science Society of America, American Society of Agronomy. https://doi.org/10.2136/sssabookser5.1.2ed.c15

Gerke, H. H., & Van Genuchten, M. T. (1993). A dual-porosity model for simulating the preferential movement of water and solutes in structured porous media. Water Resources Research, 29(2), 305–319.

Gizachew, B., Rizzi, J., Shirima, D. D., & Zahabu, E. (2020). Deforestation and connectivity among protected areas of Tanzania. Forests, 11(2), 170.

Gumbo, D. J., Dumas-Johansen, M., Muir, G., Boerstler, F., & Zuzhang, X. (2018). Sustainable management of Miombo woodlands: Food security, nutrition and wood energy. FAO.

Hox, J., Moerbeek, M., & Van de Schoot, R. (2017). Multilevel analysis: Techniques and applications. Routledge.

Ilstedt, U., Bargués Tobella, A., Bazié, H. R., Bayala, J., Verbeeten, E., Nyberg, G., Sanou, J., Benegas, L., Murdiyarso, D., & Laudon, H. (2016). Intermediate tree cover can maximize groundwater recharge in the seasonally dry tropics. Scientific Reports, 6(1), 21930.

Jiang, Z.-Y., Hu, Z.-M., Lai, D. Y., Han, D.-R., Wang, M., Liu, M., Zhang, M., & Guo, M.-Y. (2020). Light grazing facilitates carbon accumulation in subsoil in Chinese grasslands: A meta-analysis. Global Change Biology, 26(12), 7186–7197.

Kabuye, A. M. (2015). The impact of migrant livestock keepers on the Natives and natural resources of Kilombero Valley, in Tanzania: A case of Kilombero district. Mzumbe University.

Kikoti, I. A., & Mligo, C. (2015). Impacts of livestock grazing on plant species composition in montane forests on the northern slope of Mount Kilimanjaro, Tanzania. International Journal of Biodiversity Science, Ecosystem Services & Management, 11(2), 114–127.

Kilawe, C. J., Mertz, O., Birch-Thomsen, T., & Maliondo, S. M. (2018). Transformation of shifting cultivation: Extent, driving forces and impacts on livelihoods in Tanzania. Applied Geography, 94, 84–94.

Klumpp, K., Fontaine, S., Attard, E., Le Roux, X., Gleixner, G., & Soussana, J.-F. (2009). Grazing triggers soil carbon loss by altering plant roots and their control on soil microbial community. Journal of Ecology, 97(5), 876–885.

Lange, B., Lüescher, P., & Germann, P. F. (2009). Significance of tree roots for preferential infiltration in stagnic soils. Hydrology and Earth System Sciences, 13(10), 1809–1821.

Lenth, R., & Lenth, M. R. (2018). Package 'lsmeans.' The American Statistician, 34(4), 216–221.

Lüdecke, D., Ben-Shachar, M. S., Patil, I., Waggoner, P., & Makowski, D. (2021). performance: An R package for assessment, comparison and testing of statistical models. Journal of Open Source Software, 6(60). https://pure.mpg.de/rest/items/item_3316363/component/file_3316364/content

Lulandala, L., Bargués-Tobella, A., Masao, C. A., Nyberg, G., & Ilstedt, U. (2022). Excessive livestock grazing overrides the positive effects of trees on infiltration capacity and modifies preferential flow in dry miombo woodlands. Land Degradation & Development, 33(4), 581–595.

Lusambo, L. P., Monela, G. C., & Katani, J. (2007). Socio-economic analysis of land use factors causing degradation and deforestation of miombo woodlands in Kilosa District, Tanzania. Tanzania Journal of Forestry and Nature Conservation, 76(1), 28–39.

Mair, A., Dupuy, L. X., & Ptashnyk, M. (2022). Model for water infiltration in vegetated soil with preferential flow oriented by plant roots. Plant and Soil, 478(1–2), 709–729.

Malmer, A., & Nyberg, G. (2008). Forest and water relations in miombo woodlands: Need for understanding of complex stand management. Research and Development for Sustainable Management of Semiarid/Miombo/Woodlands in East Africa. Working Papers of the Finnish Forest Research Institute, 98, 70–86.

