

**INTEGRATING LOCAL ECOLOGICAL KNOWLEDGE, FUNCTIONAL
ECOLOGY AND CONSERVATION STRATEGIES OF WILD LOQUAT
(*Uapaca kirkiana* MÜLL. ARG.) IN MALAWI**

PhD TRANSFORMATIVE COMMUNITY DEVELOPMENT THESIS

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MZUZU UNIVERSITY

DECEMBER, 2025

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CONSERVATION STRATEGIES OF WILD LOQUAT (*Uapaca kirkiana*
MÜLL. ARG.) IN MALAWI**

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DECLARATION

I, hereby declare that this thesis titled, “Integrating local knowledge, functional ecology and conservation strategies of wild loquat (*Uapaca kirkiana* müll. arg.) in malawi” has been written by me and is a record of my research work. All citations, references and borrowed ideas have been duly acknowledged. It is being submitted in fulfilment of the requirements for the award of the degree of the Doctor of Philosophy (Transformative Community Development) degree of the Mzuzu University. None of the present work has been submitted previously for any degree or examination in any other University.

Students name

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CERTIFICATE OF APPROVAL

This Thesis “Integrating Local Knowledge, Functional Ecology and Conservation Strategies of Wild Loquat (*Uapaca kirkiana* Müll. Arg.) in Malawi” by Bruno Kokouvi Kokou is submitted with our approval as university supervisors for the PhD in Transformative Community Development:

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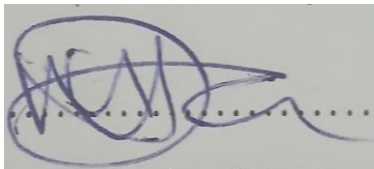
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DEDICATION

To my beloved mother, Alessi Akoua, for your constant love, prayers and guidance that have shaped my life and sustained me throughout this journey.

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ABBREVIATIONS/ACRONYMS

AGB: Aboveground Biomass

AUC: Area Under Curve

DBH: Diameter at Breast Height

FAO: Food and Agriculture Organization of the United Nations

F: False Positive Rate

GHG: Greenhouse Gas

GIS: Geographic Information System

GLMM: Generalized Linear Mixed Model

GPS: Global Positioning System

H: Sensitivity

HWSD: Harmonized World Soil Database

IDUpp: Use Diversity Index per Plant Part

IPCC: Intergovernmental Panel on Climate Change

IUCN: International Union for Conservation of Nature

IVIUpp: Use Importance Value Index per Plant Part

IVU: Interspecific Use Value

K: Kappa

LEK: Local Ecological Knowledge

NTFP: Non-Timber Forest Product

NUpp: Number of Citations of Reported Uses per Plant Part

PCA: Principal Component Analysis

PET: Potential Evapotranspiration

RC: Citation Frequency

RDA: Redundancy Analysis

ROC: Receiver Operating Characteristic

S: Specificity

SDM: Species Distribution Model

SEDI: Symmetric Extremal Dependence Index

SSP: Shared Socioeconomic Pathway

T: Threshold

TSS: True Skill Statistic

UVpp: Use Value of Plant Part

VIUpp: Use Importance Value per Plant Part

VUS: Specific Use Value

TABLE OF CONTENTS

DECLARATION.....	I
CERTIFICATE OF APPROVAL	IV
DEDICATION.....	V
ACKNOWLEDGEMENTS.....	VI
ABBREVIATIONS/ACRONYMS.....	VII
TABLE OF CONTENTS.....	IX
LIST OF TABLES	XV
LIST OF FIGURES	XVII
ABSTRACT	XX
CHAPTER 1: INTRODUCTION.....	1
1.1. Background of the study.....	1
1.2. Problem Statement.....	3
1.3. Study Objective	6
1.3.1. Main objective	6
1.3.2. Specific Objectives	6
1.3.3. Hypothesis.....	7
1.4. Justification of the study	8
1.5. Ethical Considerations.....	9
1.6. Structure of the Thesis.....	10
CHAPTER 2: LITERATURE REVIEW	13
2.0 Introduction	13
2.1. General Research Trends on <i>U. kirkiana</i>	13
2.1.1. Geographical and Disciplinary Biases.....	14
2.1.2. Ethnobotanical knowledge and Socio-economic contributions.....	15
2.1.3. Domestication, propagation and genetic diversity	17
2.1.4. Ecological Roles and Regeneration Dynamics.....	17

2.2. Ethnobotanical knowledge and socio-economic value	18
2.3. Woody species composition and phylogenetic structure	19
2.4. Functional trait variation and environmental gradients.....	21
2.5. Population structure and carbon storage	22
2.6. Climate change and future distribution	24
2.7. Conceptual framework	27
2.8. Chapter Summary.....	29
CHAPTER 3: MATERIALS AND METHODS.....	31
3.0. Introduction	31
3.1. Study Area.....	31
3.2. Research design.....	34
3.3. Sampling framework and methods.....	35
3.3.1. Community-level surveys.....	35
3.3.2. Forest inventories	36
3.3.3. Functional trait sampling	36
3.3.4. Species distribution modelling	36
3.4. Data Collection.....	37
3.4.1. Research objective one	38
3.4.2. Research objective two	43
3.4.3. Research objective three	44
3.4.4. Research objective four.....	46
3.4.5. Research objective five	47
3.5. Data Analysis	50
3.5.1. Research objective one	51
3.5.2. Research objective two	54
3.5.2.1. Demographic structure analysis of forest stands	54
3.5.2.2. Phylogenetic structure metric and quantification of taxonomic	56
3.5.3. Research objective three	60

3.5.4. Research objective four.....	61
3.5.4.1. Floristic diversity and species associations of <i>U. kirkiana</i> habitats.....	62
3.5.4.2. Assessment of the structural diversity and population structure of <i>U. kirkiana</i> across Malawi regions.....	64
3.5.4.3. Estimation of the carbon storage by <i>U. kirkiana</i>	65
3.5.5. Research objective five	66
3.5.5.1. Model development and evaluation	66
3.5.5.2. Mapping habitat suitability and determining priority areas	68
3.6. Ethical Considerations.....	70
3.7. Chapter Summary.....	70
CHAPTER 4: RESULTS.....	72
4.0 Introduction	72
4.1 Local ecological knowledge, ethnobotanical uses, and community-based conservation strategies of <i>U. kirkiana</i> in Malawi.....	72
4.1.1. Perception of the dynamics of <i>U. kirkiana</i>	72
4.1.2. Local practices for <i>U. kirkiana</i> conservation	74
4.1.3. Socio-economic factors affecting local community's conservation practice	75
4.1.4. Local community perception about ecosystem services from <i>U. kirkiana</i> in Malawi.....	76
4.1.5. Importance of local uses and ecological vulnerability of <i>U. kirkiana</i>	77
4.2 Species composition and phylogenetic patterns along elevation gradients.....	84
4.2.1 Community species composition and demographic structure in different elevation area.....	84
4.2.2 Phylogenetic diversity and the analysis of similarity in different elevation area	88
4.2.3 Differences among the phylogenetic community compositions in the different elevation areas	91
4.2.4 Community phylogenetic structure responses to elevation and environmental factors	93
4.3 Functional trait variation of <i>Uapaca kirkiana</i> across eco-geographical regions	98
4.3.1 Morphological variability of <i>U. kirkiana</i> among geographical region.....	98
4.3.2 Pairwise correlation between morphological traits	99
4.3.3 Discriminant morphological and functional traits of <i>U. kirkiana</i> according to the region	101
4.3.4 Relationships between environmental variables and discriminant morphological and functional traits of <i>U. kirkiana</i> trees	104

4.3.5 Discriminant morphological and functional traits of <i>U. kirkiana</i> and their relationships with the least correlated bioclimatic variables	105
4.3.6 Morphotypes identified across geographical region in Malawi	109
4.3.7 Phenotypic plasticity of <i>U. kirkiana</i> trees in Malawi	111
4.4 Population ecology and carbon storage of <i>Uapaca kirkiana</i> across regions.....	113
4.4.1. Floristic composition and diversity pattern	113
4.4.2 Structural, demographic, and dendrometric characteristics of <i>U. kirkiana</i> populations along Malawi regions	117
4.4.3 Natural regeneration and tree branches of <i>U. kirkiana</i> across the region.....	123
4.4.4 Biomass, carbon potential and ecological value of carbon storage by <i>U. kirkiana</i> across regions in Malawi	125
4.5 Shifts in suitable habitats of <i>U. kirkiana</i> under climate change in Malawi	126
4.5.1. Model performance and relative importance of environmental variables	126
4.5.2. Suitable habitats for <i>U. kirkiana</i> in Malawi.....	130
4.5.3. Priority conservation and cultivation area of <i>U. kirkiana</i> in Malawi	133
CHAPTER 5: DISCUSSION.....	135
5.0 Introduction	135
5.1 A Combined Socio-Ecological Perspective on <i>U. kirkiana</i> Health and Productivity	135
5.1.1 Local perception on the dynamics of <i>U. kirkiana</i> Population: Insights for awareness raising	135
5.2 Local conservation practices of <i>U. kirkiana</i> : an opportunity for capacity building.....	137
5.2.1 Uses of plant parts of <i>U. kirkiana</i> and ecological vulnerability	139
5.3 Woody species composition and phylogenetic structure along elevation gradients	142
5.3.1 Floristic composition and demographic structure in different elevation areas.....	142
5.3.2 Phylogenetic community composition in different elevation areas.....	146
5.3.3 Phylogenetic community structure in different elevation areas	148
5.3.4 The relationship between phylogenetic community structure and the environmental factors.....	150
5.3.5 Phylogenetic structure of plant communities	152
5.3.6 Conservation advice	153

5.4 Intraspecific functional trait variation of <i>U. kirkiana</i> across eco-geographical regions	154
5.4.1 Morphological and functional traits variation across geographical regions.....	154
5.4.2 Pairwise correlation between morphological traits	155
5.4.2 Discriminant morphological and functional traits and regional differentiation patterns of <i>U. kirkiana</i>	156
5.4.3 Morphotypes identified across the geographic region in Malawi	158
5.4.4 Interactions between environmental factors and <i>U. kirkiana</i> traits	160
5.4.5 Plasticity in the morphological and functional traits of <i>U. kirkiana</i>	160
5.4.6 Implications of the findings for <i>U. kirkiana</i> conservation and domestication	161
5.5 Population ecology and carbon storage potential of <i>U. kirkiana</i> in Malawi.....	162
5.5.1 Floristic composition and diversity of <i>U. kirkiana</i> habitat.....	162
5.5.2 Structural diversity of <i>U. kirkiana</i> stand: insight for ecosystem sustainable management	165
5.5.3 Variation in diameter class structure of <i>U. kirkiana</i> populations across regions	167
5.5.4 Diameter structure of <i>U. kirkiana</i> populations variation across the altitudinal gradient.	170
5.5.5 Natural regeneration and branching dynamics of <i>U. kirkiana</i> across different regions..	170
5.5.6 Biomass capture and carbon sequestered by <i>U. kirkiana</i> across regions in Malawi	172
5.6 Implications of climate change on habitat suitability and altitudinal shifts of <i>U. kirkiana</i> ...	173
5.6.1 Overview of the choice of methodological approach.....	173
5.6.2 Temperature-related climatic variables determine the current potential distribution of <i>U. kirkiana</i> in Malawi.....	174
5.6.4 Prioritisation and conservation zone of <i>U. kirkiana</i> in Malawi.....	176
5.6.5 Implications of the findings for the conservation of <i>U. kirkiana</i>	179
5.7 Chapter Summary.....	180
6.0 Introduction	181
6.1. Conclusion.....	181
6.2 Recommendations	183
6.2.1. Practice-Oriented / Community-Level recommendations	183
6.2.2. Research recommendations	184
6.2.3. Policy recommendations.....	185
6.3. Chapter Summary.....	185

REFERENCES.....	187
APPENDIX	229
Appendix 1: Interviewer Administered Data Collection of <i>Uapaca kirkiana</i> in MALAWI (research objective 1).....	229
Appendix 2: Stand structure to guide conservation actions of <i>Uapaca kirkiana</i> in Malawi: objective 2 and 4	238
Appendix 3: Data collection sheet on morphological and functional traits for research objective 3	241
Appendix 4: Occurrence data collection for research objective five	245
Appendix 5: Species inventoried across study area (89 genera and 39 botanical families).....	246
Appendix 6: Specific frequencies of <i>U. kirkiana</i> habitats across studies areas	249
Appendix 7: Species with IUCN status across studies areas	252
Appendix 8: MZUNIREC Ethics and Regulatory Approval	255

LIST OF TABLES

Table 1: Distribution of Households (Number of Households, N) in surveyed villages across the Geographical Regions of Malawi	40
Table 2: Illustrating the socioeconomic factors influencing the collection of use of knowledge on <i>U. kirkiana</i> across Malawi Regions.....	42
Table 3: Environmental variables used	46
Table 4: Forests sampled across the regions, with the number of sampling plots	47
Table 5: Environmental variables used in MaxEnt modeling	50
Table 6: Parameters used for vulnerability assessment	54
Table 8: Structural diversity and demographic parameters used to describe the communities.....	59
Table 9: Structural diversity, demographic and dendrometric parameters used to describe <i>U. kirkiana</i> populations and their habitat in Malawi	63
Table 10: Association of the perception of the dynamics of <i>U. kirkiana</i> populations with sociodemographic factors and Region in Malawi.....	73
Table 11: Results of the generalized linear mixed-effect model (GLMM) with Poisson distribution assessing the effects of regions and sociodemographic factors on the attitude of local communities towards the conservation of <i>U. kirkiana</i> in Malawi	76
Table 12: Importance value of the plant parts of <i>U. kirkiana</i> in Malawi	80
Table 13: Distribution of participants by ethnic groups	80
Table 14: Similarity of <i>U. kirkiana</i> use by ethnic groups in Malawi according to Sorensen index.....	81
Table 15: Mean specific uses of <i>U. kirkiana</i> according to ages	82
Table 16: Mean specific uses of <i>U. kirkiana</i> according to Gender	82
Table 18: Frequency of vegetative importance (FIV) of the dominant botanical family.....	85
Table 19: Structural indices of the six natural forests studied across their elevation in Malawi ..	87
Table 20: Environmental factors fitted on to PCoA axes	90
Table 21: Vector coordinates for significant environmental variables.....	91
Table 22: Variation of the morphological traits of <i>U. kirkiana</i> among geographical regions.	98
Table 23: Results of the selection of explanatory variables using a multivariate procedure based on Wilks' Lambda and F-tests.....	101
Table 24: Results of linear models evaluating the effect of the region on different morpho-functional variables of <i>U. kirkiana</i>	102
Table 25: Correlations between functional traits and canonical axes from discriminant analysis	103

Table 26: Significance and scores of environmental variables influencing the discriminant morphological and functional traits of <i>U. kirkiana</i> trees	105
Table 27: Loadings of the discriminating morphological and functional traits on the axes of the redundancy analysis (RDA1 and RDA2).....	105
Table 28: Correlation matrix between the first three principal components and the most discriminating morphological traits and significant environmental variable	108
Table 29: Variability of <i>U. kirkiana</i> trees, fruits, leaves and seeds traits according to cluster ...	111
Table 30: Importance Value Index	115
Table 31: Variation in diversity indices among <i>U. kirkiana</i> habitats across the regions in Malawi	116
Table 32: Demographic, structural and dendrometric parameters of <i>U. kirkiana</i> populations according to Malawian regions.	118
Table 33: Estimation per hectare of living biomass, sequestered carbon, and the ecological value of carbon storage by <i>U. kirkiana</i> across regions in Malawi	126
Table 34: Performance statistics of <i>U. kirkiana</i> distribution model.....	127

LIST OF FIGURES

Figure 1: Conceptual Framework.....	29
Figure 2a: Location map of the geographical region of Malawi, showing the studied forests	33
Figure 2b: Map showing Malawi in Africa and the 10 surveyed Districts across regions in Malawi	34
Figure 3: Perceived causes of <i>U. kirkiana</i> population decline as indicated by local communities, ...	74
Figure 4: Relative frequency of citations (Rc, %) of the local conservation strategies of <i>U. kirkiana</i> across the regions of Malawi.	75
Figure 5: Relative frequency of citations (Rc, %) of ecosystem services perceived by the local community in Malawi	77
Figure 6: Relative frequency of citations (Rc, %) of plant parts used of <i>U. kirkiana</i> across the Regions of Malawi.	78
Figure 7: Chord diagram showing the distribution of ethnobotany use of <i>U. kirkiana</i>	79
Figure 8: Vulnerability index of the different plant parts and overall, of <i>U. kirkiana</i> according to the use by local communities	84
Figure 9: Distribution of diameter class structure across elevation gradient in Malawi, with Weibull.....	88
Figure 10: The change of community PD and SES.PD with the elevation gradient.....	89
Figure 11: Principal coordinate Analysis of plots based on the community structure of woody plants	90
Figure 12: Variation of phylogenetic diversity and structure indices across different elevation classes in Malawi.	93
Figure 13: Regression analyses between community phylogenetic structure metrics and elevation	94
Figure 14: Correlations between phylogenetic diversity indices and environmental variables across the ecological gradient	96
Figure 15: Phylogenetic trees of woody species across elevation gradient of Malawi.	97
Figure 16: Pairwise correlation of morphological traits.....	100
Figure 17: Discrimination of the 72 individuals of <i>U. kirkiana</i> according to region of provenances	104
Figure 18: Principal Component Analysis (PCA) plot of morphological and functional traits, discriminant environment variable describing the variation of those traits according to different regions (Dim 1 and 2).	107

Figure 19: Principal Component Analysis (PCA) plot of morphological traits, discriminant environment variable describing the variation of those traits according to different regions (Dim 1 and Dim 3).....	108
Figure 20: Dendrogram showing clusters of <i>U. kirkiana</i> individuals based on morphological traits.	110
Figure 21: Variation of the phenotypic plasticity of the discriminant morphological and functional traits of <i>U. kirkiana</i> among the geographical regions in Malawi	112
Figure 22: Distribution of species families across the phytogeographic regions in Malawi.	114
Figure 23: Mingling of <i>U. kirkiana</i> with neighbouring trees across the regions in Malawi	117
Figure 24: Correlation matrix between structural, demographic, and dendrometric parameters of <i>U. kirkiana</i> populations in Malawi.	119
Figure 25: Correlation matrix between structural, demographic, and dendrometric parameters of <i>U. kirkiana</i> populations in Malawi across altitude.	120
Figure 26: Size (dbh) class distribution of <i>U. kirkiana</i> populations in each region in Malawi ..	121
Figure 27: Size (dbh) class distribution of <i>U. kirkiana</i> populations across altitude in Malawi ..	122
Figure 28: Quotients between <i>U. kirkiana</i> density in successive dbh size-classes (in 10 cm intervals)	123
Figure 29: Number of trees regenerated distribution of <i>U. kirkiana</i> populations in each region in Malawi.	124
Figure 30: Number of tree branches distribution of <i>U. kirkiana</i> populations in each region in Malawi.	125
Figure 31: Area Under Curve showing the performance of <i>U. kirkiana</i> distribution model based on the training and test data	126
Figure 32: Receiver Operating Characteristic (ROC) curve showing the performance of <i>U. kirkiana</i> distribution model based on the training and test data.....	127
Figure 33: Response curves showing the effects of environmental variable on the predicted habitat suitability for <i>U. kirkiana</i>	128
Figure 34: Contribution (%) of the environmental variables to the potential distribution of <i>U. kirkiana</i> in Malawi.....	129
Figure 35: Area (% of the Malawi's total land area) covered by <i>U. kirkiana</i> suitable and unsuitable habitats under the current and future climates	130
Figure 36: Predicted distribution of <i>U. kirkiana</i> under the current climate and the future climate scenarios (SSP 3-7.0 and SSP 4-8.5)	131
Figure 37: Rate of change in potential habitats of <i>U. kirkiana</i> in Malawi under SSP3-7.0 and SSP5-8.5 scenarios.....	132

Figure 38: Projection of habitat change dynamics for <i>U. kirkiana</i> under SSP3-7.0 and SSP5-8.5 scenarios.....	133
Figure 39: Priority areas for the conservation of <i>U. kirkiana</i> in Malawi	134

ABSTRACT

Uapaca kirkiana Müll. Arg. is an indigenous fruit tree of Malawi's Miombo woodlands that provides vital nutritional, economic, and ecological services. Despite its crucial importance to the ecosystems, its populations are declining due to overharvesting, unsustainable pruning, habitat loss, charcoal production, wildfires, and climate change. Its decline is a huge threat to both livelihoods and ecosystem functioning. Despite its importance, limited integrated understanding exists of its ecological, functional, and socio-economic dynamics across Malawi, which constrains sustainable management and conservation planning. This study aimed to analyse local ecological knowledge, ethnobotanical uses, and community-based conservation strategies of *U. kirkiana* in Malawi, characterize woody species composition and phylogenetic structure along elevation gradients associated with *U. kirkiana*, quantify intraspecific functional trait variation of *U. kirkiana* across eco-geographical regions and its relationship with environmental gradients, evaluate population structure, regeneration dynamics, and carbon storage potential of *U. kirkiana* across geographic regions and model the current and future distribution of *U. kirkiana* under climate change scenarios. Understanding these aspects is essential to inform sustainable conservation strategies, enhance livelihoods, and maintain ecosystem services. The methods in this study included a stratified survey of 1,222 households to capture local ecological knowledge, conservation practices, species use and perceived vulnerability. Forest inventories were conducted in six forests across the country, with two forests per region, assessing 149 plots and 72 trees for 21 morphological and functional traits. Taxonomic and phylogenetic diversity, diameter distributions, and community structure were analyzed, while trait variability was assessed using mixed-effects models, discriminant and redundancy analyses and hierarchical clustering. Species distribution modeling employed MaxEnt and habitat prioritization used Zonation. The results indicated widespread recognition of population decline, varying by region, profession and education. Deforestation and charcoal production were the main threats, whereas agroforestry, cutting prohibition, regeneration protection and pruning restrictions were key conservation measures. Fruits, trunks, and branches were most utilized for food, firewood and medicine. A vulnerability index of 2.25 reflected moderate risk. Four morphotypes indicated adaptive differentiation across environmental gradients, while small diameter classes dominated populations, suggesting active regeneration but overharvesting of large trees. Phylogenetic diversity and community assembly varied with elevation, mainly influenced by temperature. Structurally, *U. kirkiana* populations were dominated by small diameter classes (10-20 cm),

with few mature individuals (>45 cm), indicating regeneration disturbance. Diameter at breast height (DBH) was positively correlated with the structural quotient (Qs) and inter-tree distance, but negatively correlated with diameter differentiation, suggesting low heterogeneity in mature stands. *U. kirkiana* tolerated mixed-species stands (mingling index: 20-44%), supporting its suitability for agroforestry systems. The Northern region had the highest carbon storage (57.80 tCO₂/ha), significantly higher than the Southern (51.25 tCO₂/ha) and Central (43.80 tCO₂/ha) regions ($p < 0.05$), because this region is characterized by greater annual rainfall (>1,600 mm), which supports better tree growth and biomass accumulation. The estimated economic value of *U. kirkiana* was MWK 1,011,997.57 (577.95 USD/ha). The current distribution indicates that only 9% of habitats are suitable for *U. kirkiana*. Future projections suggest a decline in its range (from 9% to 6%), with a shift toward higher altitudes in the northern and central regions. Temperature emerges as a key factor determining its distribution, emphasizing the importance of strategies such as assisted migration, domestication, and climate-adapted plantations. Overall, *U. kirkiana* is a multifunctional species facing moderate anthropogenic and climate threats. Integrating LEK and functional ecology with climate models provides a more robust and socially relevant conservation framework than any single method.

Keywords: *U. kirkiana*; Miombo woodlands; vulnerability index; ecosystem services; sustainable management ; Malawi

CHAPTER 1: INTRODUCTION

1.1. Background of the study

The conservation and sustainable management of plant biodiversity, particularly non-timber forest products (NTFPs), remain central concerns in contemporary conservation biology and sustainable development agendas. NTFPs, which include fruits, seeds, leaves, resins, medicinal plant parts and other forest-derived resources, play a critical role in supporting rural livelihoods and ensuring food security. These resources provide essential nutritional, medicinal and economic benefits, particularly in regions where agricultural systems are seasonal or constrained by environmental factors (Radha et al. 2021; Husen et al. 2021).

Globally, NTFPs are a cornerstone of subsistence and income generation. It is estimated that approximately one billion people derive nearly 25% of their household income from NTFPs, and about 300 million people living in tropical forests rely on these resources as either a primary or supplementary livelihood source (Delgado et al. 2023; Mulenga et al. 2011). These resources become particularly crucial during periods of agricultural scarcity, such as the dry season, when they provide critical nutritional supplements, fodder for livestock and alternative income streams (Dossou et al. 2025; Asamoah et al. 2024). In addition to their socio-economic importance, NTFPs contribute significantly to ecosystem functioning by maintaining species diversity, supporting pollinator networks and enhancing soil fertility (Mulenga et al. 2011).

Despite their importance, NTFPs face increasing threats from unsustainable harvesting practices, habitat degradation, and anthropogenic pressures, which may lead to population declines, reduced regeneration, and in extreme cases, local or global species extinction (Shackleton 2015). The long-term sustainability of these resources therefore relies on the development of integrated conservation strategies that combine ecological knowledge, community participation, and policy frameworks (Belcher & Schreckenberg 2007). In this context, local ecological knowledge (LEK) is invaluable, as it encompasses generations of observations regarding species ecology, phenology, and

sustainable harvest practices (Berkes et al. 2000). Understanding species utilization patterns, the provisioning of ecosystem services and the community-based management approaches is critical to designing conservation interventions that simultaneously enhance biodiversity and support rural livelihoods (Shackleton & Pandey 2017).

Furthermore, neglected and underutilised wild food plants present untapped opportunities for ecological restoration, agro-biodiversity enhancement and livelihood diversification. These species are typically resilient to environmental stress, well-adapted to local ecological niches and able to thrive with minimal external inputs, while simultaneously improving soil fertility, controlling erosion, and supporting microclimatic stability (Ali and Bhattacharjee 2023; Chivenge et al. 2015, Shelef et al. 2017). The documentation of LEK associated with these species is therefore critical, as much of this knowledge is transmitted orally and is increasingly vulnerable to loss due to urbanization, cultural transformation and generational shifts (Khasbagan and Soyolt 2008). Ethnobotanical studies consistently show that communities rely heavily on wild food plants for nutrition, medicinal uses, cultural practices and economic activities, with utilization patterns strongly influenced by social, cultural, and demographic factors (Kuhnlein 2015; Samarou et al. 2021; Yaipharembi et al. 2023).

Collectively, these insights underscore the importance of research that links ecological assessment, socio-economic evaluation and ethnobotanical documentation. Such integrative studies not only inform sustainable management and conservation policies but also promote the resilience of rural communities that depend on wild plant resources (Shackleton & Pullanikkatil 2018). In this regard, the current study seeks to address knowledge gaps in the ecology, utilisation and socio-economic significance of NTFPs, with the ultimate aim of enhancing conservation outcomes and supporting sustainable livelihoods (Shackleton & Pullanikkatil 2018).