Mathewos, M., Sisay, A., & Berhanu, Y. (2023). Grazing intensity effects on rangeland condition and tree diversity in Afar, northeastern Ethiopia. Heliyon.

Meshesha, D. T., Moahmmed, M., & Yosuf, D. (2019). Estimating carrying capacity and stocking rates of rangelands in Harshin District, Eastern Somali Region, Ethiopia. Ecology and Evolution, 9(23), 13309–13319.

Mtimbanjayo, J. R., & Sangeda, A. Z. (2018). Ecological effects of cattle grazing on Miombo tree species regeneration and diversity in Central-Eastern Tanzania. Journal of Environmental Research, 2(13), 1–7.

Nakagawa, S., Johnson, P. C. D., & Schielzeth, H. (2017). The coefficient of determination R 2 and intra-class correlation coefficient from generalized linear mixed-effects models revisited and expanded. Journal of The Royal Society Interface, 14(134), 20170213. https://doi.org/10.1098/rsif.2017.0213

Navarro-Perea, M., Pueyo, Y., Moret, D., Valverde, Á., Igual, J. M., & Alados, C. L. (2023). Plant-soil interactions in response to grazing intensity in a semi-arid ecosystem from NE Spain. Arid Land Research and Management, 37(2), 184–196.

Nelson, D. W., & Sommers, L. E. (2015). Total Carbon, Organic Carbon, and Organic Matter. In A. L. Page (Ed.), Agronomy Monographs (pp. 539–579). American Society of Agronomy, Soil Science Society of America. https://doi.org/10.2134/agronmonogr9.2.2ed.c29

Paul, B. K., Groot, J. C. J., Birnholz, C. A., Nzogela, B., Notenbaert, A., Woyessa, K., Sommer, R., Nijbroek, R., & Tittonell, P. (2020). Reducing agro-environmental trade-offs through sustainable livestock intensification across smallholder systems in Northern Tanzania. International Journal of Agricultural Sustainability, 18(1), 35–54. https://doi.org/10.1080/14735903.2019.1695348

Robinson, T. P., Thornton, P. K., Francesconi, G. N., Kruska, R. L., Chiozza, F., Notenbaert, A. M. O., Cecchi, G., Herrero, M. T., Epprecht, M., & Fritz, S. (2011). Global livestock production systems. FAO and ILRI.

Ruvuga, P. (2021). Rangeland and livestock management practices for improved herder livelihoods in miombo woodland. Acta Universitatis Agriculturae Sueciae, 2021: 35.

Ruvuga, P. R., Wredle, E., Mwakaje, A., Selemani, I. S., Sangeda, A. Z., Nyberg, G., & Kronqvist, C. (2020). Indigenous Rangeland and Livestock Management Among Pastoralists and Agro-pastoralists in Miombo Woodlands, Eastern Tanzania. Rangeland Ecology & Management, 73(2), 313–320.

Ruvuga, P. R., Wredle, E., Nyberg, G., Hussein, R. A., Masao, C. A., Selemani, I. S., Sangeda, A. Z., & Kronqvist, C. (2021). Evaluation of rangeland condition in miombo woodlands in eastern Tanzania in relation to season and distance from settlements. Journal of Environmental Management, 290, 112635.

Ryan, C. M., Pritchard, R., McNicol, I., Owen, M., Fisher, J. A., & Lehmann, C. (2016). Ecosystem services from southern African woodlands and their future under global change. Philosophical Transactions of the Royal Society B: Biological Sciences, 371(1703), 20150312.

Ryan, C. M., & Williams, M. (2011). How does fire intensity and frequency affect miombo woodland tree populations and biomass? Ecological Applications, 21(1), 48–60.

Tarimo, B., Dick, Ø. B., Gobakken, T., & Totland, Ø. (2015). Spatial distribution of temporal dynamics in anthropogenic fires in miombo savanna woodlands of Tanzania. Carbon Balance and Management, 10(1), 1–15.

Thomas, A. D. (2012). Impact of grazing intensity on seasonal variations in soil organic carbon and soil CO2 efflux in two semiarid grasslands in southern Botswana. Philosophical Transactions of the Royal Society B: Biological Sciences, 367(1606), 3076–3086.

Thornton, P. K. (2010). Livestock production: Recent trends, future prospects. Philosophical Transactions of the Royal Society B: Biological Sciences, 365(1554), 2853–2867.

Timberlake, J., Chidumayo, E., & Sawadogo, L. (2010). Distribution and characteristics of African dry forests and woodlands. The

Dry Forests and Woodlands of Africa: Managing for Products and Services, 2, 11–41.

Vågen, T. G., Winowiecki, L. A., Desta, L. T., & Tondoh, J. E. (2013). The land degradation surveillance framework (LDSF). Field Guide, 4.

Van Schaik, N. (2009). Spatial variability of infiltration patterns related to site characteristics in a semi-arid watershed. Catena, 78(1), 36–47.

Wachiye, S., Pellikka, P., Rinne, J., Heiskanen, J., Abwanda, S., & Merbold, L. (2022). Effects of livestock and wildlife grazing intensity on soil carbon dioxide flux in the savanna grassland of Kenya. Agriculture, Ecosystems & Environment, 325, 107713.

Wang, Z., Johnson, D. A., Rong, Y., & Wang, K. (2016). Grazing effects on soil characteristics and vegetation of grassland in northern China. Solid Earth, 7(1), 55–65.

Watson, P. F., & Petrie, A. (2010). Method agreement analysis: A review of correct methodology. Theriogenology, 73(9), 1167–1179.

Wei, L., Hai-Zhou, H., Zhi-Nan, Z., & Gao-Lin, W. (2011). Effects of grazing on the soil properties and C and N storage in relation to biomass allocation in an alpine meadow. Journal of Soil Science and Plant Nutrition, 11(4), 27–39.

White, F. (1983). The vegetation of Africa. (Vol. 20).

Zuur, A. F., Hilbe, J. M., & Ieno, E. N. (2013). A beginner’s guide to GLM and GLMM with R. A frequentist and Bayesian. Newburgh, United Kingdom: Highland Statistics Ltd.

CHAPTER FOUR
General Discussion

4.1 Effect of grazing intensities on soil organic carbon (SOC)

The study findings revealed substantial variations in SOC across different grazing intensities. The high level of SOC was observed in light grazed areas and less values were observed in high grazed area. This variation can be attributed to a combination of the effect of livestock grazing practices on soil. Excessive livestock grazing reduces plant and root biomass which reduces amount of litters returned in the soil (Jiang *et al.,* 2020). Animal trampling increases soil compaction making in vulnerable to erosion thus removing the top soil which is rich in organic matters. Nevertheless, pressure exerted on soil by livestock tramping actions affects microbial activities and thus lowering decomposing activity of dead organic matters in the soil. In addition, intensive grazing can alter the composition of plant communities, favoring species that are less effective in sequestering carbon in the soil such as invasive species, and non-palatable species (Kikoti & Mligo, 2015).

4.2 Effect of grazing intensities on soil physical properties (Kfs, BD and Preferential flow

Findings have showed a significant decline in soil infiltrability, increasing BD and preferential flow fraction with increased grazing intensities. From the findings, it has been observed that there is negative relationship between soil compaction (BD) and soil infiltration (Abdel-Magid *et al.,* 1987). Animal trampling increase soil pressures, reduces soil porosity, alters soil structure, blocking pores connectivity which ultimately lowers soil infiltration capacity. Increasing soil compactions accelerates erosion of the top soil layers resulting to non-uniformity flow of water within the soil and facilitates preferential flow(Abdel-Magid *et al.,* 1987). Overgrazing results to collapsing of soil structure as a result of excessive recurring trampling by grazing animals and reduces SOC and vegetation cover which is a source of SOC and thus affecting soil hydrological functions (Falk *et al.,* 2024).The trampling effect of grazing activities has been reported to override the role of vegetation on soil hydrological properties (Bargués-Tobella *et al.,* 2024; Lulandala *et al.,* 2022). Reduced soil infiltration capacity increases risks for water scarcity, water stagnation on top soil, increasing surface run off and flooding during heavy rain season. Furthermore, trampling activities overrides the positive effect of microbial activities and vegetation on the soil hydrological function (Falk *et al.,* 2024).