Conservation initiatives play a transformative role in community development by linking ecosystem sustainability with improved rural livelihoods (Shackleton & Pullanikkatil 2018). Through the sustainable use of natural resources, communities derive essential benefits such as food, income, and raw materials, which strengthen their economic resilience (Shackleton & Pandey 2014). Moreover, conservation enhances local adaptation strategies by promoting ecological balance, restoring degraded landscapes, and supporting traditional knowledge systems that help communities cope with climate variability (Reed et al. 2015). Thus, integrating conservation into rural development provides a pathway toward both environmental sustainability and socio-economic empowerment.

1.2. Problem Statement

In southern Africa, indigenous fruit trees such as *Uapaca kirkiana* Müll. Arg. represents a keystone species within Miombo woodland ecosystems, and provide critical nutritional, economic and ecological services. Its fruits are rich in carbohydrates, essential vitamins (A, C, and B-complex), minerals such as potassium, calcium, and magnesium, and secondary metabolites including antioxidants, which contribute significantly to human health and nutrition (Chawafambira et al. 2020; Moombe et al. 2014; Saka et al. 2007). These characteristics render *U. kirkiana* a crucial resource during the dry season, when conventional crops fail and food scarcity is most pronounced (Shirima et al. 2011). In addition to direct consumption, the fruits are processed into jam, wine and other value-added products, supporting local economies, enhancing household resilience, and providing diversified income sources. The reliance on *U. kirkiana* is particularly pronounced among rural communities, where market accessibility is limited and alternative livelihood options are scarce (Chawafambira et al. 2020; Kalaba et al., 2009).

From an ecological perspective, *U. kirkiana* contributes extensively to forest structure, biodiversity and ecosystem functionality. Mature trees enhance canopy complexity, regulate microclimatic conditions by providing shade, reducing evapotranspiration and create microhabitats that support

a diversity of fauna, including key pollinators and frugivores that facilitate seed dispersal (Shirima et al. 2011; Kokou et al. 2023a). Leaf litter decomposition contributes to soil nutrient cycling, sustaining nitrogen and organic carbon stocks while reducing erosion and promoting soil fertility (Chidumayo, 2013; Luoga et al., 2000). Moreover, through carbon sequestration, *Uapaca kirkiana* mitigates climate change impacts and supports ecosystem resilience, as Miombo tree species are known for significant biomass accumulation and long-term carbon storage (Shirima et al. 2011). Its presence in heterogeneous landscapes fosters structural and functional connectivity, which facilitates species coexistence and maintains ecological integrity across Miombo woodlands (Frost 1996).

Despite these multifaceted contributions, multiple anthropogenic pressures increasingly threaten *U. kirkiana* populations. Overharvesting of fruits and leaves reduces reproductive output and impairs natural regeneration, while unsustainable pruning practices, particularly the removal of apical meristems, compromise flowering and fruiting capacity. Additionally, land-use changes, particularly conversion for agriculture and settlement expansion, fragment habitats and generate edge effects that heighten environmental vulnerability. Charcoal production and uncontrolled fires directly destroy juvenile and mature trees and alter soil properties that are critical for regeneration (Ngulube 1996). Between 2001 and 2023, Malawi lost approximately 250,000 ha of forest, diminishing resources for local communities and contributing to the decline of *Uapaca kirkiana*. This represents one of the highest deforestation rates within the Southern African Development Community (SADC) Region (Workeneh and Kafumbata 2020). This extensive deforestation has fragmented *U. kirkiana* populations, restricted genetic exchange, and reduced population viability. Fragmented populations are consequently more susceptible to demographic stochasticity, inbreeding depression and local extirpation, which may compromise long-term species survival (Workeneh and Kafumbata 2020).

The impacts of climate change further exacerbate these threats. Altered temperature regimes, precipitation patterns, and the frequency of extreme climatic events affect phenology, flowering

synchrony, seed set and seedling establishment. *U. kirkiana*, which exhibits specific ecological preferences, is particularly sensitive to shifts in climatic envelopes. Predictive modeling indicates potential contractions in suitable habitats, especially at lower altitudes and in regions experiencing increasing aridity (Bellard et al. 2014; Thomas 2010; Kokou et al. 2024a). Reduced rainfall and elevated temperatures may impair seed germination and seedling survival, thereby affecting regeneration dynamics and population structure. Furthermore, climate variability may interact synergistically with anthropogenic pressures, amplifying the risk of local extirpation and reducing ecosystem resilience (Frost 1996; Chidumayo & Gumbo 2010; Ryan et al. 2011).

Knowledge gaps regarding the morphological and functional traits of *U. kirkiana* remain significant. Traits such as tree height, crown diameter, leaf area, fruit size and seed characteristics are fundamental indicators of ecological adaptability, resource allocation strategies and reproductive potential. Functional traits including specific leaf area (SLA), leaf nitrogen content, water-use efficiency and photosynthetic rates are crucial for evaluating species responses to environmental gradients, disturbance and climatic stress (Houehanou et al. 2019; Lawin et al. 2021). The limited understanding of these traits constrains predictive assessments of population dynamics, vulnerability and the development of evidence-based conservation strategies.

The regeneration biology of *U. kirkiana* constitutes another critical knowledge gap. Seed dispersal mechanisms, germination rates, seedling establishment and survival under varying disturbance regimes remain poorly documented. Interactions with dispersers such as birds and mammals, seed predation and interspecific competition strongly influence natural recruitment, yet systematic studies addressing these factors are lacking (Campbell 1996; Frost 1996). Furthermore, demographic parameters including age-class distribution, population density and spatial arrangement across ecological gradients are under documented, restricting insight into population viability under combined anthropogenic and climatic pressures (Chidumayo & Gumbo 2010; Shackleton et al. 2007).

Integrating ecological and socio-cultural dimensions is essential for sustainable management. Local communities possess extensive Local ecological knowledge (LEK) regarding phenology, fruit harvesting practices, medicinal uses and sustainable utilisation strategies (Campbell 1996; Chirwa et al. 2008). However, urbanisation, cultural transformation, and generational shifts threaten the transmission of this knowledge, risking the loss of critical management information. The interactions between human activities, market demands and ecological processes are complex, potentially reinforcing or undermining species conservation (Shackleton & Gumbo 2010). Systematic research that combines ecological, demographic and ethnobotanical data is therefore lacking, particularly across Malawi's diverse agro-ecological zones (Kalaba et al. 2013).

Overall, *U. kirkiana* is simultaneously a nutritional, economic and ecological keystone species, yet it faces mounting pressures from unsustainable harvesting, habitat loss, and climate change. Gaps in understanding its morphological and functional traits, regeneration dynamics, population structure and socio-ecological interactions limit effective conservation and sustainable management. Comprehensive scientific research capturing the biological, ecological and socio-economic dimensions of *U. kirkiana* is urgently required to ensure the persistence of its populations and the ecosystem services they provide. Such integrative research will form the empirical foundation for evidence-based conservation, sustainable utilisation and culturally sensitive policy development in Malawi and southern Africa (Campbell et al. 1996; Shackleton & Shackleton 2004; Akinnifesi et al. 2006; Kalaba et al. 2013; Ryan et al. 2016; Chirwa et al. 2019).

1.3. Study Objective

1.3.1. Main objective

The main objective of the study was to investigate the Integrating Local Knowledge, Functional Ecology and Conservation Strategies of Wild Loquat (*Uapaca kirkiana* Müll. Arg.) in Malawi.

1.3.2. Specific Objectives

Specifically, the study intended to achieve the following:

1. To analyse local ecological knowledge, ethnobotanical uses and community-based conservation strategies of *U. kirkiana* in Malawi.
2. To characterise woody species composition and phylogenetic structure along elevation gradients associated with *U. kirkiana*.
3. To quantify intraspecific functional trait variation of *U. kirkiana* across eco-geographical regions and its relationship with environmental gradients.
4. To evaluate population structure, regeneration dynamics, and carbon storage potential of *U. kirkiana* across geographic regions.
5. To model the current and future distribution of *U. kirkiana* across climate change scenarios.

1.3.3. Hypothesis

1. Local ecological knowledge provides ecologically consistent insights into the distribution, use and conservation of *U. kirkiana* complementing scientific approaches.
2. Woody species composition and phylogenetic structure vary significantly with elevation, influencing the ecological associations of *U. kirkiana*.
3. Functional traits of *U. kirkiana* exhibit significant intraspecific variation across regions, primarily driven by climatic and edaphic factors.
4. Population structure, regeneration capacity and carbon storage potential of *U. kirkiana* differ across regions, reflecting both ecological conditions and anthropogenic pressures.
5. Climate change will reduce and shift suitable habitats of *U. kirkiana* towards higher elevations, leading to habitat contraction and potential population isolation.

1.4. Justification of the study

U. kirkiana is an indigenous fruit tree of Miombo woodlands with significant ecological, nutritional, and socio-economic roles in Malawi and across Southern Africa. Local communities heavily rely on its fruits for food supplements and income generation, yet the species faces mounting pressures from deforestation, wildfires, habitat fragmentation and climate change (Ntupanyama et al., 2008). While previous studies have examined distinct aspects of *U. kirkiana*, important knowledge gaps persist, particularly in integrating indigenous knowledge, functional trait variation, population dynamics and climate-driven distribution shifts. A bibliographic review of research on *U. kirkiana* from 1978 to 2023 highlights that most studies focused on biological and pharmacological activities (21%), multiplication and germination (20%), silviculture (18%) and species description (14%), whereas critical topics such as domestication, climate change impacts, socio-economic importance, management and conservation, distribution and population structure remain underexplored (Kokou et al. 2024a). A chi-square test confirmed that research themes are dependent on publication categories ($p = 0.0297$), revealing gaps in knowledge that require attention. Geographically, research has concentrated in Southern Africa, particularly Malawi, Zambia, and South Africa, with sporadic studies in Tanzania, Zimbabwe, and the DRC. Despite increasing interest, publications remain fragmented in coverage and scale, limiting their applicability for integrated conservation planning.

Phenotypic variation in fruit, seed and seedling traits has been documented in Malawi. Significant differences among provenances in fruit weight, seed weight/size, germination rates, and seedling growth traits, which are essential for domestication and selective propagation (Mwase et al. 2010). Genetic diversity studies using AFLP markers indicate that most variation exists within populations, with some regional structure, suggesting potential for trait-based selection in conservation and breeding programs. However, these studies do not fully explore how environmental gradients, such as altitude, soil properties and rainfall, drive functional trait variation and ecological interactions. Population structure and regeneration dynamics are also under-studied.

Ngulube (2000), observed high stem densities and considerable regeneration across 19 sites in Malawi, while noting that dry-season fires adversely affect survival and recruitment. Understanding these ecological dynamics is critical for developing strategies that enhance species resilience and sustainable management under changing disturbance regimes.

Climate niche modeling has provided insights into the potential impacts of climate change on *U. kirkiana*. Jinga et al. (2020) showed that climate change is likely to reduce the natural range of the species across south-central Africa, with contraction and altitudinal shifts in suitable habitats. However, their continental-scale projections did not explicitly consider local ecological interactions, functional traits, or indigenous management practices. In this context, the present study provides a country-specific assessment for Malawi, integrating high-resolution mapping of priority conservation zones, functional trait variation and community-based management knowledge. This approach allows precise identification of areas critical for conservation, sustainable management, and domestication under current and projected climate scenarios.

By combining indigenous knowledge, ecological and functional trait data, population dynamics and climate-driven distribution modeling, this study addresses significant knowledge gaps (Ngulube et al. 2000). It will guide the development of conservation priorities, inform domestication and sustainable management strategies and support policy decisions for the protection and utilization of *U. kirkiana* (Akinifesi et al. 2008). Moreover, the study strengthens scientific understanding of how this keystone species responds to multi-dimensional environmental changes, including anthropogenic pressures and identifies potential refugia for long-term conservation and climate resilience.

1.5. Ethical Considerations

This study adhered to established ethical standards for research involving human participants, ecological surveys, and indigenous knowledge. Ethical clearance was formally obtained from the Mzuzu University Research Ethics Committee (Mzuzu University - MZUNIREC) before the

commencement of fieldwork. In addition, formal permission was secured from relevant government authorities, district forestry offices, and community leaders within the study areas of Malawi. All participants were informed of the study objectives, and voluntary informed consent was obtained prior to interviews and focus-group discussions. Confidentiality, anonymity, and respect for cultural norms were maintained throughout the study. Respondents were informed about the objectives, scope and potential uses of the study and their participation was voluntary. Informed consent obtained verbally or in writing, depending on literacy levels, and participants were assured of confidentiality and anonymity. For the ecological and functional trait assessments, sampling was conducted in a manner that minimised harm to the environment and individual plants. Trees were not excessively disturbed and any collection of leaves, fruits, or seeds followed sustainable harvesting protocols to ensure the continued regeneration and survival of *Uapaca kirkiana*.

The research also respected cultural norms and traditional knowledge systems. Indigenous knowledge shared by local communities was acknowledged appropriately and findings were intended to benefit both scientific understanding and local conservation efforts. The study complied with national regulations on biodiversity research, including Malawi's Environmental Management Act and adhered to internationally recognized ethical guidelines for social-ecological research.

1.6. Structure of the Thesis

This chapter has introduced the research area and outlined the main objectives of the study, focusing on the ecological, socio-economic and conservation significance of *U. kirkiana* in Malawi. It has also highlighted critical knowledge gaps regarding indigenous knowledge, functional trait variation, population dynamics and climate-driven distribution shifts. The chapter argued that while previous research has explored individual aspects of the species, an integrated understanding combining ecological, socio-economic, and climate dimensions is still lacking, which forms the primary rationale for this thesis.

Chapter 2 presents a comprehensive review of the literature relevant to the study objectives. It covers the current state of knowledge on *U. kirkiana*, including biological and pharmacological properties, propagation and germination, silvicultural practices, population structure and socio-economic roles. The chapter further highlights the limited research on climate change impacts, functional trait variation, domestication, management and conservation strategies. By synthesizing previous studies and identifying gaps, the chapter establishes the need for a Malawi-specific approach that integrates ecological, functional and indigenous knowledge dimensions. The literature review also positions the study within the framework of Sustainable Food Systems and Sustainable Livelihood approaches, which provide analytical tools to understand species-environment-society interactions.

Chapter 3 presents the epistemological and methodological foundations of the study. It justifies the choice of a mixed-methods approach combining qualitative ethnobotanical surveys with quantitative ecological and functional trait assessments, population structure analysis and climate niche modelling. This chapter demonstrates that such an approach is appropriate for addressing research questions that require understanding both ecological patterns and community perceptions.

Chapter 4 presents the study results. These include findings on local ecological knowledge, ethnobotanical uses and community-based conservation strategies; woody species composition and phylogenetic structure along elevation gradients; intraspecific functional trait variation across eco-geographical regions; population structure, regeneration dynamics and carbon storage potential; and current and projected distribution under climate change scenarios. The results provide detailed insights into how ecological, socio-economic and climatic factors interact to shape the status and management of *U. kirkiana* in Malawi.

Chapter 5 provides a discussion of the results in the context of existing literature. It compares findings with studies from Southern Africa and beyond, highlighting similarities and differences in functional traits, population dynamics and local management practices. The chapter demonstrates

how this study advances understanding of species conservation by integrating ecological, functional and indigenous knowledge perspectives.

Chapter 6 concludes the thesis by summarising the main findings, emphasizing the contribution of the study to knowledge and policy. It highlights priority areas for conservation, recommends strategies for sustainable management, domestication and underscores the importance of integrating community-based knowledge with scientific approaches for climate-resilient species management. Finally, the chapter situates the study's contribution to scholarship by providing a comprehensive, multi-dimensional perspective on *U. kirkiana* conservation and utilisation in Malawi.

CHAPTER 2: LITERATURE REVIEW

2.0 Introduction

This chapter engages with the wider body of literature related to *U. kirkiana*, its ecological, socio-economic and cultural significance, and how anthropogenic pressures and climate change are shaping its current and future conservation status. The chapter introduces the theoretical approaches of Sustainable Food Systems and Sustainable Livelihoods, justifying their relevance for this research. It further reviews empirical studies on the species' ethnobotanical uses, domestication potential, ecological functions, population dynamics and responses to climate variability in Malawi and other parts of sub-Saharan Africa. Finally, a conceptual framework, informed by both theoretical and empirical literature is presented to guide the study.

2.1. General Research Trends on *U. kirkiana*

Over the past four decades, research on *U. kirkiana* has experienced a gradual but significant evolution, reflecting broader shifts in ethnobotanical and ecological research paradigms in Southern Africa. Initially, studies were largely descriptive, aiming to document traditional knowledge and uses of the species, including its nutritional, medicinal and cultural importance (Ngulube 2000; Saka et al. 2007). These early investigations provided baseline information on fruit consumption patterns, local management practices, and the role of *U. kirkiana* in rural diets, particularly during periods of food scarcity. Such studies were primarily qualitative and ethnographic, often relying on interviews, participatory observations and informal surveys to capture local ecological knowledge (LEK) (Ngulube 2000; Saka et al. 2007).

From the early 2000s, research focus shifted toward applied and experimental studies, driven by the need to promote domestication and sustainable utilization. Investigations increasingly examined germination ecology, clonal propagation, and grafting techniques to improve seedling establishment and fruit yield (Mwase et al. 2010; Akinnifesi et al. 2008). Simultaneously, genetic diversity assessments using morphological and molecular markers highlighted substantial

intraspecific variation, both within and among populations, revealing opportunities for selective breeding and provenance selection. These studies provided critical insights for agroforestry programs and the development of improved germplasm for rural communities, yet most remained limited in geographic scope and sample size, often focusing on Malawi, Zambia and Zimbabwe (Saka et al. 2007).

More recently, the scope of research has expanded to encompass ecological roles and climate-related vulnerabilities. Studies have begun to explore *U. kirkiana*'s contributions to woodland structure, nutrient cycling, and carbon sequestration, as well as its interactions with pollinators and seed dispersers (Shirima et al. 2011; Kokou et al. 2025b). Climate change research has emerged, modeling potential shifts in suitable habitat under different emission scenarios. However, these studies are still relatively few, largely localised and often rely on bioclimatic variables without incorporating functional trait data, population demographics or LEK (Jinga et al. 2020).

Overall, the literature demonstrates a clear utilitarian bias: the socio-economic benefits of *U. kirkiana*, particularly its contribution to household nutrition and income are well documented whereas its ecological resilience, adaptive capacity and long-term population dynamics under environmental stress remain insufficiently understood (Kokou et al. 2024a). This trend underscores the urgent need for interdisciplinary studies that integrate ethnobotany, ecology, functional traits and climate projections to comprehensively assess the species' sustainability and inform conservation, management and domestication strategies in Southern Africa (Yanou et al. 2023).

2.1.1. Geographical and Disciplinary Biases

A critical examination of the literature on *U. kirkiana* reveals pronounced geographical and disciplinary biases. The majority of empirical studies have been conducted in Malawi, Zambia and Zimbabwe, reflecting the high reliance of rural households on the species for both nutrition and income (Moombe et al. 2014; Chawafambira et al. 2020). These regions have therefore received disproportionate research attention, resulting in well-documented ethnobotanical practices,

propagation techniques and domestication efforts. By contrast, populations in Mozambique, Angola, and the Democratic Republic of Congo despite being integral components of the species' natural distribution remain poorly studied. This geographical imbalance constrains our understanding of *U. kirkiana*'s adaptive capacity across diverse ecological and climatic contexts, potentially overlooking local adaptations or unique population dynamics in understudied regions.

At the disciplinary level, a similar asymmetry emerges. Ethnobotanical and domestication-focused research is relatively advanced, providing detailed insights into traditional uses, propagation methods, and genetic variability (Mwase et al. 2010; Akinnifesi et al. 2008). Conversely, ecological, demographic and climate-oriented studies are sparse, often localized and methodologically limited. Long-term population monitoring, regeneration studies, and functional trait assessments across environmental gradients are notably absent. Such imbalances underscore the urgent need for integrative, cross-regional and interdisciplinary research that bridges ethnobotany, ecology, genetics and climate science to achieve a holistic understanding of the species' resilience and sustainability (Biaou et al., 2023).

2.1.2. Ethnobotanical knowledge and Socio-economic contributions

A critical review of existing research on *U. kirkiana* exposes significant geographical and disciplinary biases that continue to limit the advancement of knowledge on the species. Although the literature often portrays *U. kirkiana* as well studied, this perception is largely shaped by the concentration of research in Malawi, Zambia, and Zimbabwe (Moombe et al., 2014; Chawafambira et al., 2020). These countries have become research “hotspots” primarily because of their documented dependence on the species for food and income. However, this overrepresentation raises a fundamental concern: to what extent do findings from these regions accurately represent the species' full ecological and socio-cultural variability? The answer remains unclear.

Populations in Mozambique, Angola, and the Democratic Republic of Congo, although part of the species' natural range, have received little to no empirical attention. This geographical blind spot is not trivial; it restricts our ability to understand how *U. kirkiana* responds to diverse ecological pressures, climatic gradients, and management systems. The absence of data from these regions introduces a systematic bias that may distort conclusions about the species' adaptability, genetic structure, and population dynamics. In other words, current knowledge is regionally skewed and potentially ecologically incomplete.

A parallel imbalance characterizes the disciplinary scope of the literature. Research on the ethnobotany, domestication, and propagation of *U. kirkiana* is relatively mature, driven by the priorities of agroforestry programs and rural livelihood studies (Saka et al. 2007; Moombe et al. 2014). While these insights are valuable, they have inadvertently overshadowed ecological and demographic research. For example, long-term population monitoring, regeneration ecology, and functional trait analyses across environmental gradients are either missing or methodologically superficial (Kokou et al. 2024). The few ecological studies available are typically short-term, localized, and lack comparative or longitudinal depth, making it difficult to generalize findings or infer long-term resilience (Ngulube 2000). This disciplinary skew leads to a deeper conceptual weakness: the current literature tends to treat *U. kirkiana* primarily as a socio-economic resource, rather than as a biological system subject to ecological constraints and climate pressures (Chawafambira et al. 2020). As a result, our understanding of its vulnerability under climate change, population viability, or adaptive differentiation remains fragmented at best. Taken together, these biases point to an urgent need for integrative, cross-regional, and interdisciplinary research that combines ethnobotany, ecology, genetics, and climate science. Without such a shift, the existing body of literature will continue to offer only a partial and potentially misleading picture of the species' resilience, conservation needs, and long-term sustainability.

2.1.3. Domestication, propagation and genetic diversity

Research on the domestication of *U. kirkiana* has consistently highlighted significant intraspecific variation in key agronomic traits, including fruit size, seed weight and germination success across different provenances (Mwase et al. 2010). This phenotypic variability reflects strong local adaptation and constitutes a valuable resource for selective breeding and domestication programs. Genetic studies indicate that the majority of diversity maintained within populations rather than between them, emphasizing the potential of leveraging existing local variability to enhance desired traits (Dai et al. 2024).

Despite this potential, the distribution of improved planting material remains highly restricted, limiting the practical benefits of domestication for smallholder communities. Moreover, the integration of advanced genomic tools and molecular breeding techniques is largely absent, constraining efforts to align propagation strategies with climate adaptation objectives. Addressing this gap by combining ecological, phenotypic and genetic information could improve both productivity and fruit quality, while enhancing resilience to environmental stressors, including drought, temperature fluctuations and pest pressures. Such integrative approaches are recognised as essential for developing sustainable and climate-resilient domestication programs (Akinnifesi et al. 2008; Mwase et al. 2010).

2.1.4. Ecological Roles and Regeneration Dynamics

U. kirkiana functions as a keystone species within Miombo woodland ecosystems. It contributes critically to canopy structure, soil nutrient cycling and carbon sequestration, thereby maintaining ecosystem productivity and resilience (Shirima et al. 2011; Kokou et al. 2023b). Its fruits serve as an important food resource for a wide range of fauna, including birds and mammals, which in turn facilitate pollination and seed dispersal, sustaining biodiversity and woodland regeneration processes.

However, population persistence and regeneration are threatened by anthropogenic pressures, such as land-use conversion for agriculture, overharvesting of fruits and timber and recurrent wildfires. Fire intensity has been shown to strongly influence mortality rates and recruitment success, thereby shaping population structure and long-term regeneration potential (Ngulube 2000). Despite these insights, there remains a critical lack of long-term demographic and population dynamics data and limited understanding of how cumulative disturbances, in combination with climate variability, affects resilience and species persistence. Addressing this knowledge gap is essential for the design of evidence-based conservation strategies, sustainable management interventions, and ecosystem restoration initiatives (Kokou et al. 2023).

2.2. Ethnobotanical knowledge and socio-economic value

U. kirkiana is one of the most ecologically and socio-economically important indigenous fruit trees in the Miombo woodlands of Southern Africa. Its fruits, rich in carbohydrates, vitamins and minerals, provide essential nutrition during the dry season, particularly when staple crops such as maize and cassava are scarce (Saka et al. 2007; Chawafambira et al. 2020). Beyond subsistence consumption, the informal trade of *U. kirkiana* fruits constitutes a critical source of supplementary income for rural households. However, the commercialization of this species is highly fragmented, with limited integration into formal markets and value chains, which constrains its broader economic potential (Moombe et al. 2014).

Local ecological knowledge (LEK) surrounding *U. kirkiana* is extensive, reflecting centuries of interaction between communities and the species. LEK includes practices such as selective pruning, fire regulation, soil conservation and the protection of naturally regenerating individuals (Ngulube 2000). These practices presumed to sustain population viability by reducing direct anthropogenic pressures and maintaining recruitment processes. Nevertheless, few empirical studies have systematically assessed the effectiveness of LEK in maintaining population structure, recruitment, or resilience to environmental change (Biaou et al. 2023; Samarou et al 2023). This gap limits

understanding of how traditional management practices can be integrated with scientific conservation strategies.

Furthermore, despite increasing evidence of anthropogenic pressures including overharvesting of fruits and timber, expansion of agricultural land and climate-related stressors no studies prior to this thesis have quantified the ecological vulnerability of *U. kirkiana* (Nduche et al. 2021). Vulnerability assessments are essential for evaluating the species' sensitivity to these pressures, as well as its capacity to recover from exploitation and adapt to environmental change. By measuring ecological vulnerability, this thesis provides novel insights into the relative risk posed by human use and environmental factors, offering a framework to prioritise conservation interventions. This approach allows the identification of the most at-risk populations, informs sustainable harvesting guidelines, and provides a scientific basis for integrating LEK with adaptive management strategies (Akinnifesi et al. 2008).

In summary, the literature indicates that while *U. kirkiana* is highly valued for its nutritional and economic contributions, there remains a critical lack of data linking traditional knowledge, socio-economic use and ecological resilience. The integration of vulnerability assessment into the study of *U. kirkiana* addresses this knowledge gap, enabling a holistic understanding of the species' sustainability under combined anthropogenic and climatic pressures. This perspective is essential for developing evidence-based, community-oriented conservation strategies that reconcile livelihood needs with ecological sustainability (Ngulube 2000; Saka et al. 2007; Moombe et al. 2014; Kokou et al. 2025a).

2.3. Woody species composition and phylogenetic structure

Miombo woodlands are globally recognized as biodiversity-rich ecosystems, exhibiting high woody species diversity and complex community assembly patterns shaped by multiple environmental gradients, particularly elevation, temperature and soil fertility (Shirima et al. 2011; Chidumayo and Gumbo 2010; Campbell et al. 2007). Elevational gradients act as strong ecological

filters, influencing species richness, functional traits and ecological strategies, as abiotic conditions such as temperature, precipitation and soil texture vary systematically with altitude (Kraft et al. 2015; Swenson 2011). These gradients can result in phylogenetic clustering in more stressful, higher-elevation environments, where closely related species with similar adaptive traits dominate, or phylogenetic overdispersion in more heterogeneous lowland habitats, reflecting competitive interactions among distantly related taxa (Cavender-Bares et al. 2017; Gonzalez et al. 2022).

U. kirkiana, a key indigenous fruit tree of Miombo woodlands, frequently co-occurs with dominant genera such as *Brachystegia*, *Julbernardia* and *Isoberlinia*, forming essential components of canopy structure and contributing to nutrient cycling and fruit provisioning for frugivorous birds and mammals (Shirima et al. 2011). Despite its ecological importance, the species' role in shaping phylogenetic community structure and its position within evolutionary lineages remain poorly understood. Integrating phylogenetic approaches with species composition studies is crucial to identify patterns of environmental filtering, niche differentiation and potential evolutionary constraints that influence *U. kirkiana*'s persistence along elevation gradients (Gonzalez et al. 2022; Cavender-Bares et al. 2017).

Empirical studies explicitly examining the interplay between species composition, phylogenetic structure and elevation in Miombo woodlands are scarce. Most investigations have primarily documented species inventories or assessed traditional ecological knowledge, with limited attention to evolutionary relationships or phylogenetic diversity metrics (Chidumayo and Gumbo 2010). This knowledge gap restricts understanding of how environmental stressors, including climate change, land-use modification and fire regimes, may alter species assemblages and phylogenetic diversity.

Understanding *U. kirkiana*'s phylogenetic context along elevation gradients has practical conservation implications. It can reveal vulnerability or resilience of populations to environmental change, guide selection of conservation priority areas and inform sustainable management

strategies aimed at maintaining ecosystem functions such as carbon sequestration, soil fertility and regeneration potential (Shirima et al. 2011; Gonzalez et al. 2022; Chidumayo and Gumbo 2010). Integrating phylogenetic and functional perspectives with species composition data thus offers a holistic framework to assess ecological interactions and adaptive strategies of *U. kirkiana* in heterogeneous Miombo landscapes.

2.4. Functional trait variation and environmental gradients

Functional traits are widely recognized as fundamental indicators of plant ecological strategies and adaptation to heterogeneous environments, as they mediate growth, survival, reproduction and competitive interactions under variable climatic and edaphic conditions (Violle et al. 2007; Kraft et al. 2015; Díaz et al. 2016). For *U. kirkiana*, provenance trials have demonstrated substantial intraspecific variation in key agronomic traits, including fruit size, seed weight and germination success (Mwase et al. 2010). Such variation not only reflects potential local adaptation but also underpins the species' suitability for selective breeding and domestication programs (Akinnifesi et al. 2008).

Despite these insights, research has predominantly focused on agronomic traits and propagation techniques, with limited attention to ecological functional traits, such as specific leaf area, leaf dry matter content, wood density, hydraulic conductivity, leaf phenology and seedling growth responses (Poorter et al. 2012; Chave et al. 2014; Wright et al. 2004). These traits are critical for understanding how *U. kirkiana* responds to key environmental stressors, including water limitation, nutrient-poor soils, fire regimes and temperature extremes, which vary substantially across the Miombo woodland landscape (Shirima et al. 2011).

Linking functional trait variation to environmental gradients allows the detection of adaptive strategies and potential trade-offs, such as the classic growth stress tolerance continuum, where resource allocation to seed size, root structure, or leaf morphology balances growth and survival under limiting conditions (Westoby 1998; Swenson 2011). Elevation, temperature, rainfall, and

soil fertility act as environmental filters, potentially driving trait convergence in harsh environments or trait divergence under heterogeneous conditions (Kraft et al. 2015; Violle et al. 2007).

Furthermore, functional trait analyses are increasingly important for predicting species responses to climate change. Traits such as wood density and hydraulic properties can indicate drought tolerance, while phenological traits inform reproductive timing under shifting seasonal rainfall patterns (Poorter et al. 2012; Wright et al. 2004). In the context of Miombo woodlands, where *U. kirkiana* coexists with other dominant taxa such as *Brachystegia*, *Julbernardia* and *Isoberlinia*, trait variation also mediates competitive interactions and community assembly processes, influencing species coexistence and ecosystem functioning (Shirima et al. 2011).

Currently, the scarcity of studies linking functional trait variability to climatic and edaphic gradients in *U. kirkiana* limits our understanding of its adaptive capacity and resilience to environmental change. Integrating functional trait data with provenance and environmental information would allow for robust predictions of local adaptation, inform trait-based selection in domestication programs and guide conservation strategies aimed at sustaining population viability under projected climate stress (Díaz et al. 2016; Violle et al. 2007). This approach is crucial for bridging ecological theory with applied conservation and management of *U. kirkiana* in Southern African Miombo ecosystems.

2.5. Population structure and carbon storage

U. kirkiana populations in Miombo woodlands are subjected to multiple anthropogenic pressures, including unsustainable fruit and timber harvesting, charcoal production and conversion of woodland to agricultural land or settlements (Chirwa et al. 2008; Ntupanyama et al. 2008). These activities have profound effects on population structure, often resulting in skewed diameter class distributions dominated by smaller, juvenile individuals and a relative scarcity of large, reproductive trees (Ngulube 2000). Such structural alterations indicate active recruitment in some

sites but also highlight elevated mortality rates among older trees, raising concerns about the long-term demographic stability and persistence of populations under sustained disturbance (Ngulube 2000).

Regeneration dynamics of *U. kirkiana* are influenced by both biotic and abiotic factors. Fire regimes are common in Miombo landscapes and they significantly affect seedling survival, sapling recruitment and overall demographic trajectories (Shirima et al. 2011; Chidumayo and Gumbo 2010). Overharvesting of fruits reduces the availability of viable propagules, limiting natural regeneration and potentially altering age structure and genetic diversity (Ngulube 2000). Soil fertility, moisture availability, and interspecific competition further modulate growth and survival, creating complex spatial heterogeneity in population dynamics (Shirima et al. 2011; Kokou et al. 2023a). Despite the importance of these processes, long-term demographic studies are limited and there is a lack of integrated analyses linking disturbance regimes, population structure and environmental variables across Miombo regions (Shirima et al. 2011).

In addition to its ecological role, *U. kirkiana* significantly contributes to carbon sequestration due to its large biomass and longevity. Trees store carbon in both aboveground (trunks, branches, leaves) and belowground (roots, soil organic matter) pools, influencing the carbon balance of Miombo woodlands (Shirima et al. 2011; Lawley et al. 2013). However, species-specific carbon stock assessments remain scarce, which constrains their inclusion in ecosystem service valuation and climate mitigation strategies. Empirical studies indicate that carbon storage in Miombo species varies substantially with tree size, stand density and site fertility, suggesting that *U. kirkiana*'s contribution could be highly context-dependent (Chidumayo and Gumbo 2010; Shirima et al. 2011).

Recently, approaches integrating economic valuation of carbon stocks have gained prominence in linking biodiversity conservation with livelihood benefits. By converting the carbon stored in *U. kirkiana* biomass into potential financial values via carbon markets or Payment for Ecosystem

Services (PES) schemes, it becomes possible to quantify the economic importance of conservation actions (Chidumayo and Gumbo 2010). Such valuation not only provides incentives for sustainable management but also strengthens the case for incorporating indigenous fruit trees into broader climate mitigation and land-use planning strategies. Despite these advances, significant knowledge gaps persist.

Most research has yet to comprehensively couple population structure, regeneration dynamics, and carbon storage with economic valuation, leaving a fragmented understanding of how anthropogenic and climatic pressures jointly influence both ecological function and socio-economic value (Shirima et al. 2011). Addressing these gaps is critical for developing integrated conservation strategies that maintain population viability, enhance carbon sequestration and provide sustainable livelihood opportunities for communities dependent on Miombo woodland resources. By synthesizing demographic, ecological, and economic perspectives, future research can establish a robust framework for linking species-level population dynamics of *U. kirkiana* with ecosystem service provision and climate adaptation, thereby informing both policy and community-based management interventions (Lawley et al. 2013).

2.6. Climate change and future distribution

Indigenous fruit trees in southern Africa, including *U. kirkiana*, are recognized for their ecological, nutritional, and socio-economic importance, providing essential resources for both wildlife and rural livelihoods (Saka et al. 2007; Chawafambira et al. 2020). Climate change, manifested through shifts in temperature, precipitation regimes and disturbance frequencies, represents a significant threat to the persistence of these species by potentially altering their distributions, regeneration patterns and associated ecosystem services (Fred et al. 2023; Kokou et al. 2025b). Understanding the response of *U. kirkiana* to such environmental changes is therefore essential for informed conservation planning, sustainable management and the design of adaptive restoration interventions across Miombo landscapes.

Previous studies modelling the potential distribution of *U. kirkiana* have predominantly relied on correlative species distribution models (SDMs) using bioclimatic variables such as mean annual temperature and precipitation to predict habitat suitability under future climate scenarios (Jinga et al. 2020). While these models provide valuable insights into broad-scale trends and potential altitudinal shifts, they often neglect critical fine-scale environmental drivers, including soil texture, fertility, moisture availability and elevation gradients, as well as anthropogenic factors such as land-use change, fruit harvesting, and fire regimes, all of which strongly influence establishment, growth, and persistence (Shirima et al. 2011; Chidumayo and Gumbo 2010). The omission of these variables can result in overestimation or underestimation of suitable habitats, and limit the ecological relevance and applicability of SDM outputs for local management.

Soil properties and topography play a central role in shaping the ecological niche of *U. kirkiana*. Soil texture, nutrient content, and water-holding capacity directly influence germination, seedling survival, and adult tree productivity (Kraft et al. 2015; Shirima et al. 2011). Similarly, elevation serves as a composite environmental gradient that modifies local temperature, moisture and microclimatic conditions, which in turn regulate species richness, functional trait expression and community assembly patterns (Swenson 2011; González-Caro et al. 2014). These edaphic and topographic factors interact with climate to determine species-specific tolerances and adaptive responses, highlighting the necessity of including them in predictive distribution modelling to enhance ecological realism and conservation relevance (Swenson 2011; González-Caro et al. 2014).

A major limitation of current distribution studies for *U. kirkiana* and related Miombo species is their exclusive reliance on climatic variables, without incorporating demographic and ecological dynamics such as regeneration rates, recruitment bottlenecks, or interspecific interactions (Jinga et al. 2020; Fred et al. 2023). Anthropogenic pressures, including unsustainable fruit harvesting, fire management practices and conversion of woodlands to agriculture, are rarely integrated into models, despite evidence that these factors significantly influence population structure, survival

and regeneration potential (Ngulube 2000; Ntupanyama et al. 2008). This represents a critical gap, as species vulnerability cannot accurately assessed without considering the combined effects of environmental stressors and human activities.

Environmental filtering along elevational gradients has been shown to drive non-random phylogenetic and functional assemblages, with closely related species often clustering under stressful conditions and more diverse lineages co-occurring in heterogeneous habitats (Cavender-Bares et al. 2017; González-Caro et al. 2014). For *U. kirkiana*, these processes may interact with specific functional traits such as drought tolerance, seed dispersal mechanisms and growth rates to influence adaptive capacity and resilience under climate change. Incorporating these ecological and evolutionary insights into distribution models can improve predictions of species persistence and inform strategies for maintaining ecological functionality across gradients (González-Caro et al. 2014)

Spatial prioritization frameworks, including Zonation, have proven effective for identifying areas of high conservation value and restoration potential in diverse ecosystems (Kujala et al. 2013). For *U. kirkiana*, such approaches can be combined with habitat suitability modelling and ecological vulnerability assessments to target priority landscapes where conservation and restoration interventions would maximize both ecological and socio-economic benefits (Biaou et al. 2023). Integrating multiple layers of information climatic, edaphic, topographic, demographic and human impact provides a holistic tool for decision-makers, guiding the allocation of resources toward areas that sustain species populations, ecosystem services and carbon storage potential (Samarou et al. 2023).

Socio-ecological factors critically modulate species vulnerability and restoration outcomes. Local ecological knowledge (LEK) indicates that harvesting intensity, selective pruning and fire management practices can either enhance or constrain regeneration, depending on their application (Ngulube 2000). Consequently, predictive models that incorporate both environmental and socio-

economic dimensions yield more realistic assessments of habitat suitability, population resilience and the feasibility of conservation interventions. Understanding the interplay between climate stressors and human management is particularly important for indigenous fruit trees like *U. kirkiana*, whose persistence is closely linked to local livelihoods and cultural practices.

Despite progress in modelling climate-driven habitat changes, there remains a notable gap in integrating fine-scale environmental variables, ecological vulnerability and socio-economic considerations for *U. kirkiana*. Existing studies have rarely combined climate projections with soil, elevation, regeneration dynamics, functional traits and human use patterns, resulting in limited capacity to predict species responses under multifaceted stress scenarios (Shirima et al. 2011; González-Caro et al. 2014). Future research should employ integrative frameworks that link species distribution models with spatial prioritisation tools and vulnerability assessments, enabling comprehensive evaluation of resilience, adaptive capacity and conservation priorities. Such an approach is crucial for guiding targeted restoration, evidence-based management and climate-adaptive conservation strategies, ensuring the long-term sustainability of *U. kirkiana* populations in the Miombo woodlands and the maintenance of associated ecosystem services.

2.7. Conceptual framework

Drawing on theoretical and empirical literature, a conceptual framework was developed to illustrate how ecological, climatic and socio-cultural factors interact to shape the functional traits, spatial distribution and conservation outcomes of *U. kirkiana* in Malawi (Figure 1). The framework integrates two complementary theoretical approaches Sustainable Food Systems and Sustainable Livelihoods adapted to the management of indigenous tree species.

First, it highlights the mediating role of local ecological knowledge, including ethnobotanical uses, cultural practices and community-based management (Biaou et al. 2023). These knowledge systems influence how the species respond to environmental gradients and can either exacerbate or reduce pressures from harvesting, fire and climate variability, thereby affecting regeneration and

population resilience. Second, the framework links environmental drivers (altitude, soil, rainfall, temperature) with functional traits of *U. kirkiana* (examples, leaf, fruit, and seed traits) and interactions within plant communities. This ecological interplay is further shaped by human-mediated factors such as land-use practices, harvesting intensity and socio-economic dependence, which collectively determine both ecological performance and livelihood contributions (Shirima et al. 2011; González-Caro et al. 2014).

Finally, the framework incorporates exogenous pressures, including climate change scenarios and market dynamics, which may shift species distributions, reduce habitat suitability and redefine conservation priorities. By integrating local knowledge, trait variation, demographic processes and climate projections, the framework provides a comprehensive lens for understanding the multi-dimensional drivers of species persistence and sustainable use. The literature highlights *U. kirkiana* as both an ecological keystone and a socio-economic resource, yet increasingly threatened by anthropogenic pressures and climate change. While studies have explored its ethnobotanical uses, domestication potential, and population dynamics, they remain fragmented, geographically limited and rarely integrate functional traits, ecological resilience, or socio-ecological dimensions. Climate-driven distribution models further indicate habitat contraction and altitudinal shifts, but often neglect fine-scale drivers and local knowledge. This thesis addresses these gaps by combining ecological vulnerability assessment, functional trait analysis, population structure evaluation and predictive modelling within a holistic framework. The approach advances ecological theory and provides practical strategies for conservation, restoration and sustainable livelihoods.

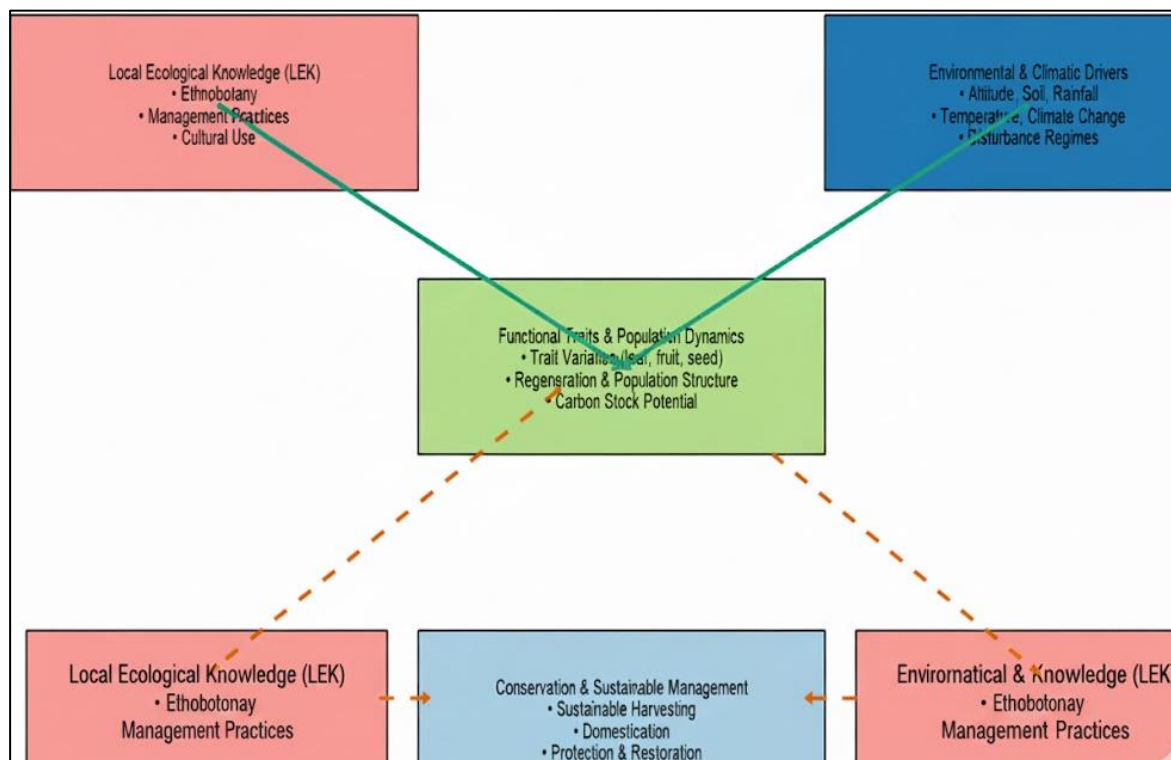


Figure 1: Conceptual Framework

2.8. Chapter Summary

The literature highlights *Uapaca kirkiana* as both an ecological keystone and a socio-economic resource increasingly threatened by anthropogenic pressure and climate change. While previous studies have explored its ethnobotanical uses, domestication potential, and population dynamics, these efforts remain fragmented and geographically restricted, often treating ecological, functional, and socio-cultural dimensions separately. Functional trait ecology provides insights into the mechanisms underlying the species' resilience and adaptation, yet it overlooks the human-driven factors that influence regeneration, harvesting, and land-use change. Conversely, studies based solely on local ecological knowledge (LEK) capture valuable insights on management practices and utilization but lack the ecological and quantitative depth needed to explain adaptive variation. Similarly, species distribution models (SDMs) reveal large-scale habitat contraction and altitudinal shifts under climate change but often neglect fine-scale environmental heterogeneity and local adaptive strategies.

To address these limitations, this thesis develops an integrative framework that combines LEK, functional trait analysis, population structure assessment, and predictive modelling. This approach allows for a multidimensional understanding of *U. kirkiana*'s vulnerability and adaptive potential by linking community-based perceptions with measurable ecological traits and spatial modelling outputs. In doing so, the study bridges social and ecological knowledge systems, advancing theoretical understanding of species resilience while generating practical guidance for conservation, restoration, and the development of sustainable livelihood strategies in Malawi's changing environments.

CHAPTER 3: MATERIALS AND METHODS

3.0. Introduction

This chapter presents the methodology adopted for this study. The research design was structured following the principles of Saunders et al.'s (2019) Research Onion, which provides a logical framework for organizing key methodological elements, including research philosophy, approach to theory development, research design, research strategy, time horizon and data analysis. The philosophical stance underpinning this study is grounded in pragmatism, recognizing the value of both scientific measurements and local ecological knowledge in understanding the ecology and conservation of *U. kirkiana*. Accordingly, the study employed a mixed-methods approach, combining quantitative ecological and functional trait assessments with qualitative ethnobotanical and socio-cultural inquiries. The approach to theory development was largely inductive, building insights from field-based data across ecological gradients and community contexts to inform species-specific conservation strategies. The subsequent sections provide detailed descriptions of the methodological choices, data collection procedures and analytical techniques used to address the research objectives.

3.1. Study Area

The study was conducted in Malawi, located in southern Africa (9°-17°S; 32°-36°E) in three administrative Regions (North, Central and South). Ten districts from three ecologically and climatically representative regions of the country were selected, with six villages sampled per district, totaling 60 villages. The selection was based on species availability, local wild fruit markets, ethnic group distribution and previous studies (Kokou et al. 2024a; Kokou et al. 2025b) (Figure 2a). In parallel, forest inventories were conducted in six representative forest reserves distributed across the three administrative regions of Malawi. Two forests were selected in the Northern Region (Kaning'ina Forest, 11.43840°S, 34.10732°E and Perekezi Forest, 12.04126°S, 33.61079°E), two in the Central Region (Dzalanyama Forest, 13.78330°S, 33.53420°E and Chongoni Forest, 14.28880°S, 34.22060°E) and two in the Southern Region (Zomba Mountain

Forest, 15.38590°S, 35.31820°E and Mangochi Forest, 14.47870°S, 35.25890°E) (Figure 2b). The selection of forests followed ecological representativeness along the altitudinal gradient, species occurrence and reference to earlier studies (Kokou et al. 2024a).

Overall, the country covers about 118,000 km². Malawi has a subtropical climate, which means that variations in the climate are mainly determined by altitude rather than latitude (Kaonga et al. 2015). The weather in the Lower Shire Valley of Malawi is semi-arid, but changes from semi-arid to sub-humid on the plateaus. In the highlands, the weather becomes sub-humid. The Inter-Tropical Convergence Zone (ITCZ) influences Malawi's rainy and dry seasons. The rainy season (November to April) is marked by hot and humid weather, with average temperatures between 30 and 35 °C. The dry season (May to October) is characterized by cooler temperatures, with an average of around 13 °C (Demissie and Gebrechorkos 2024). Moreover, the potential evapotranspiration (PET) is affected by temperature variations and can reach 600 mm and 1400 mm in the low and highlands (For example, Lake Malawi) of the country, respectively (Demissie and Gebrechorkos 2024). Ecologically, the country is subdivided into four agroecological zones based on relief, climate and floristic composition. The dry lowlands of the country are dominated by savannahs. Miombo forests cover the arid plateaus and grasslands and forests mainly cover the highlands. With one of the densest populations in southern Africa, the majority of Malawians depend on agriculture; many are subsistence farmers, earning an average of less than USD 1 per day (Devereux, 2009).