CHAPTER FIVE

5.0 General conclusion and recommendations

5.1 Contribution of the study

This study investigates how different grazing intensities affects soil functioning ie; carbon storage and hydrological functions. The following contribution have been made from the study,

i. Understanding the consequences of increased livestock grazing intensities in Miombo woodlands is important for the proper prediction of management strategies and planning. This knowledge can contribute to decision and policymakers to make reliable decision and appropriate policies for sustainable management of the Miombo ecosystems.
ii. This study, has created a better understanding on the detrimental effect of poor livestock grazing management practices on Miombo woodland and soil functioning including soil carbon storage and hydrological functions.
iii. The study has provided the scientific insight on the role of soil in sustaining this important biome and human wellbeing

.

5.2 Conclusion

The study shows how different grazing intensities affect soil properties including soil hydrological properties (field-hydraulic conductivity, soil organic carbon, bulk density, uniform flow depth, and preferential flow) in Miombo woodlands. Grazing intensity was classified using stocking rate method based on livestock population records and scoring method based on field observation. Then, these grazing intensities were investigated on how they affect the soil properties.

Main conclusions are;

i. Increasing grazing intensities degrades soil health by depleting SOC and lowering soil infiltration capacity
ii. Anywhere where grazing is taking place, trampling effect of livestock is the major influencing factor governing many soil

functions such as carbon storage and water infiltration in areas

iii. Reduced soil infiltration, SOC, uniform flow and increased preferential flow may results to further detrimental effect of soil degradation such waters scarcity, surface runoff, soil erosion and flooding risks during heavy rain season.

iv. Soil functions such as Soil infiltration capacity and SOC storage can be improved with reduced grazing intensity in Miombo woodlands of Tanzania

5.3 Recommendations

Considering the increasing trend of livestock grazing in the Miombo ecosystem, the following amendments are recommended;

i. Establishment of the appropriate carrying capacity and adhering to proper livestock grazing practices such as seasonal grazing and zero grazing which will reduce the detrimental effect of increasing grazing intensities especially in Miombo woodlands.

ii. Setting aside many grazing areas that will able to reduce grazing pressure in Miombo woodlands

iii. To solve the problem of controlling livestock in Miombo woodlands pastoralists and farmers are encourages to plant grass species which as stress tolerant in their areas and adopt advanced pastoral systems such as silvopastoral systems in order to have a control of their livestock.

References

Abdel-Magid, A. H., Schuman, G. E., & Hart, R. H. (1987). Soil bulk density and water infiltration as affected by grazing systems. Rangeland Ecology & Management/Journal of Range Management Archives, 40(4), 307–309.

Bargués-Tobella, A., Winowiecki, L. A., Sheil, D., & Vågen, T.-G. (2024). Determinants of Soil Field-Saturated Hydraulic Conductivity Across Sub-Saharan Africa: Texture and Beyond. Water Resources Research, 60(1), e2023WR035510. https://doi.org/10.1029/2023WR035510

Falk, D., Winowiecki, L. A., Vågen, T.-G., Lohbeck, M., Ilstedt, U., Muriuki, J., Mwaniki, A., & Tobella, A. B. (2024). Drivers of field-saturated soil hydraulic conductivity: Implications for restoring degraded tropical landscapes. Science of the Total Environment, 907, 168038.

Jiang, Z.-Y., Hu, Z.-M., Lai, D. Y., Han, D.-R., Wang, M., Liu, M., Zhang, M., & Guo, M.-Y. (2020). Light grazing facilitates carbon accumulation in subsoil in Chinese grasslands: A meta-analysis. Global Change Biology, 26(12), 7186–7197.

Kikoti, I. A., & Mligo, C. (2015). Impacts of livestock grazing on plant species composition in montane forests on the northern slope of Mount Kilimanjaro, Tanzania. International Journal of Biodiversity Science, Ecosystem Services & Management, 11(2), 114–127.

Lulandala, L., Bargués-Tobella, A., Masao, C. A., Nyberg, G., & Ilstedt, U. (2022). Excessive livestock grazing overrides the positive effects of trees on infiltration capacity and modifies preferential flow in dry miombo woodlands. Land Degradation & Development, 33(4), 581–595.

APPENDICES

Appendix 1: Village characteristics found in Handeni district

Village characteristics	Handeni district		
	Kwamsundi Village	Gole Village	Madebe Village
Annual rainfall (mmHg)	600-1300		
Elevation (m.s.l.)	600 -1,000		
Total Area (ha)	3804.239	12087.73	8309.902
Grazing area woodland (ha)	2472.04	8425.74	6235.99
Number of shoots	403	1362	4212
Number of cattle	2381	1132	3179
No of livestock (Total TLU)	1707	929	2647
Stocking rate (TLU/grazing area (ha)	0.7	0.1	0.4
Main livelihood strategies	Farming Agro-pastoralism Pastoralism	Farming Agro-pastoralism Pastoralism	Farming Agro-pastoralism Pastoralism
Soil Characteristics			
Bulk density (gcm-3)	1.49	1.57	1.56
Clay (%)	17.9	10.1	22.1
Silt (%)	18.1	13.5	12.8
Sand (%)	64	76.4	65.1

Appendix 2: Village characteristics found in Kilosa district

Village characteristics	Kilosa District		
	Ihombwe Village	Chabima village	Ulaya Mbuyuni Village
Annual rainfall (mmHg)	800-1500		
Elevation (m.s.l.)	550-2200		
Total Area (ha)	20976.47	14546.08	3598.947
Grazing area woodland (ha)	13855.04	13663.19	1763.16
Number of shoots	3035	30	730
Number of cattle	6211	1158	1812
Number of livestock (Total TLU)	4651	814	1341
Stocking rate (TLU/grazing area (ha)	0.3	0.1	0.8
Main livelihood strategies	Farming Agro-pastoralism Pastoralism	Farming Agro-pastoralism Pastoralism	Farming Agro-pastoralism Pastoralism
Soil Characteristics			
Bulk density (gcm-3)	1.41	1.42	1.6
Clay (%)	20.3	14.1	17.3
Silt (%)	10.6	7.5	12.3
Sand (%)	69.1	78.4	70.4

Appendix 3: Village characteristics found in Handeni district

Village characteristics	Kilombero District		
	Utengule village	Miyomboni village	Iduindembo village
Annual rainfall (mmHg)	1200-1800		
Elevation (m.s.l.)	281- 685		
Total Area (ha)	13172.06	2323.8	3268.916
Grazing area woodland (ha)	5424.63	178.43	934.77
Number of shoots	1557	2416	1118
Number of cattle	2937	6468	1903
Number of livestock (Total TLU)	2212	4769	1444
Stocking rate (TLU/grazing area (ha)	0.4	>1.5	1.5
Main livelihood strategies	Farming Agro-pastoralism Pastoralism	Pastoralism	Farming Agro-pastoralism Pastoralism
Soil Characteristics			
Bulk density (gcm-3)	1.4	1.68	
Clay (%)	35.1	15.9	25.7
Silt (%)	10.3	13.7	13.3
Sand (%)	54.7	70.4	61.1

Appendix 4: Summary of Linear mixed-effects models and Generalized Linear mixed-effects model explaining variation in Soil Organic Carbon (SOC), Soil Bulk Density (BD) and field-saturated soil hydraulic conductivity (Kfs)