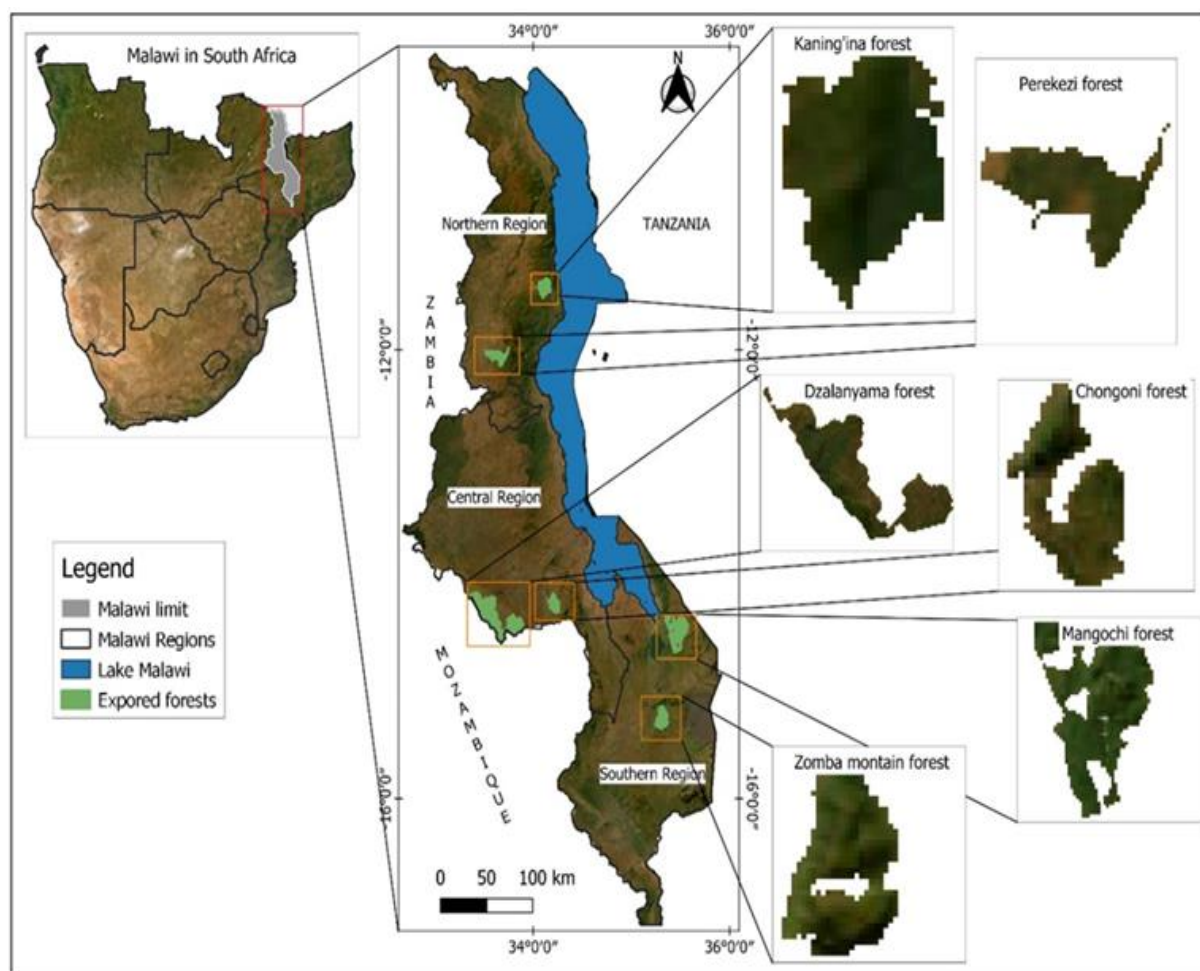


Figure 2a: Location map of the geographical region of Malawi, showing the studied forests

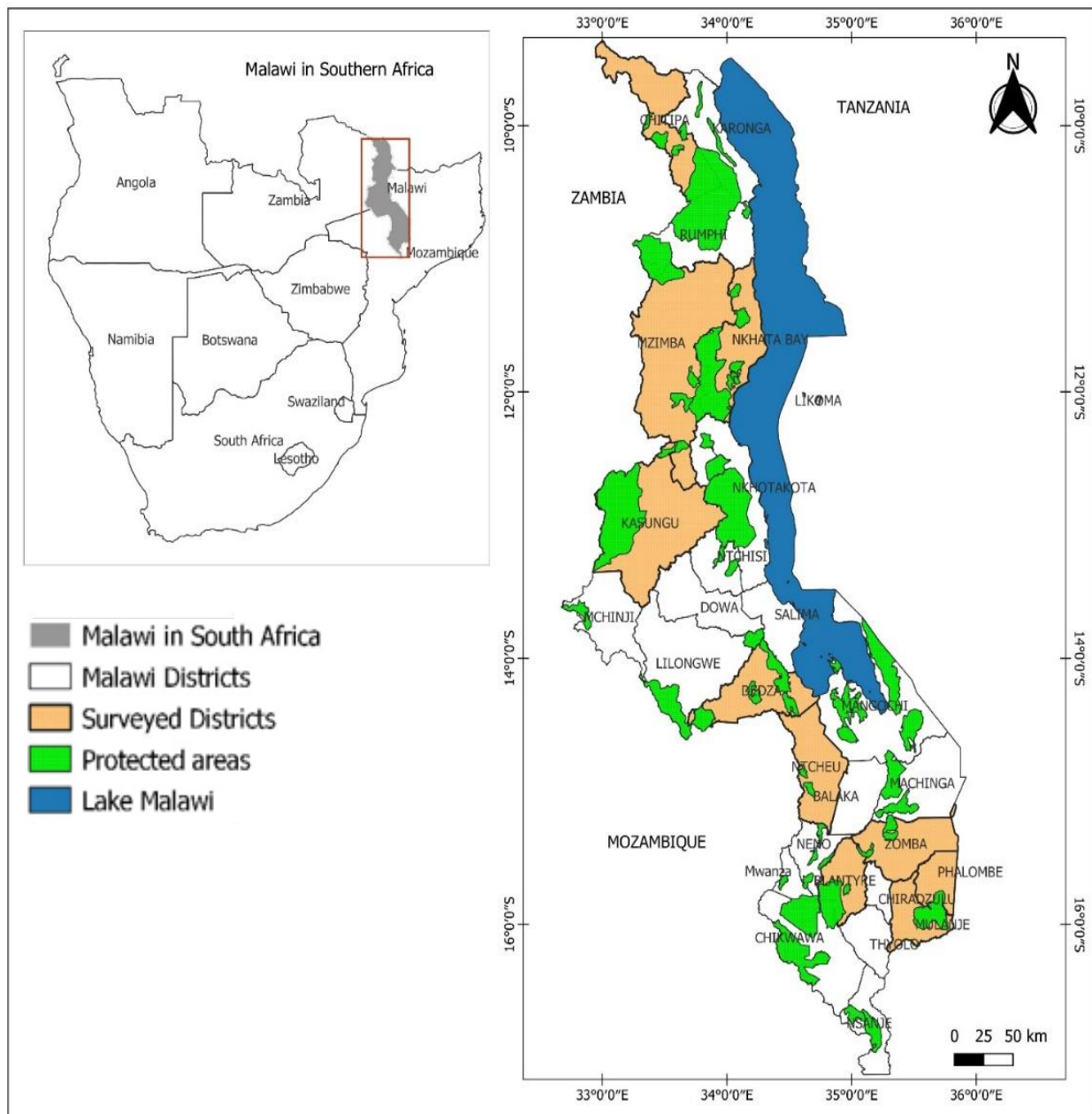


Figure 2b: Map showing Malawi in Africa and the 10 surveyed Districts across regions in Malawi

3.2. Research design

This study employed a mixed-methods research design, combining both qualitative and quantitative approaches to provide a comprehensive understanding of the ecology, ethnobotany, and conservation of *U. kirkiana* in Malawi. The design was structured to integrate community-level ethnobotanical surveys, forest inventories, functional trait assessments, and species distribution modelling.

The qualitative component focused on documenting local ecological knowledge, ethnobotanical uses, and community-based conservation practices through household surveys, key informant interviews and focus group discussions. This approach allowed for capturing perceptions, traditional knowledge and socio-cultural dimensions associated with the species. The quantitative component involved systematic forest inventories in six representative forest reserves, assessment of functional traits across ecological gradients, analysis of species composition and phylogenetic structure and modelling of the current and future distribution of *U. kirkiana* under climate change scenarios. These methods generated empirical data for testing ecological hypotheses and assessing species vulnerability. The integration of qualitative and quantitative approaches within a mixed-methods framework ensured triangulation, allowing for cross-validation of results and a holistic appreciation of the interplay between ecological, climatic and socio-cultural drivers shaping the dynamics of *U. kirkiana* in Malawi.

3.3. Sampling framework and methods

The sampling framework was designed to capture both the ecological and socio-cultural dimensions of *U. kirkiana* across Malawi. It integrated three complementary levels: community-level surveys, forest inventories and functional trait sampling.

3.3.1. Community-level surveys

A multi-stage sampling procedure was employed to ensure representative socio-cultural data. First, ten districts were purposively selected from the three administrative regions (North, Central, and South), reflecting ecological and climatic variability. Within each district, six villages were sampled, totalling 60 villages. Village selection was guided by species occurrence, presence of wild fruit markets, ethnic group distribution and reference to earlier studies (Kokou et al. 2025). Within each village, households were randomly selected proportionally to village size, ensuring representation of male and female-headed households as well as different age groups. This framework allowed capturing local ecological knowledge, ethnobotanical uses and community-based conservation strategies.

3.3.2. Forest inventories

For the ecological component, six representative forest reserves were purposively selected across the three regions. Two forests were chosen in the Northern Region (Kaning'ina Forest and Perekezi Forest), two in the Central Region (Dzalanyama Forest and Chongoni Forest) and two in the Southern Region (Malosa Forest and Mangochi Forest). Selection criteria included ecological representativeness along altitudinal gradients, species occurrence and previous research. Within each forest, systematic sampling was conducted by establishing plots along transects to record tree density, regeneration status and species composition. This combination of purposive and systematic sampling ensured robust ecological data for population structure and regeneration assessments.

3.3.3. Functional trait sampling

Data collection for functional traits was carried out from November 2024 to January 2025, accounting for the asynchronous fruiting of *U. kirkiana* across regions. In each region, two forests at least 15km apart were randomly selected following a reconnaissance survey (Hounkpèvi et al. 2020). Twelve reproductive trees ($DBH \geq 10cm$) per forest were sampled, with a minimum distance of 100m between trees to reduce the likelihood of sampling closely related individuals. From these trees, fruits, seeds, and leaves were collected to quantify intraspecific morphological variation. In total, 72 individuals were sampled across the six forests. GPS coordinates were recorded using a Garmin 62 device.

3.3.4. Species distribution modelling

Occurrence records from both community surveys and forest inventories were compiled for spatial modelling. Environmental predictors included climatic variables, altitude and soil type. Data were cleaned to remove duplicates and georeferencing errors. Future distributions were projected using climate scenarios based on Shared Socioeconomic Pathways (SSPs). This integrated approach ensured that the model incorporated both ecological and socio-economic dimensions influencing the species' distribution.

The SSP3-7.0 and SSP5-8.5 scenarios were selected to represent high and very high greenhouse gas emission pathways, which are particularly relevant for assessing worst-case climate change impacts on species distribution in Sub-Saharan Africa. SSP3-7.0 (“Regional Rivalry - Fragmented World”) assumes limited international cooperation, high population growth, and low investment in environmental sustainability. This scenario is suitable for exploring the effects of regional environmental degradation and weak adaptation capacity conditions that closely resemble current socio-economic and environmental trends in parts of Malawi and the broader southern African region. SSP5-8.5 (“Fossil-fuel Development High Emissions”) depicts a world with rapid economic growth driven by intensive fossil fuel use and high-energy demand. It represents an upper-bound emission scenario that helps assess the potential range contraction or altitudinal shift of species like *Uapaca kirkiana* under extreme warming conditions. Together, these two scenarios provide a robust contrast for evaluating how varying socio-economic pathways and associated climate forcing could alter the potential habitat suitability and distribution of *Uapaca kirkiana* across Malawi.

This multi-level sampling framework, combining community surveys, forest inventories, and functional trait sampling, provides a comprehensive dataset linking ecological, climatic and socio-cultural drivers of *U. kirkiana*. It allows robust analyses of population structure, regeneration, functional trait variation and species distribution under current and future climate scenarios.

3.4. Data Collection

Data collection was carried out using a mixed-methods approach that combined both ecological field surveys and socio-economic household surveys. This design allowed for the integration of quantitative ecological measurements with qualitative and quantitative socio-cultural information. Different tools and protocols were applied according to the specific objectives of the study, ranging from household questionnaires interviews to vegetation inventories, functional trait measurements, and climatic data extraction. The following subsections present the data collection procedures used for each objective in detail.

3.4.1. Research objective one

Fieldwork was carried out from October to December 2024, coinciding with the fruiting period of *U. kirkiana* and peak availability in local markets. Following approval from the Mzuzu University Ethics Committee (Appendix 8), socio-economic data were gathered through semi-structured household surveys in 60 villages across ten districts surrounding the forest reserves where the species had been previously documented (Kokou et al. 2024a; Kokou et al. 2025b). This method was selected for its ability to combine structure with flexibility, allowing both the collection of standardized, comparable data across sites and the opportunity for respondents to elaborate on their personal knowledge, practices, and perceptions regarding the species. This approach also aligns with prior ethnobotanical and socio-economic research (Biaou et al. 2021; Samarou et al. 2021; Thattantavide and Kumar 2024; Anju and Kumar 2024), where individual knowledge plays a central role in understanding the use and management of species. The sample size was estimated using the formula proposed by Dagnelie (1998) (Eq. 1). This formula has been widely used (Biaou et al. 2021; Samarou et al. 2021; Thattantavide and Kumar 2024; Anju and Kumar 2024) to avoid arbitrarily defining the sample size, which may affect the representativeness of the population studied. This approach reduces errors by fixing the required accuracy (Biaou et al. 2021).

The sample size determination for the *Uapaca kirkiana* study was conducted in two main steps. First, an exploratory survey was carried out in three geographical regions of Malawi: North, Central, and South. In this preliminary survey, 30 households per region were randomly selected to gather initial information. Based on these results, the minimum statistical sample size was calculated using the formula: $N = \frac{U^2(1-\alpha/2) \times p(1-p)}{d^2}$ (Eq. 1), where $Z = 1.96$ corresponds to a 95% confidence level, $p = 0.97$ is the proportion of respondents aware of *U. kirkiana*, and $d = 0.08$ represents the acceptable margin of error. Substituting the values, the calculation $0.97 \times (1-0.97) = 0.0291$ was performed, leading to a minimum sample size of 18 households per village. For consistency, the total sample size was rounded to the nearest whole number to 1,222 households distributed across the country (10 to 35 households per village) (Table 1).

The regional breakdown was as follows: North region, 448 households; Central region, 494 households; and South region, 280 households. This sampling approach ensured a statistically robust representation of households for assessing the ecological and socio-economic aspects of *Uapaca kirkiana* in Malawi. N is the sample size to be determined (number of households). “ p ” is the proportion of household participants with knowledge about *U. kirkiana*. $U^2_{1-\alpha/2} = 1.96$, is the value of the normal distribution at the probability value $1-\alpha/2$ with $\alpha= 5\%$ (Atindehou et al., 2022). Respondents in the three regions belonged to 10 ethnic groups irrespective of their gender and age: Lomwe (347 respondents, 28.40%), Chewa (240 respondents, 19.64%), Tumbuka (192 respondents, 16.04%), Ngoni (181 respondents, 14.81%) and Tonga (119 respondents, 9.74%). The remaining ethnic groups ranged from 1 to 2.29%. Age categories were distributed as follows: young (19-29 years, 272 respondents, 22.26%), adults (30-59 years, 776 respondents, 63.5%) and elders (≥ 60 years, 172 respondents, 14.24%) (Table 2). The majority of participants were farmers (69.23%), and 19.56% of the participants had no formal education.

The data collected included socio-demographic (age, gender, marital status, professions, and education level) and cultural information (e.g., sociolinguistic group) of the head of the household or a representative in their absence, local perceptions of the dynamics of *U. kirkiana*, and reasons underlying trends in the species population dynamics. Data was also collected on the local conservation practices for *U. kirkiana*, its plant parts use (fruit, root, branches, stem bark, leaves), management and harvesting methods as well as its ecosystem services. The concept of ecosystem service was explained to each participant before the survey (Gouwakinnou et al. 2019). The four categories of ecosystem services (MEA 2005) were considered during the survey. These are provisioning ecosystem services (timber and fuel, edible plants, honey, edible fruits, edible insects, medicinal plants, and fungi), regulating ecosystem services (benefits from natural and ecological processes; e.g., pest control, pollination), supporting ecosystem services (healthy soil), and cultural ecosystem services (tourism and recreation). After collecting the participants’ demographic and socioeconomic data, each participant was allowed to rate the ecosystem services provided by *U.*

kirkiana in terms of their importance, from “not important” to “extremely important” (Mensah et al. 2017). The interview guide is presented in Appendix 1.

Table 1: Distribution of Households (Number of Households, N) in surveyed villages across the Geographical Regions of Malawi

Regions	Villages	Number of households (N)	Total
Central	Chakudza	22	280
	Chamwabvi	10	
	Chilowamatambe	10	
	Chimbiya	17	
	Chimphepo	12	
	Chiole	11	
	Chongoni	10	
	Dombole	10	
	Kankhuni	18	
	Lithipe 3	15	
	Makanda	13	
	Mbuzi	16	
	Mpalale	35	
	Mphepozinai	13	
	Mthiko	11	
	Ntholomisi	22	
	Pinji	25	
	Tongole	10	
North	Chankamatete	26	448
	Chitheka	21	
	Dimakuli	21	
	Ibanda	38	
	Kamwamphimbi	25	
	Kaning'ina Ward	26	
	Korongo	34	
	Luwinga	41	
	Mchengautuwa Ward	17	
	Mlanda Ng'ombe	18	
	Mwenewanda	20	448
	Mzikubola	16	

	Reuben Ngambi	20	
	SC Kapingo Sibande	22	
	Tembwe	18	
	Thundezi	27	
	Wazengauli	20	
	Zolozolo	38	
South	Bwana	20	
	Chanasa	21	
	Chigumulu	22	
	Chilasanje	13	
	Chilemba	17	
	Chilombo	20	
	Chisitu	27	
	Kambenje	24	
	Khombwe	12	
	Kisagala	15	
	Likabula	10	
	Liphala	26	
	Makanjira	16	
	Makungwa	16	494
	Malabvi	14	
	Malonga	12	
	Mphika	10	
	Muhowa	36	
	Mzedi ward	15	
	Namiwawa	12	
	Ndirande South Ward	30	
	Nkhulambe	29	
	Phalombe	21	
	Samson	13	
	Sekeni	28	
	Zakazaka	15	
Total			1222

Table 2: Illustrating the socioeconomic factors influencing the collection of use of knowledge on *U. kirkiana* across Malawi Regions

Variables	Levels of variables	Percent (%)
Socio-cultural groups	Chewa	19.64
	Lomwe	28.4
	Mang'anja	1.47
	Ngoni	14.81
	Nyakyusa	2.29
	Nyanja	1.31
	Sena	1.31
	Tonga	9.74
	Tumbuka	15.96
Profession	Yao	5.07
	Hunter	0.9
	Traditional practitioner	1.96
	Civil servant	4.58
	Others	8.59
	Seller	14.73
Gender	Farmer	69.23
	female	48.85
	male	51.15
Religion	Animist	3.19
	Others	6.22
	Muslim	8.59
	Christian	82
Education level	Secondary	1.88
	University	3.52
	None	19.56
	High school	26.35
	Primary	48.69
Marital status	Widow	10.72
	Single	20.38
	Married	68.9
Age categories	19-29	22.26
	30-59	63.5
	≥60	14.24

3.4.2. Research objective two

To achieve the second research objective, focused on woody species composition and phylogenetic structure, field surveys were conducted in six representative forest reserves across Malawi's three regions (Figure 2). Site selection was informed by elevation, species presence, and proximity to local fruit markets (Kokou et al. 2024a). Fieldwork took place between November 2024 and January 2025. Vegetation was sampled along 100 m × 3 km strip transects set in both north-south and east-west directions from random starting points. Within each transect, 20 × 20 m plots were established every 100-150 m, yielding 149 plots in total (24-25 plots per forest). All trees with DBH ≥ 5 cm were measured at 1.3 m above ground. Species were identified in the field using botanical keys and confirmed through reference collections at the Mzuzu University Herbarium, the National Herbarium, and the Botanic Gardens of Malawi.

The GPS coordinates of each sampled plot were employed to retrieve relevant bioclimatic variables from the WorldClim platform (www.worldclim.org, version 2.1). Soil characteristics, including soil depth, nitrogen content, phosphorus, and potassium, as well as topographic variables such as slope, were obtained from the FAO global database (www.web.archive.iiasa.ac.at/). The aridity index for each tree location was derived from the SPEI database (<https://digital.csic.es/handle/10261/332007>). All environmental layers were clipped to the extent of the study area and resampled to a resolution of 30 arc-seconds (~1 km), following common practices for bioclimatic data processing (Platts et al., 2011). Among the full set of environmental variables, the ten least correlated ones were selected for analysis (see Supplementary Material, Table S8). Using the GPS coordinates of each tree, values for these ten variables were extracted with the “Raster” package in R.

To ensure dataset consistency, species names were harmonised using the plantlist package (Zhang et al., 2021). The phylogenetic framework was constructed with the V.PhyloMaker package, which integrates information from 48 fern families, 12 gymnosperm families, and 418 angiosperm families, following the classification of the Angiosperm Phylogeny Group IV (APG) (Meng et al.

2025; Qin et al. 2020). Unlike conventional diversity indices that rely solely on species richness and composition while disregarding evolutionary histories, this study employed phylogenetic diversity as a measure of plant diversity. The PD index, defined as the sum of branch lengths linking all species within a community, provides insights into the evolutionary relationships among taxa and offers a more integrative perspective on community structure (Qin et al. 2020; Faith 1992).

3.4.3. Research objective three

For research objective three, data collection focused on quantifying the intraspecific functional trait variation of *U. kirkiana* across different ecological and geographical regions, aiming to understand how environmental gradients influence phenotypic diversity and potential local adaptation. Morphological data were collected at four hierarchical levels: tree size, fruit, seed, and leaf. For each sampled tree, the following size-related traits were measured: diameter at breast height (DBH) at 1.3m above ground using a diameter tape; total height, bole height (BH) and canopy height using a Vertex; bole height (BH) measured as the distance from the ground to the base of the canopy; mean diameter of canopy (MDC) calculated as the average of two perpendicular canopy diameters following the formula:

$$MDC = \frac{D1+D2}{2}$$
 (Eq 1), where D1 and D2 are longitudinal and transverse canopy diameters); canopy shape (CS) calculated as the ratio of canopy height to MDC following the formula:

$$CS = \frac{\text{Canopy Height}}{MDC}$$
 (Eq 2), reflecting canopy form and the number of primary branches (NB) counted manually. Ten ripe fruits were randomly collected from each tree using Dreamtop 4M Fruit Harvester. Trees were included in the study if they were correctly identified as *Uapaca kirkiana*, were accessible for measurement, and were healthy (not severely damaged by disease, pests, or human activity). To ensure consistency and comparability of fruit-related data, only trees with at least ten ripe fruits at the time of sampling were considered. Trees were excluded if they had fewer than ten ripe fruits, were dead or heavily damaged, were inaccessible due to terrain or

property restrictions, or could not be confidently identified as *Uapaca kirkiana* (Dai et al. 2024). These criteria ensured that all measured trees provided reliable and representative data for analyses of fruit traits and reproductive parameters. Each fruit was labeled, and traits such as total fruit length (FL), fruit width (FWi) and fruit shape (FS), were measured using a digital caliper (Mitutoyo, Model 500-196-30, 0-150 mm, accuracy ± 0.01 mm). Fruit weight was determined using a digital balance (Ohaus Scout Pro, Model SPX123, capacity 0-200 g, accuracy ± 0.01 g). The number of seeds (NS) and weight of seed from each fruit (SW) was also recorded. Furthermore, five leaves were harvested from the branch closest to the terminal bud (the 1st, 3rd, 5th, 7th, and 9th positions) from each selected tree (Dai et al. 2024). In total, 60 leaves were collected from each forest to determine the variation in leaf morphological traits (Dai et al. 2024). Leaf length (LL), leaf width (LW), leaf shape (LS), and fresh leaf weight (FLW) were taken after labeling. To determine the dry weight of the leaf (DLW), mass loss by desiccation (MLD), and leaf water content (LWC). Each leaf sample was oven-dried at 70°C for 72 hours in a laboratory oven (Memmert, Model UN55, 50-250 °C, ± 1 °C accuracy) at Mzuzu University Laboratory. After drying, samples were weighed using an electronic balance (Ohaus Scout Pro, Model SPX123, 0-200 g, ± 0.01 g accuracy) to determine dry mass.

The GPS coordinates of each tree were used to extract data on the bioclimatic variables from the WorldClim database, version 2.1 (www.worldclim.org). Soil property data, including depth, nitrogen, phosphorus and potassium content, along with topographic data such as slope, were obtained from the FAO global soil database (Dai et al. 2024). These data were provided for standardised soil depth intervals, which typically include layers at 0-5 cm, 5-15 cm, 15-30 cm, 30-60 cm, 60-100 cm and 100-200 cm. For this study, we focused on the topsoil and subsurface layers (0-30 cm), as these represent the primary rooting zone of *U. kirkiana* and are critical for nutrient availability affecting tree growth and morphology (www.web.archive.iiasa.ac.at/). We extracted aridity index values for each tree from the Standardized Precipitation Evapotranspiration Index (SPEI) site (<https://digital.csic.es/handle/10261/332007>). The raster files of each of these variables

were clipped down to the study area and resampled to 30 arc secs (~1 km) (Quantum GIS Development Team 2016; Platts et al. 2015). The ten least correlated environmental variables were used in the study (Table 3). All selected variables had a spatial resolution of 30 arc seconds (approximately 1 km).

Table 3: Environmental variables used

Codes	Variables	Units
bio 01	Annual Mean Temperature	°C
bio 03	Isothermality (BIO2/BIO7) (*100)	%
bio 04	Temperature seasonality (standard deviation * 100)	°C
bio 05	Max Temperature of Warmest Month	°C
bio 10	Mean Temperature of the Driest Quarter	°C
bio 11	Mean Temperature of the Coldest Quarter	°C
bio 12	Annual Precipitation	mm
bio 16	Precipitation of Wettest Quarter	mm
bio 18	Precipitation of the Warmest Quarter	mm
bio 19	Precipitation of the Coldest Quarter	mm

3.4.4. Research objective four

From October 2024 to January 2025, forest inventory was conducted using strip transects of at least 100 m wide and 3 km long, oriented in both meridional and latitudinal directions from a randomly chosen starting point. *U. kirkiana* trees were identified along the transect, and the first observed trees served as the reference for the first 20 m × 20 m sampling plot. Subsequent sampling plots were installed at intervals of at least 100 to 150 m apart from each other, starting from the first one (Biaou et al. 2023b). The number of sampling plots in each forest is shown in Table 4. A total of 149 plots were surveyed, with 24 to 25 plot per forest.

In each 20 × 20 m plot, all trees with DBH ≥ 5 cm were measured. The structural diversity parameters were recorded from a reference tree per plot (Pommerening 2006; Pommerening 2002; Salako et al. 2015). The distance from the first four neighbouring trees to the reference tree was measured (Ahoyo et al. 2023; Salako et al. 2015). Regeneration was defined as woody species with DBH ≤ 5 cm and a height ≤ 1.5 m (Mekonnen et al. 2023). The regeneration density was quantified by counting the regenerating trees of all species in five 5 m × 5 m subplots, established at the four corners and center of the main plot. The disturbance level (i.e., pruning intensity), was recorded by visually estimating the proportion of the crown affected by pruning for each *U. kirkiana* tree encountered in the sampling plots. Within these plots, all species associated with *U. kirkiana* were also measured to enable the assessment of the floristic diversity of the *U. kirkiana* habitat across each region.

Table 4: Forests sampled across the regions, with the number of sampling plots

Regions	Forest	Plot number
North	Kaning'ina forest	25
	Perekezi forest	25
Central	Chongoni forest	25
	Dzalanyama forest	25
South	Zomba mountain forest	24
	Mangochi forest	25

3.4.5. Research objective five

For Research Objective Five, data collection was oriented toward assembling the environmental and species occurrence datasets required for ecological niche modelling of *U. kirkiana*. This included compiling bioclimatic variables, altitude and species presence records across Malawi to assess the potential distribution of the species under current and future climate scenarios.

Occurrence data for the species were obtained from various databases covering southern Africa and field surveys in Malawi. To gather field data on occurrences, field surveys were carried out in

Malawi's primary ecological regions along established trails. Gentry (1988) showed that trails are useful for recording plant diversity in tropical forests. Moreover, the trails facilitate the optimization of spatial coverage in challenging environments and have been considered for data collection in biodiversity studies (Guisan et al. 2017). Targeting areas historically known to harbor *U. kirkiana* has been made possible by information derived from the Global Biodiversity Information Facility (GBIF) platform (<http://www.gbif.org>), local knowledge, botanical gardens, and forestry agents, as suggested by Gentry (1988). Initial data cleaning involved the removal of duplicated, doubtful, non-valid and incorrect occurrence coordinates through cross-referencing. After this process, 480 occurrences of *U. kirkiana* were considered for the study. Of these, 34.37% (165) were downloaded from GBIF database (<http://www.gbif.org>), while 65.63% (315) originated from the field surveys.

Environmental data included the 19 bioclimatic variables (Table 6), elevation derived from the Shuttle Radar Topography Mission (SRTM), and soil type (Assang et al. 2023). The bioclimatic variables represent annual and seasonal average, extreme, and intra-annual values of rainfall and temperature (Booth et al. 2014). Their ecological influence on the distribution of species have been demonstrated in many previous studies (Kokou et al. 2024b; Birhane et al. 2020a). The data on the bioclimatic variables were acquired from the CHELSA (Climatologies at high-resolution for the earth's land surface areas) website (<https://chelsa-climate.org/>).

The elevation data were obtained from the version 2.1 of the WorldClim database (<https://www.worldclim.org/data/worldclim21.html>) (Fick and Hijmans 2017). The data on the soil type were obtained from the version 1.2 of the Harmonized World Soil Database <http://www.fao.org/land-water/databases-and-software/hwsd/en/> (Fao and ISRIC 2012). These datasets were extracted and converted into ASCII format using ArcGIS 10.5 by considering southern Africa as the mask feature. A total of 21 environmental variables were used in the study, including one categorical variable (example, soil type) and 20 continuous variables. All selected variables had a spatial resolution of 30 arc seconds (approximately 1 km).