Soil Organic Carbon (SOC			
Predictors	Estimates	CI	P
Intercept	2.25	1.97 – 2.54	<0.001
GI [Medium]	-0.45	-0.76 – -0.14	0.004
GI [High]	-0.78	-1.05 – -0.50	<0.001
ICC	0.14		
N village	9		
N district	3		
Observations	188		
Marginal R2/ Conditional R2	0.152/0.268		
Soil Bulk Density (BD)			
Predictors	Estimates	CI	P
Intercept	1.34	1.30 – 1.38	<0.001
GI [Medium]	0.12	0.06 – 0.17	<0.001
GI [High]	0.29	0.25 – 0.34	<0.001
ICC	0.02		
N village	9		
N district	3		
Observation	188		
Marginal R2	0.455		
Field-saturated soil hydraulic conductivity (Kfs)			
Predictors	Estimates	CI	P
Intercept	94.13	61.88– 143.18	<0.001
GI [Medium]	0.56	0.41 – 0.78	0.001
GI [High]	0.27	0.20 – 0.37	<0.001
ICC	0.38		
N village	8		
N district	3		
Observation	117		
Marginal R2/ Conditional R2	0.329/0.581		

Note: The estimates of the fixed effects, their associated 95% confidence intervals (CI) and corresponding p-values are shown (based on t-tests using Satterthwaite's method in the case of LMMs and Z-tests in the case of Gamma GLMMs). The random effects i.e; number of observations, districts and villages within districts, the marginal and conditional R^2, and the Interclass Correlation Coefficient (ICC) are included as well. The effects and corresponding p-values for the fixed factors GI (Scoring method) are in relation to their baseline levels (light GI).

Appendix 5: Summary of Linear mixed-effects models and Generalized Linear mixed-effects model explaining variation in field-saturated soil hydraulic conductivity (Kfs), Percentage Dye Coverage (DC%), Uniform infiltration depth, and Preferential Flow

Field-saturated soil hydraulic conductivity (Kfs)			
Predictors	Estimates	CI	P
Intercept	94.13	61.88– 143.18	<0.001
GI [Medium]	0.56	0.41 – 0.78	0.001
GI [High]	0.27	0.20 – 0.37	<0.001
ICC	0.38		
N village	8		
N district	3		
Observation	117		
Marginal R2/ Conditional R2	0.329/0.581		
Percentage Dye Coverage (DC%) LMM			
Predictors	Estimates	CI	P
Intercept	84.74	53.78 – 115.71	<0.001
GI [Medium GI]	-13.11	-23.94 – -2.28	0.019
GI [High GI]	-36.64	-47.61 – -25.67	<0.001
ICC	0.68		
N village	8		
N district	3		
Observation	188		
Marginal R2/ Conditional R2	0.300 / 0.773		
Uniform infiltration depth LMM			
Predictors	Estimates	CI	P
Intercept	30.47	22.79 – 38.15	<0.001
GI [Medium]	-4.75	-10.63 – 1.12	0.110
GI [High]	-13.75	-19.79 – -7.72	<0.001
ICC	0.14		
N village	9		
N district	3		
Observations	188		
Marginal R2/ Conditional R2	0.395/0.568		

Preferential Flow LMM			
Predictors	Estimates	CI	P
Intercept	36.47	21.47 – 51.47	<0.001
GI [Light GI]	-11.30	-27.35 – 4.76	0.163
GI [Medium GI]	-10.19	24.96 – 4.59	0.171
ICC	0.27		
N village	8		
N district	3		
Observation	117		
Marginal R2/ Conditional R2	0.049 / 0.309		

Note: The estimates of the fixed effects, their associated 95% confidence intervals (CI) and corresponding p-values are shown (based on t-tests using Satterthwaite's method in the case of LMMs and Z-tests in the case of Gamma GLMMs). The random effects i.e. number of observations, districts and villages within districts, the marginal and conditional R^2, and the Interclass Correlation Coefficient (ICC) are included. The effects and corresponding p-values for the fixed factors GI (Scoring method) are in relation to their baseline levels (light GI for Kfs, DC and Uniform infiltration depth and High GI for preferential flow fraction).