Examining a range of climate scenarios (example low, medium and high) allows for a more accurate assessment of the potential impact of climate change over a given timescale (Harris et al. 2014). In this regard, the future climate scenarios based on the Shared Socio-economic Pathways (SSPs) were used in this study (Riahi et al. 2017). The SSPs suggest, for example, that a future with “resurgent nationalism” and fragmentation of the international order could make the “well below 2°C” Paris target impossible (Masson-Delmotte et al. 2021). We selected the scenarios SSP3-7.0 and SSP5-8.5 to represent different development and concentration pathways. SSP3-7.0 and SSP5-8.5 are high radiative forcing scenarios, entailing high challenges for climate change mitigation and adaptation (Riahi et al. 2017). The SSP3-7.0 and SSP5-8.5 scenarios were selected because they represent realistic future pathways for Malawi under contrasting socio-economic and emission conditions. SSP3-7.0 (“Regional Rivalry”) reflects a scenario of high population growth, limited technological advancement, and weak environmental governance conditions that mirror current development challenges in many parts of rural Malawi. In contrast, SSP5-8.5 (“Fossil-fueled Development”) represents a high-emission trajectory characterized by rapid economic growth and intensive energy use, serving as a worst-case benchmark for assessing the potential impacts of climate change on species distribution. Using both scenarios allows for a robust comparison of possible future outcomes of *Uapaca kirkiana* under varying climate and socio-economic pressures.

We downloaded the future climate data from the General Circulation Models (GCM; MPI-ESM1.2-HR) because this GCM has a well-balanced radiation budget, and its climate sensitivity is explicitly tuned to 3 Kelvin. Reliable predictions of regional climate fluctuations are made possible by this model, which is renowned for its precision in replicating the intricate interactions between the atmosphere, ocean, biosphere, and cryosphere (Loughran et al. 2021; Mauritsen et al. 2019). Although the reductions in long-term biases are modest, the improvements in atmospheric dynamics make this model well-suited for forecasting and climate impact assessments (Müller et al. 2018). The SSP data were downloaded for the year 2055 (2041-2060).

Table 5: Environmental variables used in MaxEnt modeling

Codes	Variables	Units
Elev	Elevation	m
Soil	Soil types	
bio 01	Annual Mean Temperature	°C
bio 02	Mean Diurnal Range (Mean of monthly (Max temp - min temp)	°C
bio 03	Isothermality (BIO2/BIO7) (*100)	%
bio 04	Temperature seasonality (standard deviation * 100)	°C
bio 05	Max Temperature of Warmest Month	°C
bio 06	Min Temperature of of Coldest Month	°C
bio 07	Temperature Annual Range (BIO5-BIO6)	°C
bio 08	Mean Temperature of the Wettest Quarter	°C
bio 09	Mean Temperature of the Warmest Quarter	°C
bio 10	Mean Temperature of the Driest Quarter	°C
bio 11	Mean Temperature of the Coldest Quarter	°C
bio 12	Annual Precipitation	mm
bio 13	Precipitation of Wettest Month	mm
bio 14	Precipitation of the Driest Month	mm
bio 15	Precipitation Seasonality (Coefficient of Variation)	mm
bio 16	Precipitation of Wettest Quarter	mm
bio 17	Precipitation of the Driest Quarter	mm
bio 18	Precipitation of the Warmest Quarter	mm
bio 19	Precipitation of the Coldest Quarter	mm

3.5. Data Analysis

The analysis of the collected data followed a mixed and integrative approach tailored to each research objective. Both quantitative and qualitative techniques were applied to ensure triangulation and robustness of the findings. Socio-economic and ethnobotanical data from household surveys were coded and entered into R 4.4.3 for descriptive and inferential statistical analysis, while qualitative responses were subjected to thematic content analysis to capture perceptions, knowledge and practices related to *U. kirkiana*. For the ecological component, inventory data were analyzed to assess population structure, regeneration status and species associations, using standard dendrometric methods and biodiversity indices. Functional trait measurements were statistically processed to quantify intraspecific variability across ecological gradients, with analyses conducted in R 4.4.3. For the modelling objective, species occurrence data were combined with environmental predictors, and species distribution modelling was performed

under current and future climate scenarios using the maximum entropy (MaxEnt) algorithm. This combined approach ensured that both the human and ecological dimensions of *U. kirkiana* were adequately captured, providing complementary insights into its conservation, management, and potential response to climate change.

3.5.1. Research objective one

For this objective, the analysis examined participants' perceptions of *U. kirkiana* population dynamics and local conservation practices using descriptive statistics and thematic content analysis. Participants were grouped into three age categories as follows: young (19-29 years), adult (30-59 years) and old (≥ 60 years) (Biaou et al. 2023b). The relative frequencies of citations (Rc) were calculated for each response to the questions on changes in the species population, causes of its decline, and conservation practices, according to socio-demographic factors (age, gender, ethnicity, profession, and education level). A Fisher's test was performed to test the link between each socio-demographic factor and the local knowledge of change in the species' population. Attitudes towards the conservation of *U. kirkiana* were assessed based on the number of conservation practices cited by the participants. The perception of ecosystem services provided by *U. kirkiana* was analyzed based on the number of ecosystem services mentioned by respondents. A generalized linear mixed effects model (GLMM) with Poisson distribution was performed using the "lme4" R package to test the effect of age, gender, ethnicity, professions, education level and region zone on the attitudes towards the species conservation. All analyses were performed in R statistical software, version 4.4.3. (Team 2022).

Subsequently, the analysis evaluated the significance of endogenous uses of *U. kirkiana* and its ecological vulnerability, using descriptive statistics and comparative ecological indicators to identify regional patterns and pressures. *U. kirkiana* uses have been evaluated based on the use value indices defined by Gomez-Beloz (2002) and adapted to a species by previous studies (Padakale et al. 2018; Atakpama et al. 2015). Several parameters were considered: the relative citation frequency (Rc), the number of citations of reported uses (NU), the use importance value

(VIUpp), the interspecific use value (VUI), the use diversity index (IDUpp) and the use importance value index (IVIUpp) (Atakpama et al. 2021). The citation frequency (Rc) of a plant part corresponds to the ratio between the number of respondents (n) who cited the plant part and the total number of respondents (N): $Rc = \frac{n}{N}$. The total number of reported usage citations (NUpp) per plant part is the sum of the number of citations per plant part. The plant part use value (UVpp) is the ratio between its reported use (NUppi) and the total number of citations reported for all parts ($\sum NUpp$) (Atakpama et al. 2021): $UVpp = \frac{NUppi}{\sum NUpp}$. The plant parts with the highest UVpp are the most commonly used.

The specific use is the use as described by the participants. The specific use value (VUS) expresses the number of times a particular use was cited. The interspecific use value (IVU) is the ratio between the VUS and the NUpp. The use diversity index (UDIpp) of a plant part is the ratio between the number of specific uses (Mustapha et al.) of the plant part i and that of the plant part with the maximum number of specific uses (NUSmax) (Atakpama et al. 2021): $IDUpp = \frac{NUSi}{NUSmax}$. The use importance value index of a target plant part (UIVIpp) is the sum of the frequency of citations, the use importance value and the use diversity of the plant part: $Fr + VIUpp + IDUpp = IIVIpp$. This index makes it possible to estimate the importance of use of the plant part based on its knowledge of use by all respondents, the value of use and diversity of specific uses. Its maximum value is three.

Differences in knowledge of uses of *U. kirkiana* tree by gender, age, education level and ethnicity were based on the comparison of the average number of specific uses reported per respondent. The degree of similarity of specific uses between ethnic groups was assessed using the Sorensen index (Samarou et al. 2021). According to the formula: $Is = \frac{2C}{A+B}$, number of specific uses of the ethnic group, 1 (A) and 2 (B) and C, the number of uses common to the two entities 1 and 2. The statistical

test (ANOVA One-way) was used to test if there is a significant difference in the degree of plant parts used among ethnic groups.

The vulnerability of *U. kirkiana* in the study area was determined through the ecological impact of the use of its plant parts. The parameters chosen for the vulnerability assessment were the frequency of citation of the species, the plant parts used, the number of categories of uses of the plant parts (Nu), the method of collection, the age of harvest and the plant part used (Table 1) (Betti 2001; Traore et al. 2011; Samarou et al. 2021). Frequency of use N1 (the vulnerability of a woody species increases with its frequency of use (popularity); types of species use N2 (the vulnerability of a woody species increases with the number of uses in which the plant is solicited. As the number of uses the greater the pressure on the individual, being solicited); plant part used N3 (a plant's vulnerability of a plant increases according to whether the regenerates easily or not); harvesting method N4 (the main harvesting methods used are hand by hand, with a hoe and with a cutter); plant part development stage harvested N5 (the development stages used in this work are those used by Betti et al. (2001), young, adult, and old). The relative frequency of use N1 of a species i in a use j is calculated according to the following formula: $N1 = \frac{n_{pij}}{ntpe} \times 100$, where n_{pij} = number of people who cited species i in use j, $ntpe$ = total number of informants.

The calculation of vulnerability risk indices (I_v) based on the demands of *U. kirkiana*, showed that 11 plant parts were recorded. Cutting disrupts the long-term stability and increases the vulnerability of the species. The vulnerability of *U. kirkiana* is a function of the frequency of use of the collected plant part, the large number of use categories, the plant parts used (stems, leaves, bark, roots, fruits, flowers), the method of collecting the organs (cutting, stripping, uprooting and picking) and development stage.

$$IV = \frac{N1+N2+N3+N4+N5}{5} \text{ (Eq. 2). If } I_v < 2, \text{ the plant is weakly vulnerable; if } 2 \leq I_v < 2.5, \text{ the plant is moderately vulnerable; if } I_v \geq 2.5, \text{ the plant is very vulnerable (Ayéna et al. 2016).}$$

Table 6: Parameters used for vulnerability assessment

Selected parameters	Low (scale = 1)	Medium (scale = 2)	High (scale = 3)
Frequency of quotation	P1 <20%	20% ≤ P2 <60%	P3 ≥ 60%
Number of uses:	P2 <2	2 ≤ P2 ≤ 4	P2 ≥ 5
Plant parts used:	Leaf, latex	Fruit	Wood, seed, bark, root, flower
Harvesting method	By hand	-	with a hoe, with the cutter
Development stage	Old	Adult	Young

Key: Table 1 presents the five parameters used to assess the vulnerability of *Uapaca kirkiana*, each weighted equally in the calculation of the vulnerability index (Iv). These parameters were selected based on their relevance to ecological pressure and sustainability. The frequency of citation (N1) reflects the popularity and demand for the species, while the number of use categories (N2) indicates the versatility and therefore the intensity of exploitation. The type of plant parts used (N3) is critical, as harvesting more vital or non-regenerative parts (e.g., roots, bark) increases vulnerability. The harvesting method (N4) captures the potential destructiveness of collection practices and the developmental stage at harvest (N5) highlights whether the plant is being exploited at a regenerative or reproductive stage. Each parameter is scored on a scale from 1 (low impact) to 3 (high impact), and the Iv is calculated as the average of these five scores. Equal weighting was adopted to reflect the complementary importance of all parameters in contributing to overall species vulnerability

3.5.2. Research objective two

The analysis under this objective focused on characterizing woody species composition and phylogenetic structure along elevation gradients associated with *U. kirkiana*, using diversity indices and phylogenetic metrics

3.5.2.1. Demographic structure analysis of forest stands

The recorded species were classified by family and genus according to the Angiosperm Phylogeny Group IV (APG IV) phylogenetic classification (APG 2016). To analyze the demographic structure of forest stands, tree diameter classes were defined using 5 cm intervals for describing horizontal structure (West 2015). Based on these classes, several structural indices were calculated using the R statistical software (Team 2022). These included the Permutation Index (PI) to evaluate distribution irregularity, skewness and kurtosis to describe asymmetry and peakedness using the moments package (Komsta and Novomestky, 2015), the Gini index to measure inequality in trees size distribution with the ineq package (Zeileis and Kleiber 2014), and the Shannon index to

estimate structural diversity across diameter classes, calculated using the vegan package (Oksanen et al. 2001). These indices provided detailed insights into stand dynamics, heterogeneity, and regeneration status (Magurran 2021).

Additionally, the distribution of diameter at breast height (DBH) was modeled using a two-parameter Weibull function, which is commonly used in forest ecology to characterize stand structures under varying levels of disturbance, age, and regeneration intensity (Burkhardt and Tomé 2012). In this analysis, the location parameter (a) was fixed at 5 cm to standardize comparisons across sites, and the shape and scale parameters were estimated for each forest stand using the fitdistrplus (Delignette-Muller and Dutang 2015) and MASS packages (Venables and Ripley 2013). The horizontal structure of the woody populations was established using Microsoft Excel® spreadsheet coupled with R 4.4.3 software. This structure was adjusted according to the probability distribution function "f" of Weibull density distributions (Rondeux, 2021); where $f(x) = \frac{c}{b} \left(\frac{x-a}{b}\right)^{c-1} e^{-\left[\frac{x-a}{b}\right]^c}$, a: position parameter, b: scale parameter, and c: shape parameter of the structure. The position parameter "a" considered in the present study was set at 5 cm for the diameter classes. These threshold values allow for the standardization of demographic structure analysis and better interpretation of the obtained results.

Table 7: Various forms of the Weibull distribution depending on their value (Idrissa et al. 2020)

Value of "c"	Distribution Forms
c < 1	Inverted-J distribution, characteristic of multispecific or uneven-aged stands.
c = 1	Exponentially decreasing distribution, typical of declining or dying populations.
1 < c < 3.6	Positively skewed (right-skewed) distribution, typical of stands dominated by young or small-diameter individuals.
c = 3.6	Symmetrical distribution; normal structure, typical of even-aged or monospecific cohorts.
c > 3.6	Negatively skewed (left-skewed) distribution, characteristic of monospecific stands dominated by older individuals.

The Family Index Vegetation (FIV) is an ecological indicator used to assess the relative representation of botanical families within a given ecosystem. It is commonly used in floristic studies to identify the families richest in species, and therefore potentially the most influential in the structure and functioning of the plant community. This index is calculated using the following formula: $FIV (\%) = \frac{N_i}{N} \times 100$, where N_i represents the total number of species belonging to a specific family, and N represents the total number of species inventoried, all families combined. The FIV is expressed as a percentage and reflects the relative species richness of a given family. A high FIV value indicates that the family in question contributes significantly to local floristic diversity, which may reflect its ecological adaptability, frequency of occurrence, or importance in local ecological interactions. This index is particularly useful for identifying dominant families in a landscape, comparing the floristic composition between different sites or ecological gradients, or supporting ethnobotanical studies by highlighting the families preferentially used by local communities. Thus, the FIV is a useful tool for analyzing taxonomic diversity at the family level and for guiding flora conservation strategies.

3.5.2.2. Phylogenetic structure metric and quantification of taxonomic

The phylogenetic diversity was calculated using the “pd” function in the R package “picante” (Team 2022). Moreover, we identified the linear relationship between phylogenetic diversity and species richness. Therefore, we calculated the standardized effect size of phylogenetic diversity (SES.PD) using the “sespd” function in the R package “Picante”, which eliminates the influence of species richness on the PD (Kembel et al. 2010). The formula is listed below:

$SESPD = \frac{PD_{\text{observed}} - \text{mean}(PD_{\text{random}})}{sdPD_{\text{random}}}$; where PD observed is the observed PD in a community, PD random is the mean PD in null communities, and sdPD random is the standard deviation of PD in null communities. Meanwhile, we choose the “taxa.labels” null model and calculated it 999 times to meet the statistical requirements (Jarzyna 2021). The phylogenetic reconstruction was performed using the V.PhyloMaker2 package (Jin and Qian 2022), which builds phylogenies by inserting

missing species into a global mega-tree (GBOTB.extended.TPL) based on higher taxonomic ranks (family or genus). This extended tree is derived from comprehensive molecular data and represents one of the most complete vascular plant phylogenies available (Smith and Brown 2018). Scenario S3, which places unsampled taxa at the basal node of their respective clades, was chosen as it is recommended for ecological analyses to minimize bias due to missing molecular information.

Only species occurring both in the community matrix and the final tree were retained to ensure consistency between phylogenetic structure and floristic composition. Phylogenetic analyses were conducted using the R packages *picante* (Kembel et al. 2010), *vegan* (Oksanen et al. 2001), *ape* (Paradis et al. 2004) and *tidyverse*. The species abundance matrix was converted to relative abundance using the function `decostand` (`method = "total"`) to control for sampling effort across sites. Three widely used phylogenetic alpha diversity metrics were computed: Faith's Phylogenetic Diversity, which sums the branch lengths linking all species in a community and reflects evolutionary richness (Faith 1992), Mean Pairwise Distance (MPD), the average phylogenetic distance between all species pairs in a plot; and Mean Nearest Taxon Distance (MNTD), which calculates the mean distance from each species to its closest relative in the same community (Webb et al. 2002). In this study, we measured the plant diversity using phylogenetic diversity for the traditional diversity index only takes into account differences in the number and composition of species in communities and does not take into account lineages relationship between species pairs.

To assess non-random patterns of community structure standardized indices NRI (Net Relatedness Index) and NTI (Nearest Taxon Index) were computed by comparing observed phylogenetic distances to null distributions generated by 999 randomizations under the taxa. Labels model. Positive values of NRI or NTI indicate phylogenetic clustering, often interpreted as the outcome of environmental filtering, while negative values suggest phylogenetic over dispersion possibly linked to competitive interactions (Webb et al. 2002; Cavender-Bares et al. 2009).

The following formula was used:

$$NRI = -\frac{MPD_{obs} - mean(MPD_{rand})}{sd(MPD_{rand})} \quad ; \quad NTI = -\frac{MNTD_{obs} - mean(MNTD_{rand})}{sd(MNTD_{rand})} .$$

Phylogenetic beta diversity was quantified using the `comdist` function from `picante`, which computes pairwise dissimilarity between communities based on MPD across sites. To examine the differences in species composition and phylogenetic composition of woody plant communities in different areas, we performed PCoA in this study. Principal coordinates analysis (PCoA) was used to assess variations and visualize the similarities based on Bray-Curtis distances using the R package “`vegan`” (Dixon 2003; Wang et al. 2024). An analysis of similarity (ANOSIM) followed non-metrical multidimensional scaling to assess the differences in woody plant communities compositions across the different elevation (Luo et al. 2023; Kebebew and Ozanne 2022).

Table 8: Structural diversity and demographic parameters used to describe the communities

Parameters	Formulas	Descriptions	References
Permutation index (PI)	$PI = \sum_{i=1}^n (J_i - 1) J_i$	J_i = the rank of size class i ($i=1$ for the smallest trees), with the highest rank ($J_i=1$) given to the most frequent size class.	(Birhane et al. 2020a)
Shannon index (H')	$H' = - \sum_{i=1}^s p_i \ln(p_i)$	p_i is the proportion of individuals of species i	(Kitikidou et al. 2024)
Gini index(G)	$G = \frac{\sum_{i=1}^n (2i - n - 1) + zi}{n \sum_{i=1}^n zi}$	Measures inequality in size distribution among individuals. A Gini value close to 0 indicates uniform size, while a value close to 1 indicates that few individuals dominate in size or biomass	(Weiner 1990)
Skewness	$\frac{n}{(n-1)(n-2)} \sum \left(\frac{x_i - \bar{x}}{s} \right)^3$	Describes the symmetry of the DBH distribution, positive skewness indicates dominance of small trees (regeneration stands); negative skewness implies dominance of large trees (older stands).	(Komsta and Novomestky 2015)
Kurtosis	$= \frac{n(n+1)}{(n-1)(n-2)(n-3)} \sum_{i=1}^n \left(\frac{x_i - \bar{x}}{s} \right)^4 - \frac{3(n-1)^2}{(n-2)(n-3)}$	Indicates the peakedness of the distribution, High kurtosis (leptokurtic) shows dominance of a specific cohort (e.g. plantation), while low kurtosis (platykurtic) suggests structural heterogeneity.	(Komsta and Novomestky 2015)

3.5.3. Research objective three

The analysis for this objective examined intraspecific functional trait variation of *U. kirkiana* across eco-geographical regions and its relationship with environmental gradients, using multivariate statistical approaches.

All statistical analyses were performed in R statistical software, version 4.4.2 (R Core Team 2020). Descriptive statistics including arithmetic mean, standard error of the mean and coefficient of variation (CV; standard deviation/mean) were calculated for each morphological trait by region. The CV was used to describe the variability of morphological traits. A CV < 25% indicated low variability (Reza et al. 2017). Linear mixed-effects models were used to assess the variation in measured traits according to “forest”, “population”, and “tree”. Individual trees from the same forest were considered as a population. The linear mixed-effects models were run using the “nlme” package (Pinheiro 2011). In these models, “region” was considered as a fixed factor, while the random term included “population” nested within “tree” (1/population/tree). We assumed that variability in the traits may result from differences between the regions and accounted for pseudo-replication at the levels of individual and population through the random term. We performed Tukey’s post-hoc tests on the outputs of the linear mixed-effect models for mean comparison using the function “glht” of the “multcomp” package (Hothorn et al. 2008).

Next, we identified the traits that best discriminated the trees according to the region by performing a canonical discriminant analysis (CDA) on the traits of the 72 sampled individual trees using the “candisc” package (Friendly et al. 2017). This analysis ranks traits in their order of significance by discriminating trees according to the population and the region. The most important morphological traits differentiating the trees between the regions were identified using “greedy.wilks” function with the R package klaR (Roever et al. 2020).

To examine the impact of environmental factors, including the bioclimatic variables, aridity index and elevation on the morphological traits of *U. kirkiana* trees, we first used Spearman’s correlation

test to explore patterns of association between pairs of these variables. A pairwise correlation matrix between morphological traits was constructed to explore correlation patterns among traits (Dai et al. 2024). Then, a redundancy analysis (RDA) was performed to assess the relationship between the most discriminating traits of region and the environmental variables. A principal component analysis (PCA) was performed to better illustrate the correlation patterns among the most discriminating morphological traits and the significant environmental variables from the RDA. To explore the existence of morphotypes within the species based on the morphological traits, a hierarchical clustering with the calculation of Ward's distance was performed. To determine the optimal number of clusters (k), we used the Silhouette Method (Dinh et al. 2019).

To assess phenotypic plasticity in the morphological traits of *U. kirkiana* in response to aridity gradients among regions, we calculated the phenotypic plasticity index (PPI) as defined by Valladares et al. (2006). This index, which ranges from 0 to 1, quantifies trait plasticity for each pair of regions. It was calculated using the following formula:

$P_i = \frac{X_{\max} - X_{\min}}{X_{\max}}$ (Eq 3), where $X_{\max}$ and $X_{\min}$, are the maximum and minimum mean values of the trait between two forest sites, respectively. The index was computed for each measured trait and each pairwise region comparison. Data processing was conducted using the ggplot2 packages for computation and visualization.

3.5.4. Research objective four

The analysis for this objective focused on evaluating population structure, regeneration dynamics, and carbon storage potential of *U. kirkiana* across geographic regions, employing a combination of demographic assessments, regeneration indices, and biomass estimation techniques.

3.5.4.1. Floristic diversity and species associations of *U. kirkiana* habitats

The recorded species were classified by family and genus according to the Angiosperm Phylogeny Group IV (APG IV) phylogenetic classification (APG 2016). Species were categorized according to their conservation status as defined by the International Union for Conservation of Nature (IUCN). Species citation frequencies were calculated to identify those most associated with *U. kirkiana* in its natural habitat. Various ecological indices were used to analyse the species diversity and structure of plant communities, including species richness (S), Shannon index (H'), Simpson's index (D), Pielou's evenness index (J'), Hill's diversity index (Nq), Jaccard's similarity index (Table 9). The analyses were conducted using R (v4.3.2) to perform the analyses, with the vegan package for ecological analyses, ggplot2 for graphing, corrplot for visualizing correlations, BiodiversityR for biodiversity analyses, and reshape2 for data transformation (Kindt, 2018).

Importance value index provides knowledge on important species of a plant community. IVI is useful to compare the ecological significance of species (Lamprecht 1989). IVI combines data from three parameters, which include Relative frequency, Relative Density and Relative Dominance (Kent and Coker 1992). Trees species importance values were then calculated for the five (05) top species as the sum of species relative Frequency, species relative dominance, species relative abundance (Magurran 2004) as showed in Table 10.

The attributes relative Frequency, relative abundance and relative dominance indicated what contributed to the overall importance values of a species in the forest. A high relative density indicates many individuals of the species in the plots. A high relative dominance indicates large-sized individuals of the species in the plots and a high relative frequency indicates a wider distribution of the species in most of the plots.

Table 9: Structural diversity, demographic and dendrometric parameters used to describe *U. kirkiana* populations and their habitat in Malawi

Parameters	Formulas	Descriptions	References
Disturbance			
Pruning intensity of each <i>U. kirkiana</i> tree in the stand (Pi)	$Pi = \frac{NBP}{NTB} \times 100$	NBP = number of pruned branches; NTB = total number of branches borne by an individual tree	(Amahowe et al. 2018)
Structural diversity			
Mingling (Mi)	$Mi = \frac{1}{n} \times \sum_{j=1}^n Vij$	Vij = 0 if tree "i" and neighbouring tree "j" are of the same species and Vij = 1 if tree i and neighboring tree j are of different species; n is the number of neighbours (n = 4 in this study).	(Pommerening 2006, 2002 ; Salako et al. 2015)
Tree-to-tree distance (Di)	$Di = \frac{1}{n} \times \sum_{j=1}^n Sij$	Sij = distance of the i <i>U. kirkiana</i> tree from the j neighbouring tree, n = number of sampled neighbours (n = 4)	
dbh differentiation	$DDi = \frac{1}{n} \sum_{j=1}^n (1 - aij)$	$aij = \frac{dbh\ of\ U.\ kirkiana}{dbh\ of\ j\ neighbour}$; n = number of sampled neighbours (n = 4)	
Permutation index (PI)	$PI = \sum_{i=1}^n (Ji - 1) Ji$	Ji = the rank of size class i (i=1 for the smallest trees), with the highest rank (Ji= 1) given to the most frequent size class.	(Birhane et al. 2020)
Demographic and dendrometric			
<i>U. kirkiana</i> density (NPE, trees/ha)	$NPE = n/s$	n is the total number of <i>U. kirkiana</i> trees per plot and s is the size of the plot	(Biaou et al. 2023)
Mean diameter (Dg, cm)	$\sqrt{\frac{1}{n} \times \sum_{i=1}^n d_i^2}$	di = diameter of the tree i in a plot; n = total number of trees in a plot	(Biaou et al. 2023)
Regeneration ratio (Rr)	$Rr = \frac{Nsd + Nsa}{Nad}$	NSD, NSA and NAD represent the total number of seedlings, saplings, and adult trees per plot, respectively.	(Zon et al. 2022)
Diversity index			
species richness (S)		total number of recorded species	
Shannon index (H')	$H' = - \sum_{i=1}^S p_i \ln(p_i)$	pi is the proportion of individuals of species i	(Kitikidou et al. 2024)
Simpson index (D)	$D = 1 - \sum_{i=1}^S p_i^2$		
Pielou's evenness index (J')	$J' = \frac{H'}{\ln(S)}$		
	$N_q = \left(\sum_{i=1}^S p_i^q \right)^{\frac{1}{1-q}}$	for q=0: species richness, q=1: exp(H'), q=2: 1/D	

Hill's diversity index (Nq)			
Jaccard's similarity index	$J = \frac{c}{a + b - c}$	a = number of species in site A; b = number of species in site B c = number of species common to both sites	
Relative density	$Rde (\%) = \frac{f}{F} \times 100$	Where f = number of individuals of a species in a plot, F = number of individuals of all species in the plot,	(Kacholi 2014)
Relative frequency	$Rdi (\%) = \frac{n}{N} \times 100$	Where n = number of sample units a species occurred in, N = Total number of sample units	(Kacholi 2014)
Relative dominance	$Rdo (\%) = \frac{BAi}{BA} \times 100$	Where Bai = total basal area of species I in the plot, BA = total basal area of all species in the plot	(Kacholi 2014)
Importance value index	$IVI = RDi + RDe + Rdo$	Where RDi is Relative frequency, RDe is Relative Density, RDo= Relative dominance.	(Kacholi 2014)

3.5.4.2. Assessment of the structural diversity and population structure of *U. kirkiana* across Malawi regions

The structural diversity of *U. kirkiana* stands was assessed by calculating several structural parameters (Table 1). For instance, the mingling (Mi) was employed to quantify interspecific competition at each site, while the diameter differentiation index provided insights into the size of *U. kirkiana* trees about their nearest neighbouring trees (Pommerening 2002). To analyses the structure of *U. kirkiana* populations, demographic (stand density, density of adult *U. kirkiana* trees) and dendrometric (mean DBH) parameters were calculated. An analysis of variance (ANOVA) was performed to compare the means of the structural diversity, demographic and dendrometric parameters among the three regions. All models were checked for normality of residuals and

homoscedasticity. In addition, Pearson's correlation test was used to assess the strength and direction of the association between the structural diversity, demographic, dendrometric, and disturbance (Example pruning intensity) parameters for each region and altitude (Biaou et al. 2023b). The diameter size-class distribution of the species population was also established with the corresponding skewness coefficient for each region.

Furthermore, a log-linear model was used to check whether the diameter size-class distributions differed among the regions. In this analysis, the number of individuals per size class and region was used as dependent and independent variables, respectively. The quotients (Qs) between the number of trees in consecutive size classes and the permutation index (PI) were also estimated to provide additional information on the stability of the species population (Biaou et al. 2023b; Birhane et al. 2020b). The quotient (Qs) tends to a constant value in a stable population, but fluctuates when a population is unstable. Likewise, a population showing a discontinuous size-class distribution will have a $PI > 0$ while a monotonically declining population has a $PI = \text{zero } (0)$ (Pommerening 2006).

3.5.4.3. Estimation of the carbon storage by *U. kirkiana*

To estimate the biomass of *U. kirkiana*, we used site-specific allometric equations developed for the Miombo woodlands of Malawi, in line with IPCC (2006) guidelines, which recommend locally derived models where available to reduce uncertainty. Specifically, we applied the equations from Kachamba et al. (2016), which were developed based on destructive sampling data across Miombo ecosystems in Malawi and are well suited to our study area due to their climatic, edaphic, geographical, and taxonomic relevance. $AGB (kg) = (0.21691) * (DBH)^{2.318391}$ (Eq 1). Where AGB is the aboveground biomass and DBH is the diameter at breast height (1.3 m above ground). Only trees with $DBH \geq 5$ cm were considered, corresponding to the valid range of the equation. Belowground biomass (BGB) was also estimated using a site-specific model from the same study: $BGB = (0.284615) * (DBH)^{1.99268}$ (Eq 2) (Kachamba et al. 2016).

The biomass models were converted to carbon models using a carbon factor of 0.5. This factor reflects the average carbon content of dry biomass in tropical tree species and aligns with recommendations for national forest carbon assessments in Malawi: $TB = AGB + BGB$ (eq 3). Subsequently, the carbon stock was converted into carbon dioxide equivalent (CO₂-eq) by multiplying the carbon stock by a factor of 3.67, which represents the molecular weight ratio of CO₂ to carbon (44/12), in line with IPCC (2006) guidelines and widely adopted in voluntary carbon market estimations: $SC = TB * CF$ (Eq 4) and adopted by Kokou et al. (2023b). Finally, the economic valuation of the carbon stock was estimated based on the market value of carbon credits. According to Agnolucci et al. (2024) and (Saradoum et al. 2022), forest carbon credits in Africa are traded between 3 and 10 USD per ton of CO₂ on voluntary carbon.

3.5.5. Research objective five

The analysis for this objective focused on modeling the current and future distribution of *U. kirkiana* under different climate change scenarios, integrating species occurrence data with environmental predictors to project habitat suitability and potential range shifts.

3.5.5.1. Model development and evaluation

MaxEnt version 3.3.3k was used to predict the current and future potential distribution of *U. kirkiana* in Malawi. MaxEnt used species occurrence records and environmental variables to estimate the suitable area for species occurrence and survival (Elith et al. 2011; Elith and Graham 2009; Phillips et al. 2006). Among the SDMs using presence-only data, MaxEnt reportedly showed the best predictive accuracy and was applied in various studies to assess the impact of climate change (Elith et al. 2011; Elith and Graham 2009; Phillips et al. 2017; Xiao et al. 2024; Zhao et al. 2022; Kokou et al. 2024b).

To set up the model, 75% of the data was randomly selected for training and the remaining 25% for testing. The model was run with 10 replicates using a cross-validation procedure. The relative significance of the environmental factors influencing the species' potential distribution was

determined using the jackknife test and the partial dependence curves. The area under the receiver operating characteristic curve statistic was used to evaluate model performance. AUC values range from 0.5 (indicating random prediction) to 1.0 (indicating perfect discriminative ability). $AUC > 0.9$ indicates excellent model performance, $0.80 < AUC < 0.90$ shows good model performance, $0.70 < AUC < 0.80$ indicates acceptable model performance, $0.60 < AUC < 0.70$ indicates poor model performance and a model with $AUC < 0.50$ is invalid (Thuiller et al. 2009). We also used the True Skill Statistic (TSS) to evaluate model accuracy (Thuiller et al. 2009). TSS measures the model's ability to detect true presence (sensitivity) and true absence (specificity) and was calculated as sensitivity + specificity - 1. A $TSS > 0.5$ indicates a good predictive power (Allouche et al. 2006). Furthermore, the Symmetric Extremal Dependence Index (SEDI) was employed as a supplementary and improved metric of model performance assessment (Ferro and Stephenson 2011; Wunderlich et al. 2019). While the Odds Ratio Skill Score (ORSS) is considered superior to SEDI, the use of SEDI was preferred to that of ORSS in this study because of the utilization of presence-only data for modelling, rendering real absence data unavailable for ORSS computation (Wunderlich et al. 2019). SEDI was calculated based on sensitivity (true positive fraction) and specificity values. The value of SEDI approaches 1 when the model is optimal (Ferro and Stephenson 2011). Using both TSS and SEDI allowed us to obtain a more robust assessment of model performance. This comprehensive evaluation helps to cater for the strengths and limitations of the different indices of model performance evaluation considered in this study.

To predict the future suitable habitat of the species, the current potential distribution was projected in the year 2055 based on data from the SSP scenarios. The modelling outcomes were imported into QGIS 3.16 software, where two habitat categories were established based on the mean threshold value (T), known as the 10 percentile training presence: (i) suitable habitats for values exceeding T, and (ii) unsuitable for values falling below T (Moukrim et al. 2020). The suitable habitats were then further divided into three (3) subcategories: high suitability ($p \geq T$), moderate suitability ($T/2 \leq p < T$), and low suitability ($T/4 \leq p < T/2$) (Atakpama et al. 2023), where p

represents the suitability score or the probability that a habitat is suitable for the species. The changes between current and future habitats were calculated in ArcGIS 10.5 software. This allowed us to quantify the range of changes in habitat suitability, thereby illustrating the dynamic of the range extension and contraction. The rate of change was calculated by measuring the difference in the extent of suitable habitats between the baseline period and future scenarios. This was expressed as a percentage change over the projection period (Eq. 1).

$$\text{Rate of change (\%)} = \frac{\text{future habitat area (ha)} - \text{current habitat area (ha)}}{\text{current habitat area (ha)}} \times 100 \text{ (Eq. 1), where positive}$$

values indicate habitat expansion while negative values indicate habitat contraction.

3.5.5.2. Mapping habitat suitability and determining priority areas

Potential habitat dynamics for *U. kirkiana* by 2055 were inferred for each climate change scenario by contrasting the current suitable areas with those predicted under the two SSP scenarios. Using the spatial analyst extension, geoprocessing, and intersection tools in ArcGIS 10.5 software, habitat change maps of *U. kirkiana* were produced for the SSP3-7.0 and SSP5-8.5 scenarios. First, using the modeled presence probabilities, the current and future distribution maps were divided into four categories of suitable habitats: unsuitable ($p < T/4$), poorly suitable ($T/4 \leq p < T/2$), moderately suitable ($T/2 \leq p < T$), and highly suitable ($p \geq T$). The pixels corresponding to each period were then compared by overlaying these maps in ArcGIS for each scenario. With the use of this overlay, it was possible to identify areas of habitat gain (Example pixels that transition from unsuitable to suitable), habitat loss (Example pixels that moved from suitable to unsuitable) and no habitat change (i.e., pixels that remain in the same habitat category in the two periods). Ultimately, a clear visualization of the spatial dynamics of habitats was produced by classifying each pixel into one of the three categories (gain, loss, and no change) using the QGIS 3.16 software. These data were employed to generate graphs using Microsoft Excel spreadsheets.

We employed a maximum-utility method (Moilanen 2013; Samarou et al. 2023; Kokou et al 2024) for spatial prioritizations, which is one of the most popular types of spatial prioritisation algorithms

(Kukkala & Moilanen 2013). Within a certain space or financial limitation, these algorithms seek to maximize the representation value of every included species. Here, we used a heuristic, non-target-based, maximum-utility type method found in Zonation 5 v1.0, which is a popular conservation prioritizing software (Margules and Pressey 2000; Pressey and Bottrill 2008; Kokou et al. 2024b). This method has been proven effective in previous prioritization studies (Delavenne et al. 2012; Honeck et al. 2020). It uses a backward technique that begins with the assumption that all study areas are protected. It then rates and removes all sites (grid cells) in an iterative manner, consistently eliminating the site with the lowest conservation value. Each cycle updates the conservation values of the remaining grid cells and recalculates the remaining distribution for each feature. There are various options in zonation for combining conservation values across multiple features such as species, habitats, and ecosystem services. In this line, we employed a technique known as "Core Area Zonation," wherein the conservation value δ for a species is reevaluated for every site "i" at every stage of removal (Di Minin et al. 2019; Kujala et al. 2018).

All spatial units of the study site (Example pixels) were classified based on the concepts of irreplaceability and complementarity without the need to specify targets in conservation objectives (Lehtomäki and Moilanen 2013). A conservation priority map was generated by weighting the species by Zonation, which is commonly used to optimize conservation planning (Moilanen et al. 2022; Kokou et al. 2024b). The input files for Zonation comprises the results from MaxEnt modelling including the current potential habitats and the future habitats projected for 2055 under SSP3-7.0 and SSP5-8.5 scenarios. Core Area Zonation 2 (CAZ2) was selected as the marginal pixel loss rule, which represents a good compromise between species richness and rarity (Moilanen et al. 2022). Based on a number of criteria, including biodiversity, ecosystem services, and socioeconomic variables, the priority area map was spatialized to determine the relative value of each area for development or conservation (Kokou et al. 2024b; Moilanen et al. 2022). To capture differences in priority areas more precisely, priority levels were categorised into seven classes that span from 0% to 100%, with higher priority classes having narrower intervals. Based on previous

studies (Moilanen et al. 2022; Samarou et al. 2023), the priority categories considered in this study were defined as follows: 0-20% (low priority); 20-50% (moderate priority); 50-75% (high priority); 75-100% (very high priority).

3.6. Ethical Considerations

The study adhered to established ethical standards, recognizing that ethical compliance is essential in research involving human participants and ecological assessments. Ethical approval was obtained from the Mzuzu University Research Ethics Committee (MZUNIREC) under protocol Ref. No. MZUNIREC/DOR/24/104 (Appendix 8). Prior to fieldwork, community leaders and local authorities in the selected villages and forest reserves were informed about the study objectives and granted permission for the research activities. Participation in household surveys, key informant interviews, and ethnobotanical data collection was voluntary. Respondents provided informed consent using forms adapted to the local context: the English version for household surveys (Appendix 1) and a Chichewa translation for community members. Participants were assured of the confidentiality of their responses, the anonymity of personal identifiers in the research report, and their right to withdraw from the study at any stage without any consequences.

The research team also respected local social norms and schedules. Interviews were postponed or rescheduled in the event of funerals, community meetings, or other culturally significant events to ensure respectful engagement. In ecological surveys, care was taken to minimize disturbance to *U. kirkiana* populations and associated habitats, following ethical principles for sustainable field research.

3.7. Chapter Summary

This chapter presented the methodological approach employed to investigate the ecological, functional, and socio-economic dimensions of *U. kirkiana* in Malawi. A mixed-methods design integrating community surveys, forest inventories, functional trait sampling, and species distribution modelling was adopted to ensure comprehensive coverage of both human and

ecological factors. The chapter detailed the sampling framework, data collection procedures, and analytical approaches, highlighting how each was tailored to address specific research objectives. Despite logistical and field constraints, such as accessibility of forests and asynchronous fruiting periods, the study successfully collected representative and robust data across all selected sites, ensuring the reliability and validity of subsequent analyses.

CHAPTER 4: RESULTS

4.0 Introduction

This chapter presents the detailed results of the study. It begins by describing the ecological and socio-economic characteristics of the study sites and the key attributes of *U. kirkiana* populations. Findings are reported according to each specific research objective outlined in Chapter one, including local ecological knowledge, functional trait variation, population structure, regeneration dynamics, and species distribution modelling. The chapter concludes with a summary of the main results.

4.1 Local ecological knowledge, ethnobotanical uses, and community-based conservation strategies of *U. kirkiana* in Malawi

4.1.1. Perception of the dynamics of *U. kirkiana*

Participants' perceptions of the temporal dynamics of *U. kirkiana* populations across regions and professions is shown in Table 10. Participants had various perceptions of the temporal dynamics of *U. kirkiana* populations. Most respondents (935 respondents, 76.60%) reported a declining trend in the species' population, while 13.34% observed an increase, and 10.07% considered the population of *U. kirkiana* stable. The perception of the dynamics of the species populations was significantly (<0.001) dependent on the zone and professions. For example, the proportion of local populations perceiving a regressive trend was higher in the Southern (97.37%) and Central (84.64%) regions than in the North (48.66%). Regarding the profession, 100 % of the traditional practitioners reported a declining trend, while 96.43% of civil servants thought that the species populations declined.

Table 10: Association of the perception of the dynamics of *U. kirkiana* populations with sociodemographic factors and Region in Malawi

Variables	Categories	Perception of the dynamics of <i>U. kirkiana</i>			p-value
		Increase (%)	Decrease (%)	Stable (%)	
Regions	North	26.79	48.66	24.55	<0.001
	Central	11.07	84.64	4.29	
	South	2.43	97.37	0.20	
Profession	Civil servant	0.00	96.43	3.57	<0.001
	Farmer	13.36	76.60	10.05	
	Hunter	36.36	54.55	9.09	
	Others	20.95	61.90	17.14	
	Seller	13.33	77.22	9.44	
	Traditional practitioner	0.00	100.00	0.00	
Age categories	Young	15.81	74.26	9.93	0.79
	Adult	12.11	77.06	10.82	
	Old	14.94	78.16	6.90	
Gender	Female	13.28	74.12	12.94	0.39
	Male	13.44	79.20	7.36	
Education level	High school	12.11	77.33	10.56	<0.001
	None	24.69	71.13	4.18	
	Primary	9.75	78.49	11.76	
	Secondary	17.39	43.48	39.13	
	University	6.98	93.02	0.00	

Key: The p-value of the Fisher's exact test was provided

Results on the perceived causes of decline of *U. kirkiana* are presented in Figure 3a and b. Overall, the causes of the decline in *U. kirkiana* populations cited by the participants were mainly deforestation, charcoal production, human population growth, climate change, and agriculture (Figure 3a). Very few participants attributed the decline to pests (1.10%), harvesting (2%) and logging (4%). The causes for the decline in *U. kirkiana* varied according to the regions. In the North and South Regions, the participants identified charcoal production as the primary cause of the decline of *U. kirkiana* respectively 35.12% and 85.97%. In the Central Region, the participants identified deforestation (78.29%) as the primary cause of the decline of *U. kirkiana* (Figure 3b). In the Central Region, in addition to population growth and expansion of agricultural lands, lack of enforcement of legislation was also mentioned as a major driving factor (Figure 3b).

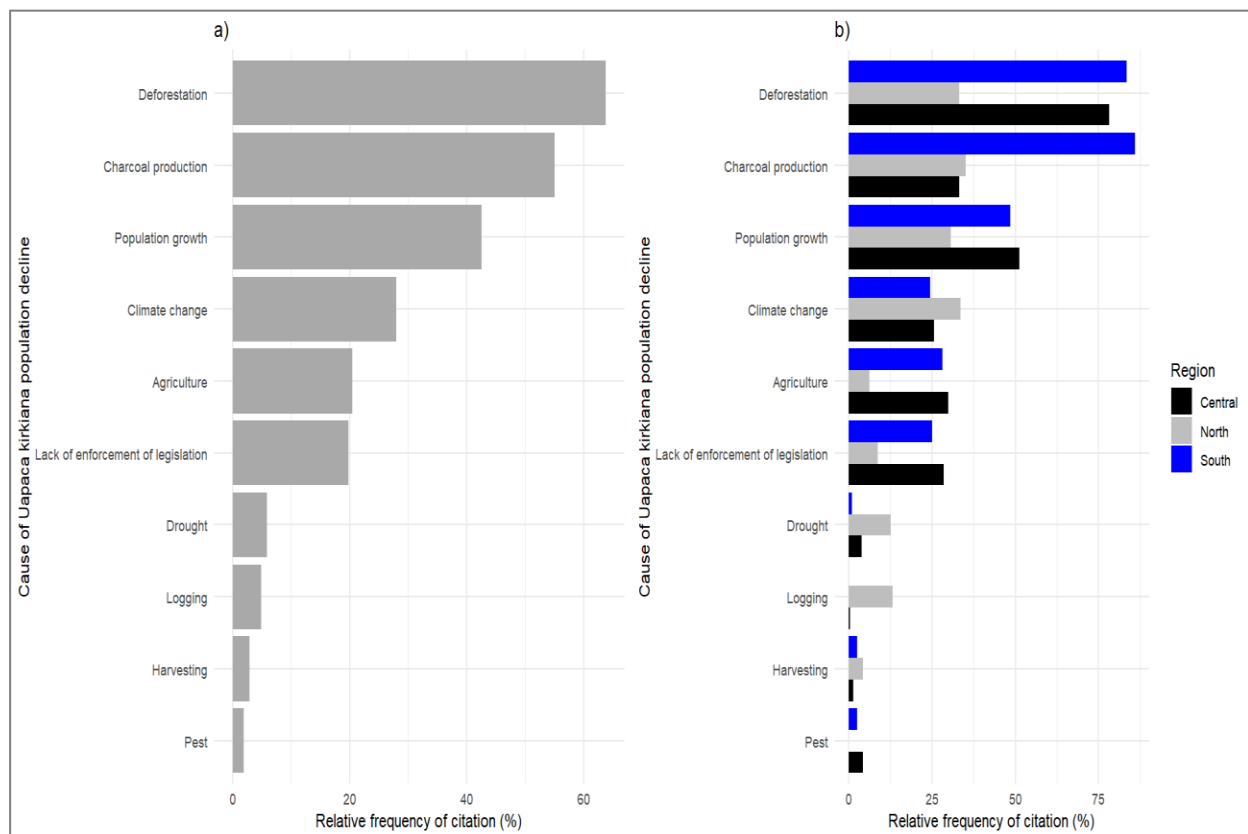


Figure 3: Perceived causes of *U. kirkiana* population decline as indicated by local communities
Key: (a) Perception of the local community across the Regions and (b) perception of the local community per region

4.1.2. Local practices for *U. kirkiana* conservation

Results on local conservation strategies of *U. kirkiana* across the regions of Malawi are presented in Figure 4. The conservation practices reported by the participants across the different regions in Malawi primarily focused on the conservation within agroforestry systems (741 respondents, 60.83%, Figure 4a). In addition, the prohibition of cutting, the protection of the species regeneration, and protection from pruning emerged as key conservation practices (Figure 4a). Notably, the conservation of the species within agroforestry systems was more common in the southern region (78.9%), followed by the Central Region (62.63%) and Northern Region (40.36%) (Figure 4b). Conversely, planting, and assisted regeneration were the frequently mentioned practices by the respondents (Figure 4a). Communities in the Northern, Central and Southern Regions (Figure 4b), mainly reported these practices. Protection of regeneration was the main

practices reported by respondents in the central regions (72.60%) and cutting protection (49.50%) was the main key practices cited by respondents in the North Region (Figure 4b).

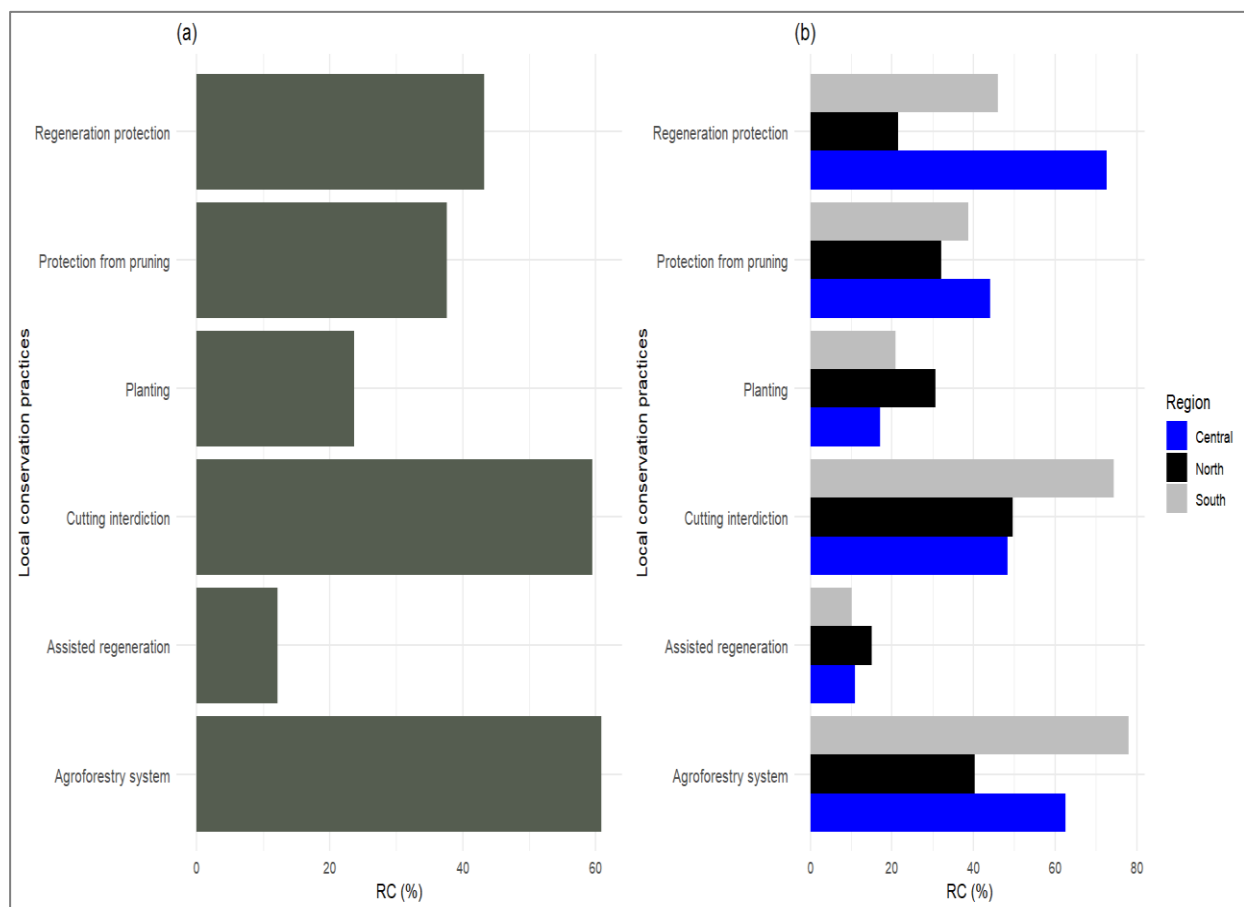


Figure 4: Relative frequency of citations (Rc, %) of the local conservation strategies of *U. kirkiana* across the regions of Malawi

Key: (a) Perception of the local community across the regions and (b) perception of the local community per region

4.1.3. Socio-economic factors affecting local community's conservation practice

Sociodemographic factors such as age and profession, which significantly affected the number of local conservation practices, are presented in Table 11. The farmer had a positive effect ($\beta = 0.73$) on the number of conservation practices. Concerning age, the younger and older mentioned a significantly higher number of conservation practices ($\beta = 0.70$ and 1.17) than the adults.

Table 11: Results of the generalized linear mixed-effect model (GLMM) with Poisson distribution assessing the effects of regions and sociodemographic factors on the attitude of local communities towards the conservation of *U. kirkiana* in Malawi

Variables	Level of variables	Estimate (β)	Std. Error	z value	Pr(> z)
	(Intercept)	1.93	1.06	1.82	0.06
Profession	Farmer	0.73	0.37	1.99	0.04*
	Hunter	0.87	0.89	0.98	0.33
	Others	0.72	0.45	1.61	0.11
	Seller	0.73	0.41	1.79	0.07
	Traditional practitioner	0.94	0.67	1.40	0.16
Gender	Male	0.02	0.16	0.15	0.88
Religion	Christian	-0.85	0.56	-1.53	0.13
	Muslim	-0.83	0.61	-1.37	0.17
	Others	-0.82	0.63	-1.32	0.19
	None	-0.35	0.25	-1.40	0.16
Education level	Primary	0.04	0.19	0.23	0.82
	Secondary	22.65	181.02	0.13	0.90
	University	0.06	0.44	0.15	0.88
Marital status	Married	-0.49	0.78	-0.62	0.53
	Single	-0.34	0.80	-0.42	0.67
	Widow	0.25	0.84	0.30	0.77
Age	Old	1.18	0.31	3.79	0.00***
	Young	0.70	0.21	3.34	0.00***
Region	North	-0.14	0.24	-0.59	0.55
	South	-0.24	0.21	-1.13	0.26

Key of Table 12: Reference levels: “Central” for regions; “Female” for gender; “Adult” for the age category; “Famer” for the profession and “no formal education” for the education level, Significant effects were highlighted in bold.