Appendix 6: SUPPLIMENTARY MATERIALS

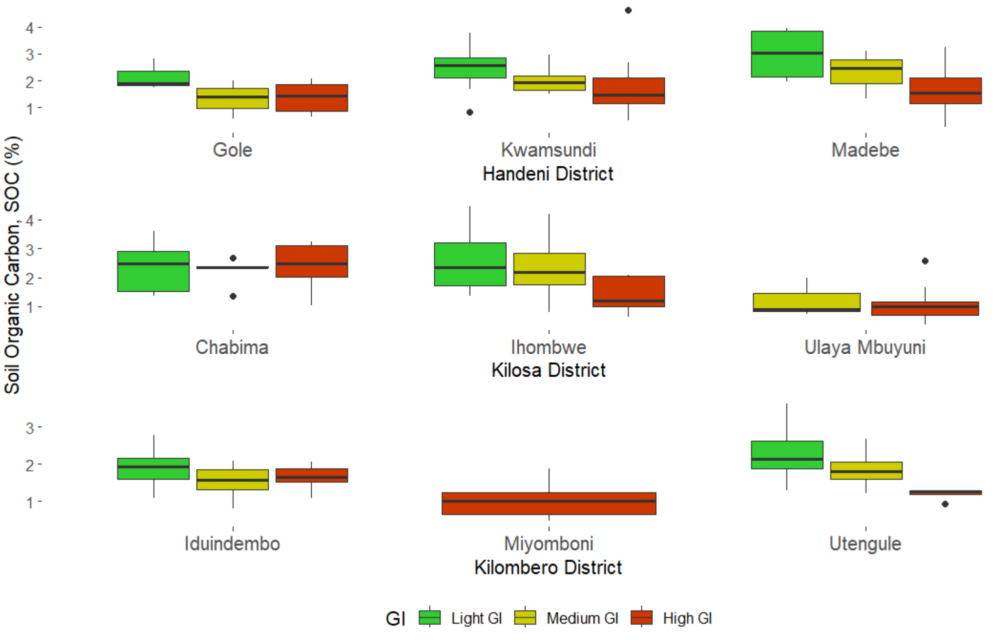

Figure S1: Boxplots (median, first and third quartile) of the SOC content under various grazing intensities (Scoring method) across study villages.

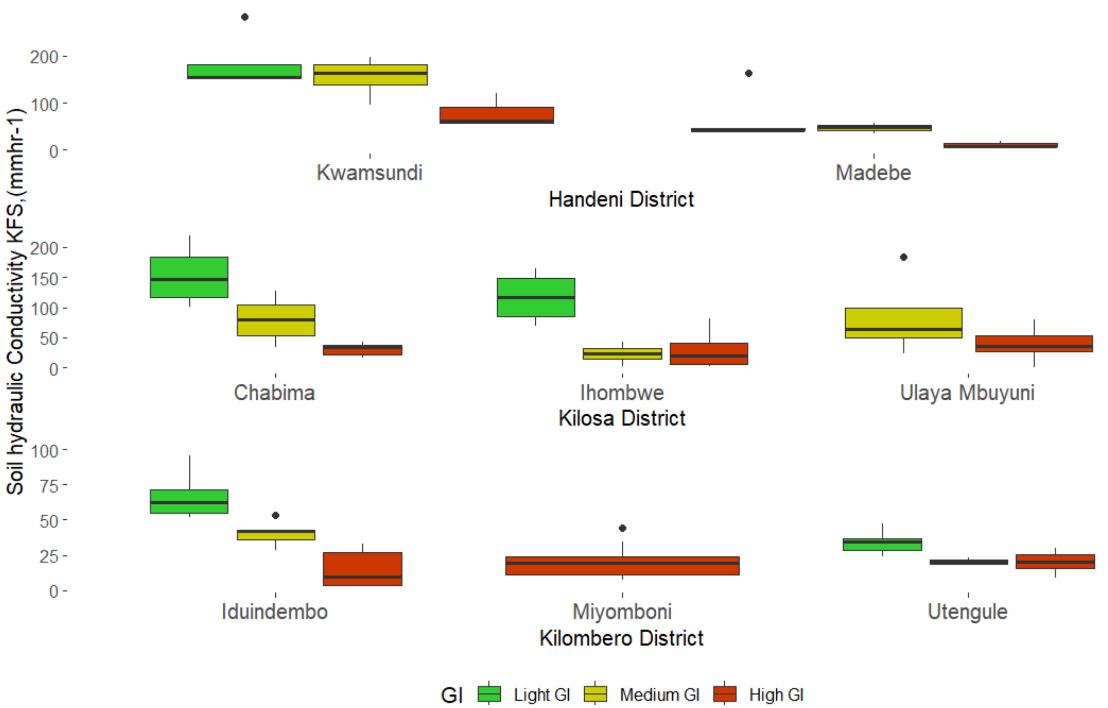

Figure S2: Boxplots (median, first and third quartile) of the Kfs under various grazing intensities (Scoring method) across study villages.