4.1.4. Local community perception about ecosystem services from *U. kirkiana* in Malawi

Ecosystem services perceived by the local community in Malawi are presented in figure 5. Ecosystem services considered very important by most participants were food provision (95.5% of participants); environmental cooling (94.09%); improves air quality (90.26%), and oxygen production (86.17% of respondents). In terms of cultural services, many participants considered aesthetic role (77.49%) and provides shade (54.75%) very important. Environmental cooling and

improving air quality were considered the most important regulating services (Figure 5). Water cycling (79.3% of participants) was considered the most important supporting service. The least reported ecosystem service was habitat for birds and wildlife, windbreak and pollination and seed dispersal.

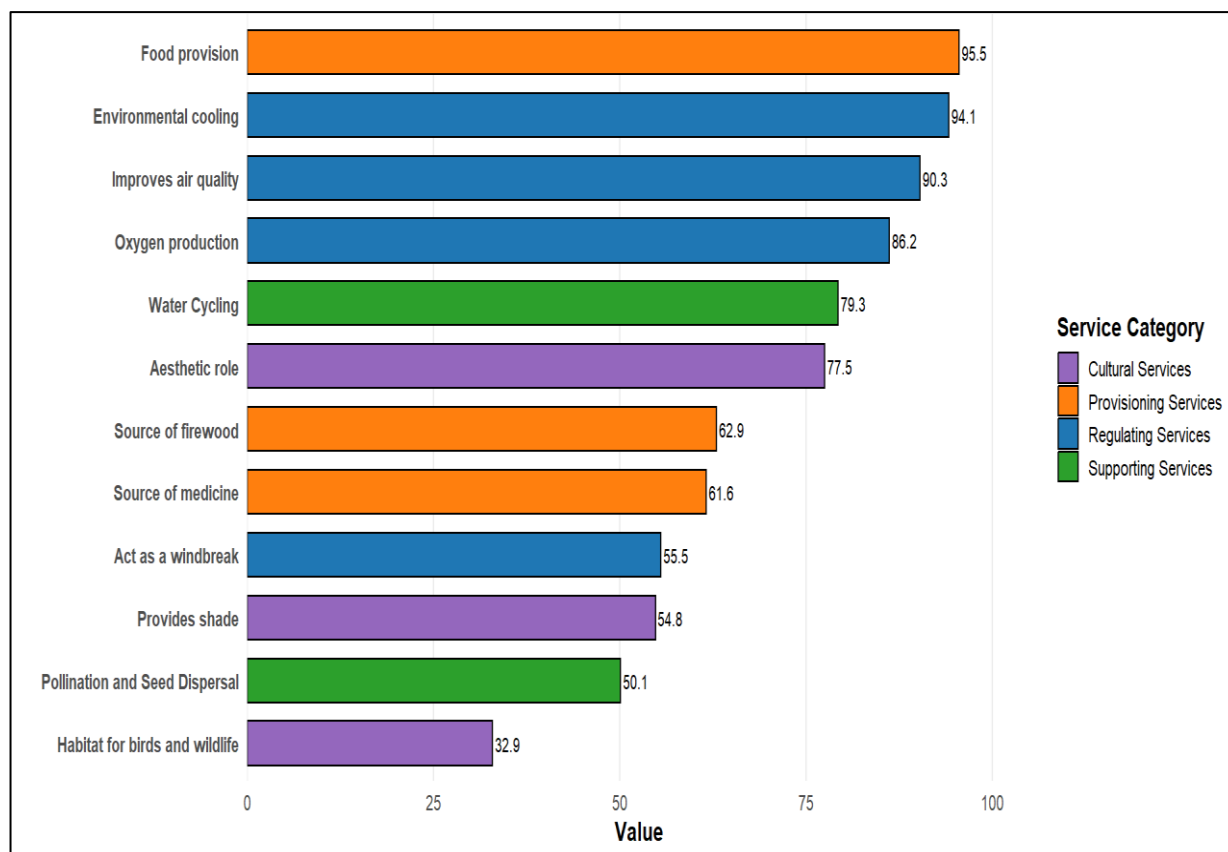


Figure 5: Relative frequency of citations (Rc, %) of ecosystem services perceived by the local community in Malawi

4.1.5. Importance of local uses and ecological vulnerability of *U. kirkiana*

The results presenting in Figure 6, shows the local use and ecological vulnerability of *U. kirkiana*. Eleven different plant parts of *U. kirkiana* in Malawi were recorded after data collection. Many respondents, in terms of frequency of citations, reported fruits (93.45% of participants), trunk (49.18%), and branch (46.81%) across the regions (Figure 6a). The least reported were flowers, kernel, sap, and seeds. Fruit and trunk were the main plant parts most cited by the respondents from these three regions North, Central and South. Fruit use varied by 84.15%; 99.64% and 98.38% in North, Central and South regions respectively (Figure 6b). Trunk was cited as the second most used

plant part in the North and Central Regions respectively at proportions of 49.78% and 91.43%. In contrast, the branch (35.63%) was cited in the South Region. Conversely, Sap, flowers and seeds were the least cited plant parts by the participants.

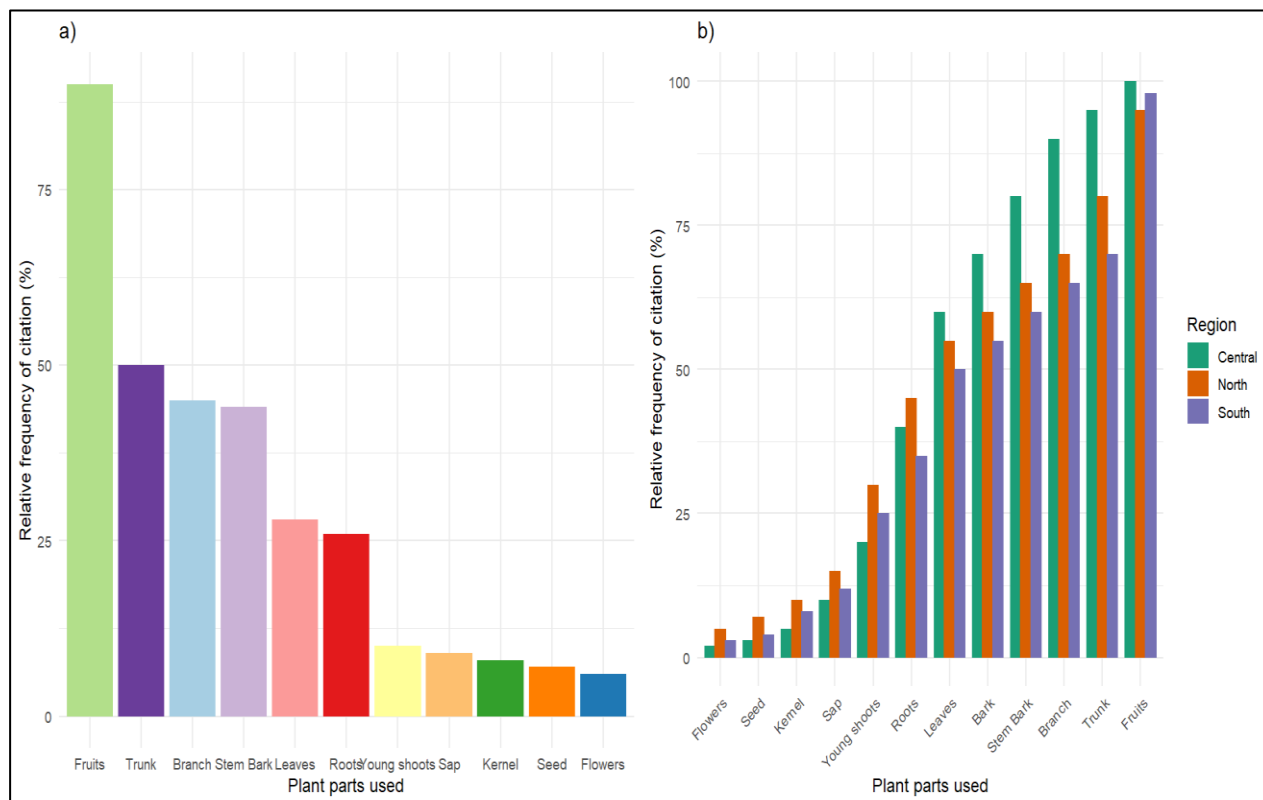


Figure 6: Relative frequency of citations (Rc, %) of plant parts used of *U. kirkiana* across the Regions of Malawi

Keys: (a) Perception of the local community across the Regions and (b) perception of the local community per regions

The distribution of ethnobotany use of *U. kirkiana* is showing in Figure 7. The types of uses across the different regions of Malawi were mainly focused on food (92%), firewood (49%) and human medicine (21.52%) (Figure 7). The used of the species for cultural practices and artisanal purposes were reported by few respondents (3%). Conversely, the cosmetics and fodder were the least reported uses. The types of use include food, human medicine (H.m), (3) energy wood (E.w), (4) service wood (S.w) and (5) others use (cultural practice, artisanal, cosmetic and forage).

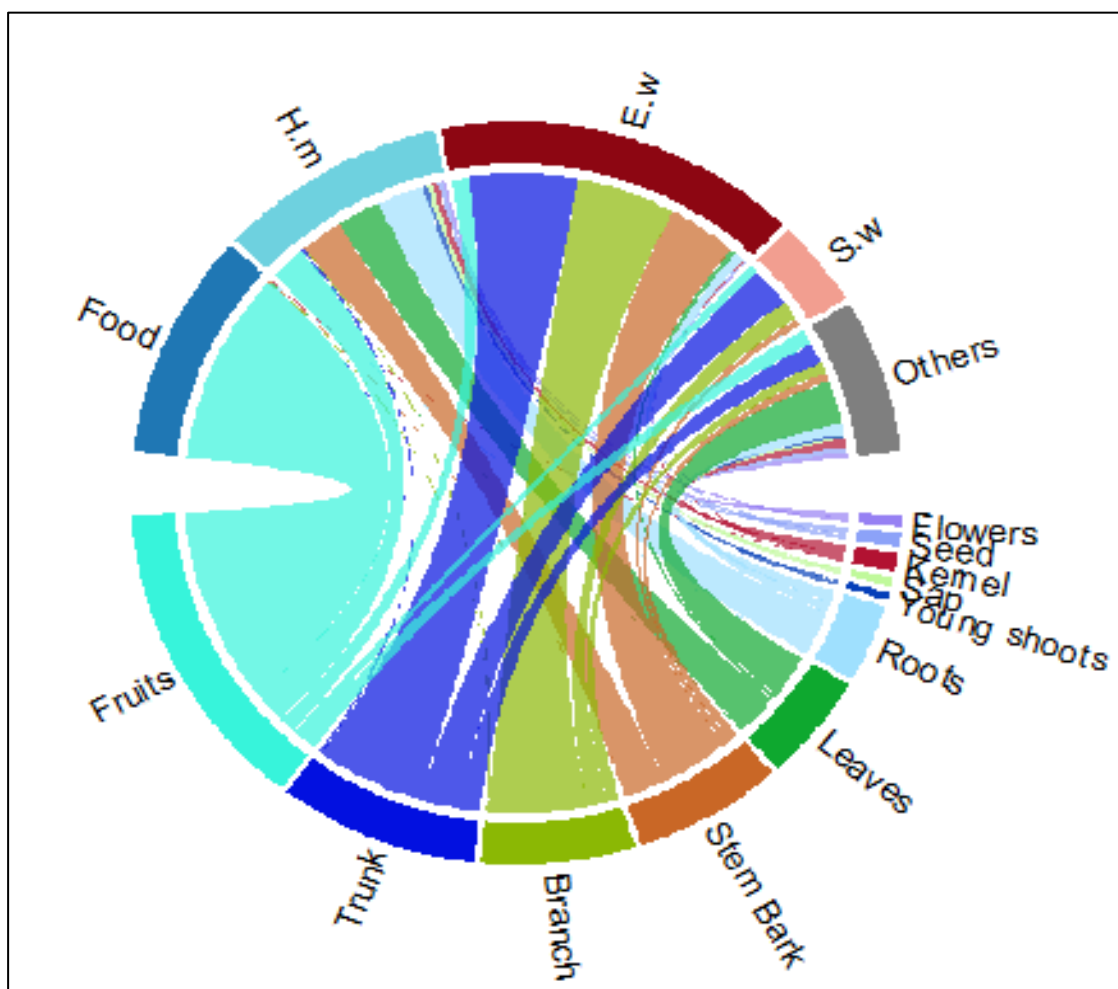


Figure 7: Chord diagram showing the distribution of ethnobotany use of *U. kirkiana*

Key: H.m (human medicine); E.w (energy wood); S.w (service wood) and others use (cultural practice, artisanal, cosmetic and forage)

The importance value of the plant parts of *U. kirkiana* is shown in Table 12. Based on the UIVI of *U. kirkiana*, the ripe fruit (2.27), leaves (1.17), stem bark (1.16) and trunk (1.14) were the most important plant parts. Knowledge of the fruit (93.5%), trunk (49.2%) and branch (47%) was higher according to the frequency of citations (Table 12). The fruit of *U. kirkiana* was the plant part with the highest number of specific uses. The young shoots, seed, sap and kernel were the least important plant parts, the least known by the participants and present the lowest used diversity indices (Table 12).

Table 12: Importance value of the plant parts of *U. kirkiana* in Malawi

Plant parts	Citation Frequency (Rc %)	Use Importance Value (UIV)	Use Diversity Index (UDI)	Use Importance Value Index (UIVI)
Fruits	0.93	0.33	1.00	2.27
Leaves	0.28	0.12	0.77	1.17
Stem Bark	0.45	0.16	0.55	1.16
Trunk	0.49	0.20	0.44	1.13
Branch	0.46	0.16	0.44	1.06
Roots	0.25	0.09	0.44	0.79
Kernel	0.05	0.02	0.44	0.51
Sap	0.05	0.00	0.44	0.50
Flowers	0.04	0.01	0.44	0.49
Seed	0.05	0.01	0.33	0.39
Young shoots	0.07	0.01	0.22	0.30

The distribution of participants by ethnic groups is shown in Table 13. The mean reported use of the plant parts of *U. kirkiana* (RU_{moyen}) varies according to ethnic groups. It is higher among the Chewa (4.5±2), the Mang'anja (3.8±1.8) and the Nyanja (3.6±1.8) (Table 13). Low RU means were observed among the Lomwe, the Tumbuka, the Yao and the Sena. Statistical tests (One-way ANOVA) showed that the variation in knowledge between ethnic groups was significant ($p \leq 0.05$).

Table 13: Distribution of participants by ethnic groups

Variables	RU mean	Group
Chewa	4.5 ± 2.0	a
Mang'anja	3.8 ± 1.8	a
Nyanja	3.6 ± 1.8	ab
Ngoni	2.9 ± 1.6	b
Nyakyusa	2.6 ± 1.6	bc
Sena	2.4 ± 1.5	bc
Yao	2.2 ± 1.4	bc
Tumbuka	1.9 ± 1.4	c
Lomwe	1.5 ± 1.3	d

Key: *Means that do not share the same letters are significantly different. Tukey's test was applied after ANOVA to determine the groups that was significantly different from each other. Letters (a, b, c, and d) were assigned to groups with significant differences

Similarity of *U. kirkiana* use by ethnic groups in Malawi according to Sorensen index are presented in Table 14. The Sorensen index, with values less than or equal to 0.55, showed that each ethnic group knew less than half of the uses which the other group knew (Table 15). The highest knowledge similarities were observed between the Yao and Chewa (IS = 0.77), Tumbuka and the Yao (IS = 0.77), and the Yao and the Ngoni (IS = 0.76). Moderate similarities were found between the Nyakyusa and Chewa (IS = 0.57), and the Ngoni and Nyakyusa (IS = 0.57). The lowest similarities were recorded between the Tumbuka and the Tonga (IS = 0.55) and the Mang'anja and the Yao (IS = 0.55).

Table 14: Similarity of *U. kirkiana* use by ethnic groups in Malawi according to Sorensen index

	Chewa	Lomwe	Mang'anja	Ngoni	Nyakyusa	Nyanja	Sena	Tonga	Tumbuka
Lomwe	0.11								
Mang'anja	0.25	0.13							
Ngoni	0	0.12	0.25						
Nyakyusa	0.57	0.46	0.36	0.57					
Nyanja	0.25	0.13	0	0.25	0.33				
Sena	0.4	0.29	0.15	0.4	0.18	0.15			
Tonga	0.11	0	0.13	0.11	0.46	0.27	0.29		
Tumbuka	0	0.12	0.12	0	0.62	0.25	0.40	0.12	
Yao	0.77	0.33	0.55	0.76	0.22	0.54	0.40	0.67	0.77

The result on the specific uses of *U. kirkiana* according to ages is presenting in table 15. The average number of uses of *U. kirkiana* reported by respondents was in the age groups between 19 and 29 years, 30 and 59 years, and over 60 years is 2.57 ± 2 ; 3.2 ± 1.8 , and 3.6 ± 1.9 , respectively.

Table 15: Mean specific uses of *U. kirkiana* according to ages

Age	RU mean
Young	2.57 ± 2.00
Adult	3.2 ± 1.80
Old	3.6 ± 1.90

Key: Fisher test ($p = 0.32$), show that there is no significant difference in knowledge of uses based on age

The result on the specific uses of *U. kirkiana* according to gender is presented in table 16. The respondents (under 30 years old) have less knowledge (2.7 ± 2). However, the Fisher test ($p = 0.32$) shows that there is no significant difference in knowledge of use according to age. Regarding gender, the average knowledge of *U. kirkiana* uses was 3.18 ± 1.56 for male and 2.90 ± 1.50 for female, Table 16.

Table 16: Mean specific uses of *U. kirkiana* according to Gender

Gender	RU mean
Man	3.18 ± 1.56
Woman	2.90 ± 1.50

Key: Fisher's tests show that there is a significant difference ($p \leq 0.05$) in knowledge of *U. kirkiana* use between genders.

Results on the mean specific uses of *U. kirkiana* according to education level is presenting in Table 17. Fisher's tests showed that there is a significant difference ($p \leq 0.05$) in knowledge of *U. kirkiana* uses between the genders. In terms of educational level, the mean number of uses of *U. kirkiana* reported by participants with more knowledge is 3.87 ± 1.93 and 3.50 ± 1.78 for those with no education and primary education, respectively (Table 17). Participants with university education have less knowledge (2.45 ± 1.78). However, Fisher's test ($p \leq 0.05$) indicates a significant difference in knowledge of uses according to education level.

Table 17: Mean specific uses of *U. kirkiana* according to education level

Education Level	RU mean	Group*
High school	3.04 ± 1.65	a
None	3.87 ± 1.93	ab
Primary	3.50 ± 1.78	ab
Secondary	3.39 ± 1.85	bc
University	2.45 ± 1.78	c

Key: *Means that do not share the same letters (e.g., a and b) are significantly different according to Tukey's test at a 5% significance level. Means sharing the same letter (e.g., ab) do not show significant differences in usage knowledge. Fisher's test ($p \leq 0.05$) shows that there is significant difference in the knowledge of uses according to the education level

The findings obtained from the vulnerability index of the different plant parts and overall, of *U. kirkiana* according to the use by local communities is presented in Figure 8. The vulnerability index of *U. kirkiana* was $I_v = 2.25$, a value close to less than 2.5 which showed that the species is moderately vulnerable in Malawi (Figure 8). Conversely, the most vulnerable plant parts were respectively the trunk (2.6), roots (2.4), and stem bark (2.4).

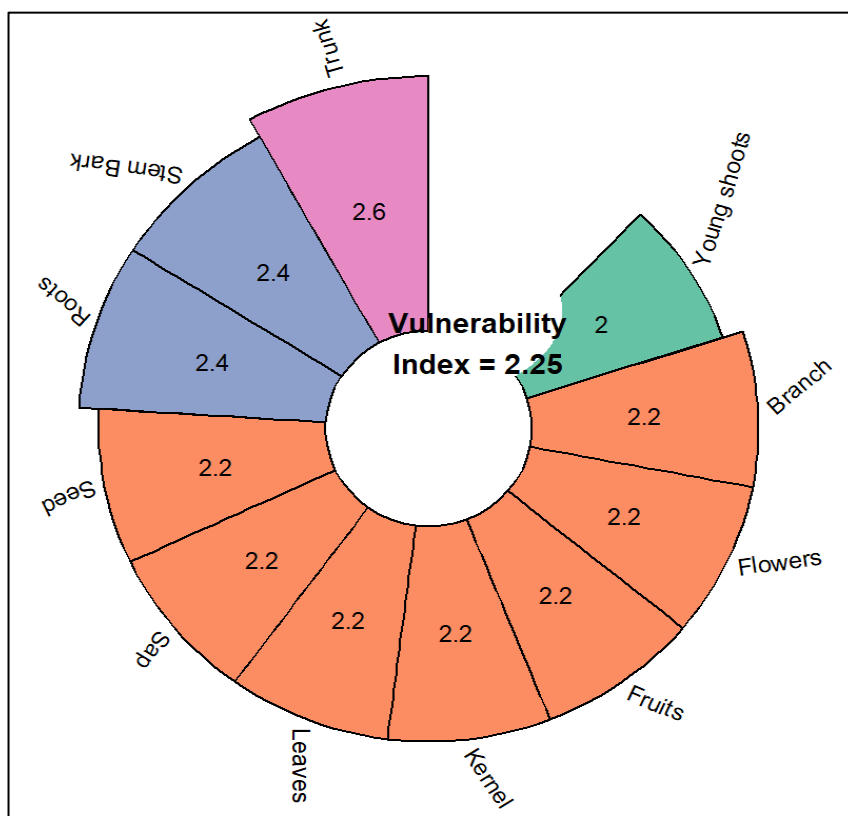


Figure 8: Vulnerability index of the different plant parts and overall, of *U. kirkiana* according to the use by local communities

Key: At the center of the doughnut chart, the vulnerability index of *U. kirkiana* was indicated in the country

4.2 Species composition and phylogenetic patterns along elevation gradients

4.2.1 Community species composition and demographic structure in different elevation area

Table 18 showed the frequency of vegetative importance of the dominant botanical family. In the 149 surveyed plots, we recorded 5,706 individuals of woody plants, representing 124 species across 89 genera and 39 botanical families (Appendix 5). The flora was mainly represented by the Fabaceae (42 species), followed by Phyllanthaceae (9 species), Rubiaceae (8 species) and Anacardiaceae (5 species), which together contributed 51.61% of the total richness (Table 18). Analysis of species frequencies highlighted that habitats of *U. kirkiana* were chiefly dominated by *Uapaca sansibarica* Pax (12.49%), while other abundant taxa included *Brachystegia spiciformis* Benth. (6.98%), *Brachystegia taxifolia* Harms (6.84%), *Parinari curatellifolia* Planch. ex Benth. (5.63%), *Julbernardia paniculata* (Benth.) Troupin (4.14%), *Combretum molle* R. Br. ex G. Don

(3.56%), *Brachystegia longifolia* Benth. (3.20%), *Brachystegia floribunda* Benth. (3.17%), and *Syzygium guineense* (Willd.) DC. (3.01%).

Table 18: Frequency of vegetative importance (FIV) of the dominant botanical family

Forest	Family	FIV
Chongoni	Fabaceae	114
	Phyllanthaceae	86.3
	Phyllanthaceae	90.3
Dzalanyama	Fabaceae	46.4
	Chrysobalanaceae	16.3
	Phyllanthaceae	97.5
	Fabaceae	30.7
Kan'ingina	Myrtaceae	27.8
	Chrysobalanaceae	25
	Phyllanthaceae	113
	Chrysobalanaceae	29.6
Mangochi	Fabaceae	28.9
	Fabaceae	112
	Phyllanthaceae	50.7
Perekezi	Combretaceae	26.6
	Phyllanthaceae	73.6
	Annonaceae	30.4
	Fabaceae	24
	Anacardiaceae	20.1
Zomba	Myrtaceae	15

Key: Chongoni forest= 1600-1770m, Dzalanyama forest= 1150-1295m, Kan'ingina forest= 1250-1370m, Malosa forest= 850-950m, Mangochi forest= 700-800m, and Perekezi forest= 1500-1600m.

The Structural indices of the six natural forests studied across their elevation in Malawi are presented in Table 19. In the Chongoni forest, the Fabaceae family is predominant with an IVI of 114, followed by Phyllanthaceae (86.3) (Table 19). In the Kaning'ina forest, Phyllanthaceae maintains a dominant position (FIV = 97.5), accompanied by secondary contributions from Fabaceae (30.7), Myrtaceae (27.8), and Chrysobalanaceae (25.0). The Mangochi forest also shows a clear dominance of Phyllanthaceae (FIV = 113), followed by Chrysobalanaceae (29.6) and Fabaceae (28.9). Finally, in the Zomba forest, the family distribution is characterised by a moderate dominance of Phyllanthaceae (73.6), followed by Annonaceae (30.4), Fabaceae (24.0), Anacardiaceae (20.1), and Myrtaceae (15.0). Overall, the Fabaceae and Phyllanthaceae appear as the two most structuring families in the majority of the studied areas, although their relative dominance varies from one elevation to another.

The structural analysis of the six natural forests of Chongoni, Dzalagnama, Kaning'ina, Malosa, Mangochi, and Perekezi revealed notable variations between the sites regarding the distribution of diameter classes (Table 19). The Permutation Index (PI), used to quantify the level of disorganization in the diameter structure, displayed values ranging from 0.37 (Chongoni) to 0.59 (Mangochi). Skewness, which indicates the asymmetry of the diameter distribution, was positive in all forests, with values ranging from 1.09 (Chongoni) to 1.57 (Dzalagnama). Kurtosis, which evaluates the degree of concentration of the data around the mean, ranged from 3.93 to 10.30. The lowest values were observed in Chongoni (3.93) and Malosa (3.95), while the highest value was recorded in Perekezi (10.30). Regarding structural inequality indices, the Gini index ranged from 0.22 (Mangochi and Perekezi) to 0.32 (Malosa), reflecting varying levels of inequality in the distribution of diameters. The Shannon index, which measures the diversity of diameter classes, showed values ranging from 0.64 (Mangochi) to 1.11 (Chongoni).

Table 19: Structural indices of the six natural forests studied across their elevation in Malawi

Forest	Permutation				
	Index	Skewness	Kurtosis	Gini	Shannon
Chongoni forest	0.37	1.09	3.93	0.28	1.11
Dzalagnama forest	0.54	1.57	5.42	0.30	0.86
Kan'ingnina forest	0.43	1.14	4.19	0.30	0.99
Malosa forest	0.46	1.17	3.95	0.32	0.99
Mangochi forest	0.59	1.14	4.57	0.22	0.64
Perekezi forest	0.50	1.41	10.30	0.22	0.73

Key: Chongoni forest= 1600-1770m, Dzalanyama forest= 1150-1295m, Kaning'ina forest= 1250-1370m, Malosa forest= 850-950m, Mangochi forest= 700-800m, and Perekezi forest= 1500-1600m.