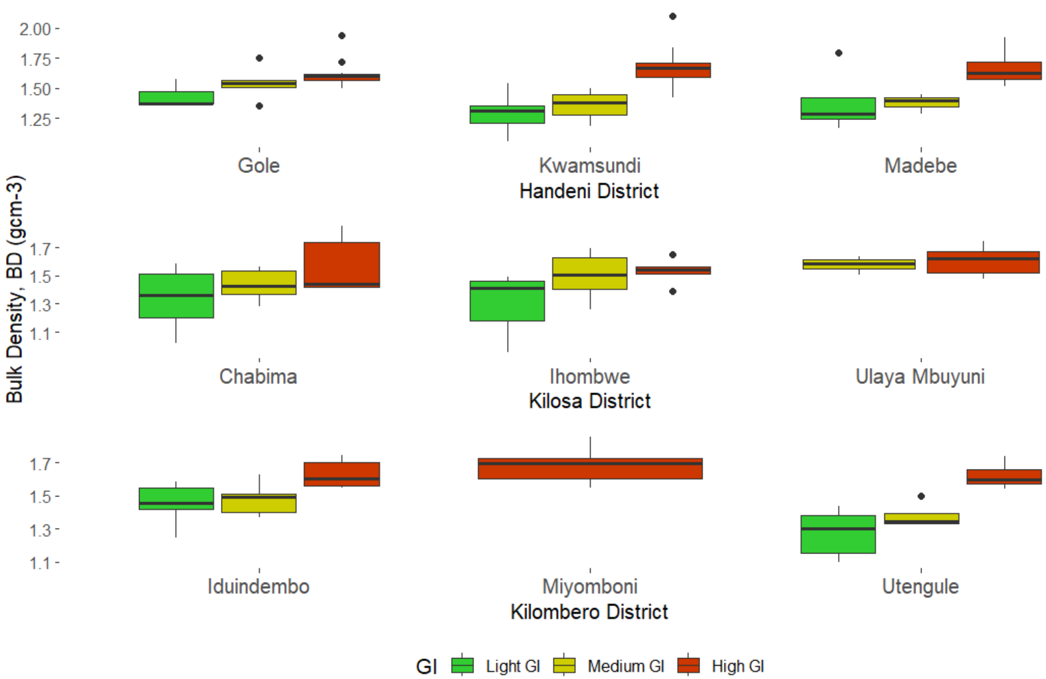

Figure S3: Boxplots (median, first and third quartile) of the BD under various grazing intensities (Scoring method) across study villages.

Table S1: Number of plots per village per grazing intensity

District		**Handeni**			**Kilosa**			**Kilombero**	
Villages	Gole	Kwamsundi	Madebe	Chabima	Ihombwe	Ulaya Mbuyuni	Iduindembo	Miyomboni	Utengule
Stocking rate	Light	High	Medium	Light	Medium	High	High	High	Medium
Total plots	20	24	22	22	24	20	21	15	20
Scoring method									
Light GI	3	7	4	11	13	0	6		10
Medium GI	5	6	3	5	6	3	9		4
High GI	12	11	15	6	5	17	6	15	6
Total plots	20	24	22	22	24	20	21	15	20
Water Infiltration measurement									
Stocking rate	Light GI	High GI	Medium	Light GI	Medium	High GI	High GI	High GI	Medium
Total Plots	0	12	16	15	13	16	15	15	15
Individual scoring method									
Light GI	0	5	4	5	4	0	5		5
Medium GI	0	4	3	4	4	3	5		4
High GI	0	3	9	6	5	13	5	15	6
Total plots	0	12	16	15	13	16	15	15	15