The diameter structure of woody plant communities across six forest sites distributed along an elevation gradient in Malawi was assessed using diameter at breast height (DBH) classes, grouped in 5 cm intervals and is presented in Figure 9. The frequency distribution of trees densities per DBH class was modeled using the three-parameter Weibull distribution. For each elevation zone, the fitted curves are represented with corresponding parameter estimates: the location parameter (a), scale parameter (b), and shape parameter (c) (Fig. 9a-f). Across all elevation sites, tree density was consistently highest in the smallest diameter classes, particularly in the [5-10[cm and [10-15[cm intervals, with a progressive decline observed toward larger diameter classes. This trend was maintained across elevations, although variations in the magnitude of densities and curve shapes were observed between sites. Despite a consistent dominance of lower diameter classes across the elevation gradient, moderate differences were noted in the estimated Weibull parameters (a, b, and c) among the forest sites. The highest elevation band (1600-1770 m; Figure 9a) yielded parameters of $a=1.43$, $b=17.1$, and $c=1.79$. In contrast, the site at 1150-1295 m (Figure 9b) presented the lowest shape parameter, $a=0.901$, alongside $b=13.9$ and $c=1.67$. The highest shape parameter was observed at the 1250-1370 m site (Figure 9c), with values of $a=2.85$, $b=13.0$, and $c=1.48$, closely followed by the 1500-1600 m site (Figure 9f), which had estimates of $a=2.61$, $b=11.8$, and $c=1.97$. Finally, the lower elevation sites displayed similar shape parameters, with the 850-950 m site (Fig.

3d) showing $a=2.21$, $b=13.4$, and $c=1.45$, and the 700-880 m site (Figure 9e) exhibiting $a=2.17$, $b=10.7$ and $c=1.90$.

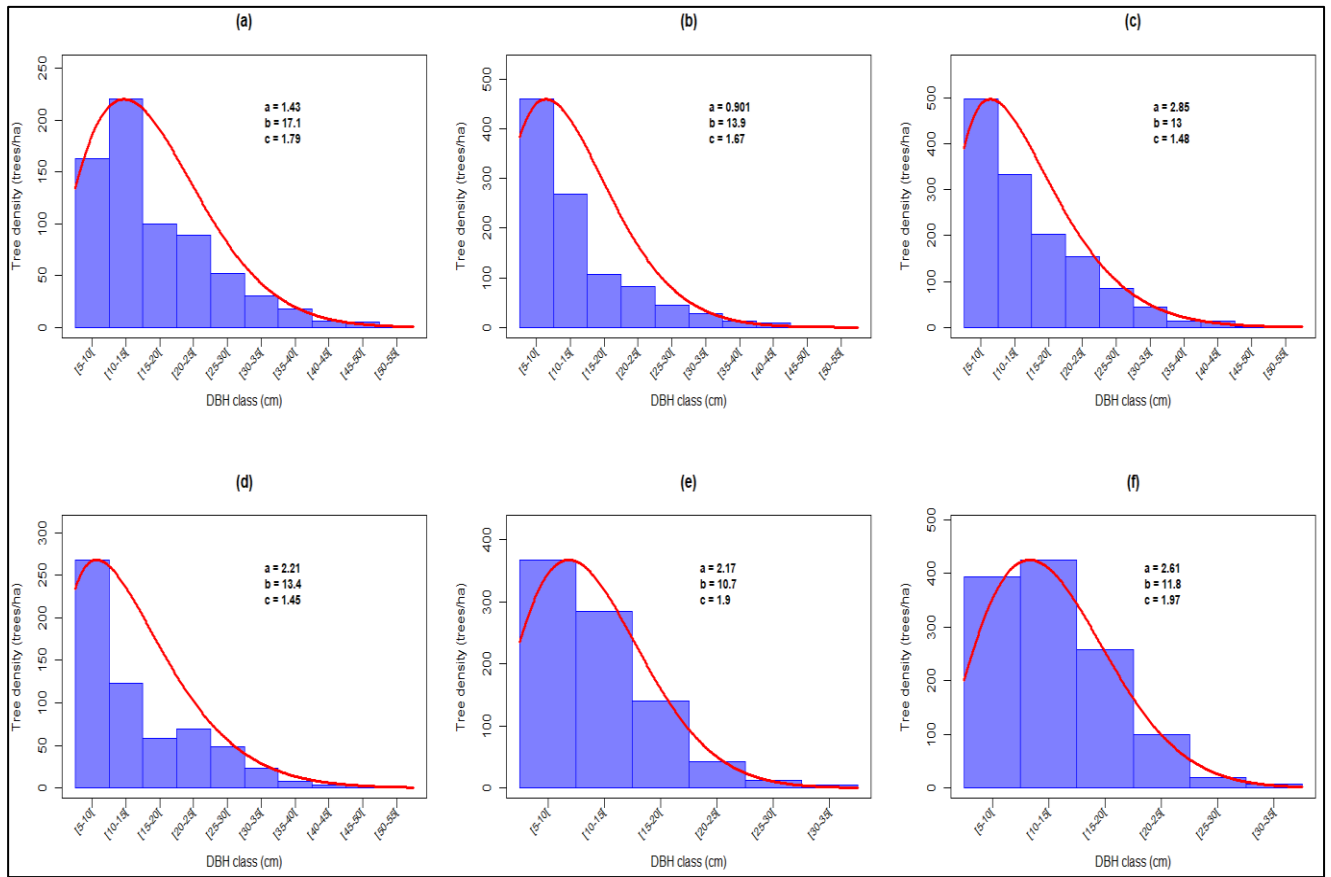


Figure 9: Distribution of diameter class structure across elevation gradient in Malawi, with Weibull Key: a= Chongoni forest (1600-1770m); b= Dzalanyama forest (1150-1295m); c= Kaning'ina forest (1250-1370m); d= Malosa forest (850-950m); e= Mangochi forest (700-800m) and f= Perekezi forest (1500-1600m.)

4.2.2 Phylogenetic diversity and the analysis of similarity in different elevation area

The result obtained from the change of community phylogenetic diversity and SES.PD with the elevation gradient is shown in Figure 10. Along the elevational gradient, the Standardized Effect Size of Phylogenetic Diversity (SES.PD) showed a significant non-linear relationship with elevation (Figure 10B). The generalised additive model (GAM) revealed a strong fit ($R^2 = 0.86$, $P < 0.001$), highlighting a pattern where SES.PD increased at low elevation, decreased at mid-elevation, and sharply increased again at higher elevation. The result of the trend fitting ($R^2 = 0.05$, $p = 0.51$) showed that the community phylogenetic diversity index first decreased and then increased with elevation (Figure 10A and B). Meanwhile, our result showed that the species

richness was significantly positively correlated with the phylogenetic diversity index. Trend lines were modeled via general additive models (GAMs) to show general trends of the PD with elevation. In contrast, the Phylogenetic Diversity (Hardcastle) index displayed a significant negative linear relationship with elevation ($R^2 = 0.2$, $P < 0.001$; Fig. 10A). The fitted linear model indicated that PD tends to decrease as elevation increases, though with notable variation among sites, particularly at mid-elevations, where local maxima in PD were also observed.

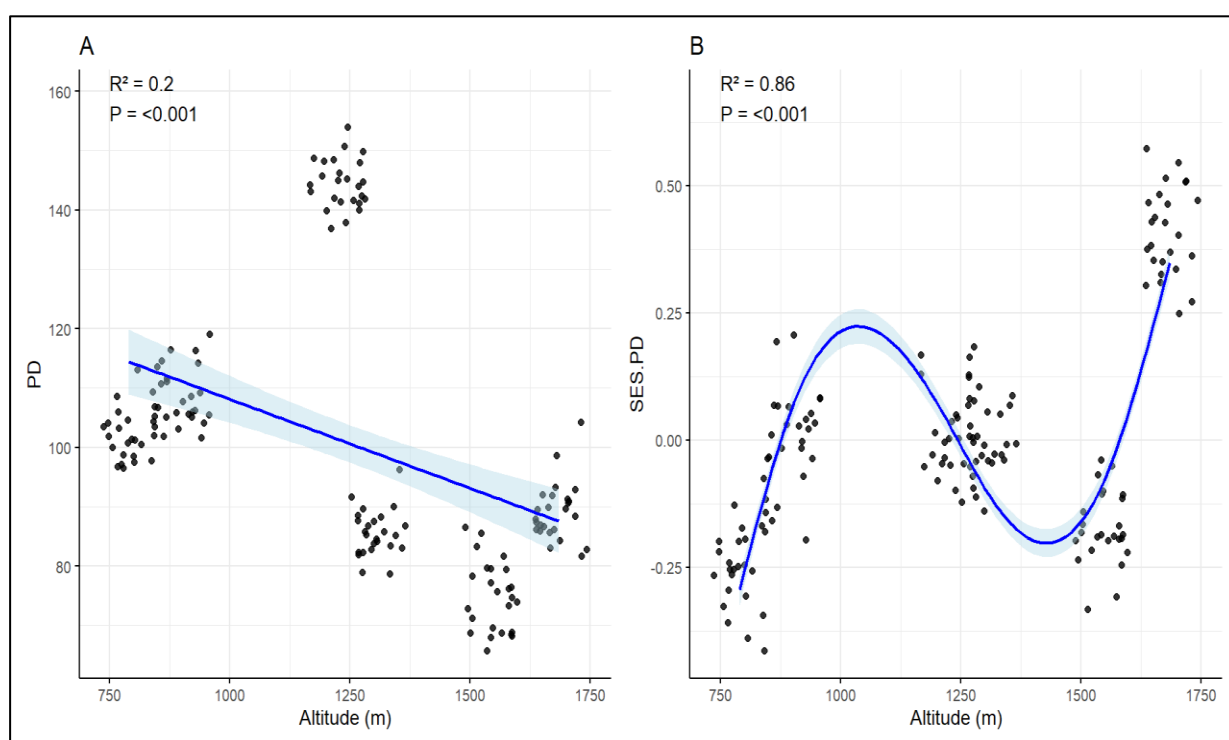


Figure 10: The change of community PD and SES.PD with the elevation gradient

Key: PD, Phylogenetic diversity; SES.PD, Standardized effect size of PD. In Figure A, the black dots are actual measured values, the blue line is the fitted value, and the shading is the 95 % confidence interval. In Figure B, the solid blue line corresponds to a generalized additive model (GAM) presented to better examine the trend and the shading is the 95 % confidence interval; Chongoni forest= 1600-1770m, Dzalanyama forest= 1150-1295m, Kaning'ina forest= 1250-1370m, Malosa forest= 850-950m, Mangochi forest= 700-800m, and Perekezi forest= 1500-1600m.

The result in Figure 11 is shown the analysis of plots based on the community structure of woody plants. The principal coordinate's analysis (PCoA) revealed not clear patterns in the phylogenetic composition of woody communities along the elevation gradient in Malawi (Figure 11). The first two axes explained a cumulative proportion of variance of 100%, with PCoA Axis 1 accounting for 33.32% and PCoA Axis 2 for 66.68% of the total variance in phylogenetic structure.

Communities distributed along these axes showed a notable differentiation between elevation classes, represented by colored points according to their elevation ranges.

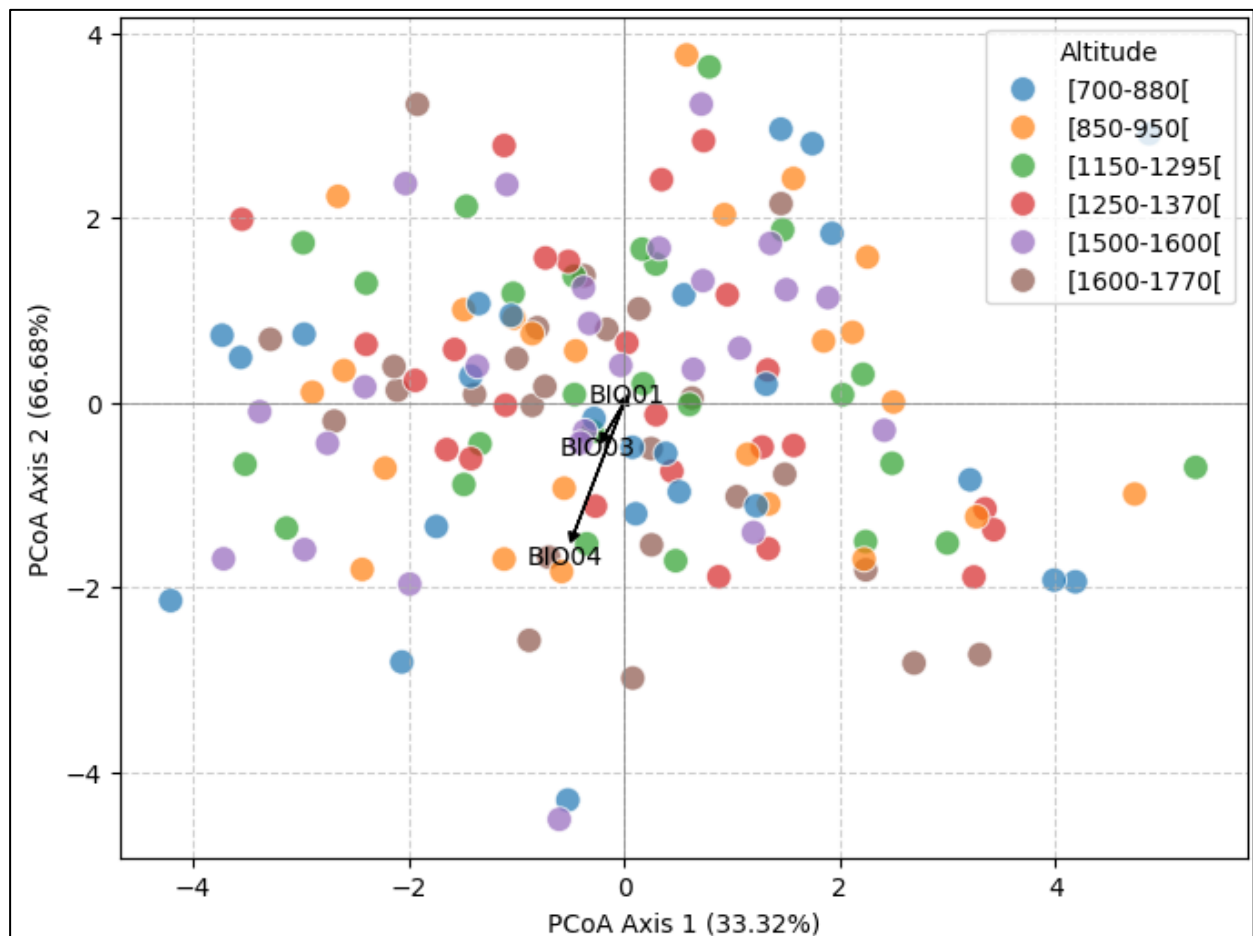


Figure 11: Principal coordinate Analysis of plots based on the community structure of woody plants

Key: Chongoni forest= 1600-1770m, Dzalanyama forest= 1150-1295m, Kaning'ina forest= 1250-1370m, Malosa forest= 850-950m, Mangochi forest= 700-800m, and Perekezi forest= 1500-1600m. BIO01= Annual Mean Temperature, BIO03= Isothermality, BIO04= Temperature Seasonality

Environmental fitting procedures (envfit) indicated that three climatic variables significantly influenced the ordination of communities ($p < 0.05$) is shown in table Table 20: Annual Mean Temperature; $p = 0.0017$, Isothermality; $p = 0.0374$ and Temperature Seasonality; $p = 0.00001$ (Table 20).

Table 20: Environmental factors fitted on to PCoA axes

Variable	P_value
Annual Mean Temperature	0.00
Isothermality	0.03
Temperature Seasonality	0.00
Temperature of Warmest Month	0.95
Temperature of Warmest Quarter	0.45

The corresponding vectors for these variables were overlaid on the ordination plot, showing distinct directions and magnitudes and are presented in Table 21. Among them, BIO04 exhibited the strongest gradient, followed by BIO03 and BIO01, based on vector lengths and orientations in ordination space. The variables Max Temperature of Warmest Month and Mean Temperature of Warmest Quarter were not statistically significant ($p > 0.05$) and thus were excluded from the vector fitting.

Table 21: Vector coordinates for significant environmental variables

Variable	Dim1	Dim2
Annual Mean Temperature	0.05	0.15
Isothermality	-0.44	-0.87
Temperature Seasonality	-0.99	-3.02

Key: Dim1 and Dim2: These are the first two principal components (PCs) of the dataset. Dim1 captures the largest amount of variation in the dataset. Dim2 (or PC2) captures the second-largest amount of variation, orthogonal (uncorrelated) to Dim1. Together, Dim1 and Dim2 provide a reduced-dimension view of the dataset, showing the main gradients of variation among the variables.

4.2.3 Differences among the phylogenetic community compositions in the different elevation areas

Variation in multiple phylogenetic diversity and structure metrics was assessed across six altitudinal classes along the elevation gradient in Malawi (Figure 12). Faith's Phylogenetic Diversity (Faith_PD) exhibited significant differences between elevation bands, with the highest values recorded in the lowest ([1150-1295[) and highest ([1600-1770[) classes. Statistical

groupings based on pairwise comparisons revealed distinct differences in phylogenetic richness among elevation zones. Mean Nearest Taxon Distance (MNTD) values remained relatively stable across elevation bands, showing no consistent directional pattern.

In contrast, Mean Pairwise Distance (MPD) values were slightly reduced in the mid-elevation class ([1500-1600[), while remaining comparable across other sites. Net Relatedness Index (NRI) and Nearest Taxon Index (NTI) showed variable patterns across the gradient. NTI values were negative in the lowest elevation class and shifted to positive values in mid and high elevation bands. Significant differences among elevation classes were observed for both indices, with NTI displaying clearer distinctions. NRI showed greater variability between classes but followed a similar elevation related shift.

The standardised effect sizes of MPD (SES_MPD) and MNTD (SES_MNTD) also varied with elevation. SES_MPD showed a pronounced increase at mid elevation ([1500-1600[), while SES_MNTD exhibited more uniform values, with a modest increase in the highest elevation class. Statistical comparisons confirmed significant variation in these indices across elevation bands.

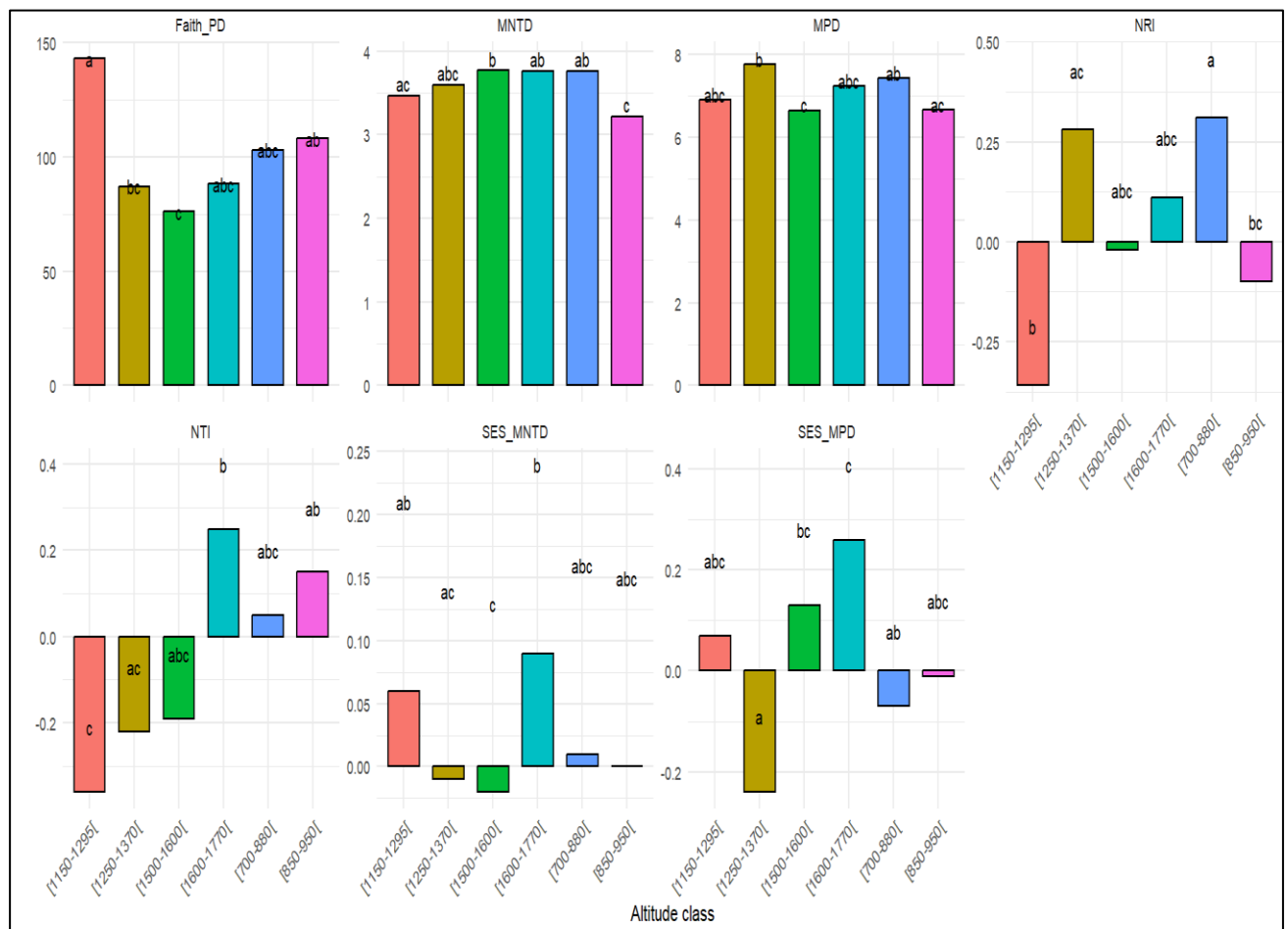


Figure 12: Variation of phylogenetic diversity and structure indices across different elevation classes in Malawi

Key: The metrics presented include Faith's Phylogenetic Diversity (Faith_PD), Mean Pairwise Distance (MPD), Standardized Effect Size of MPD (SES_MPD), Net Relatedness Index (NRI), Mean Nearest Taxon Distance (MNTD), Standardized Effect Size of MNTD (SES_MNTD), Nearest Taxon Index (NTI), and Standardized Effect Size of Phylogenetic Diversity (SES_PD). Six altitudinal classes ranging from 700 to 1770 m. Bars represent means $\pm$ standard errors group values. Different lowercase letters (e.g., a, b) indicate statistically significant differences among elevation classes based on pairwise comparisons ($p < 0.05$); Chongoni forest= 1600-1770m, Dzalanyama forest= 1150-1295m, Kaning'ina forest= 1250-1370m, Malosa forest= 850-950m, Mangochi forest= 700-800m, and Perekezi forest= 1500-1600m

4.2.4 Community phylogenetic structure responses to elevation and environmental factors

The results show the regression analyses between community phylogenetic structure metrics and elevation in presented in figure 13. Along the elevational gradient, the Net Relatedness Index (NRI) did not show a statistically significant relationship with elevation ($R^2 = 0.01$, $P = 0.3$; Figure 13A). Similarly, the Nearest Taxon Index (NTI) exhibited no significant correlation with elevation ($R^2 = 0.00$, $P = 0.4$; Figure 13B). Linear regression models were fitted to assess the relationship between

elevation and these indices. The results indicate that neither NRI nor NTI vary significantly with changes in elevation across the studied gradient. The data points and regression lines is shown in Figure 13A and B respectively.

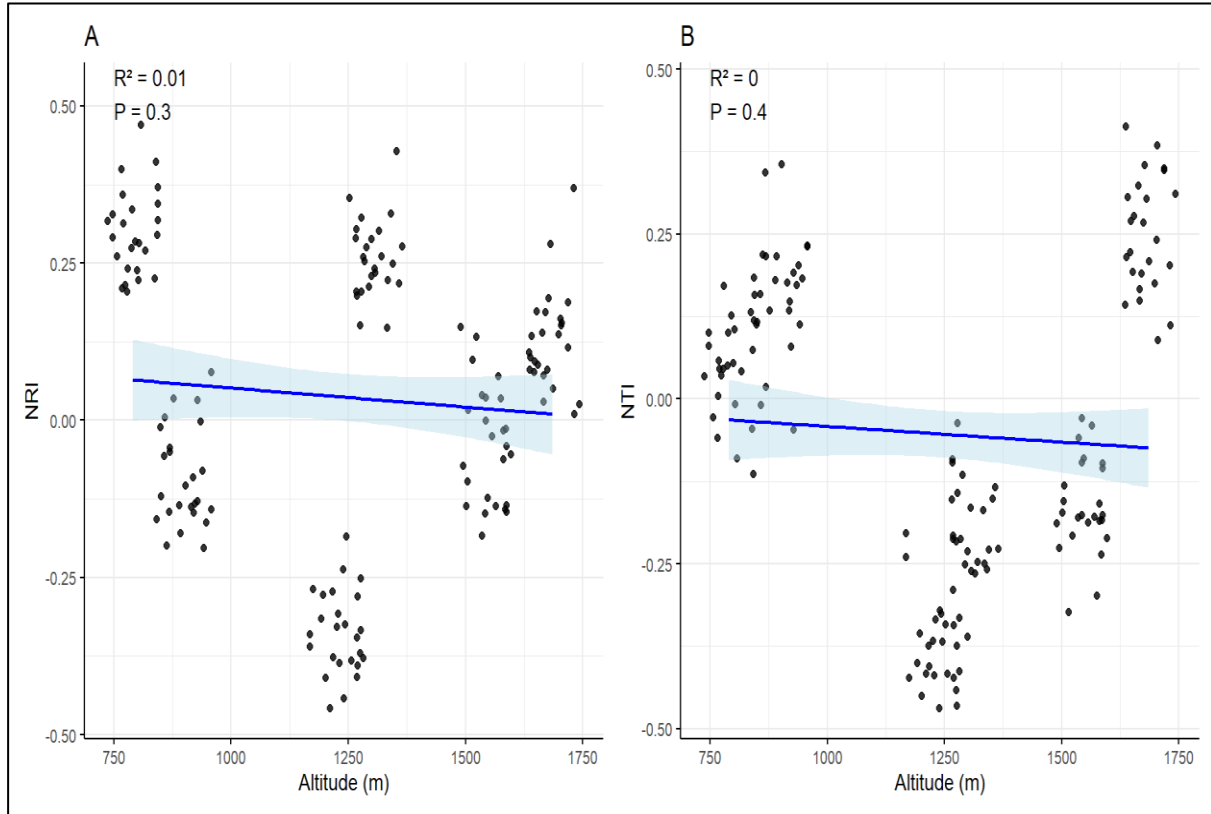


Figure 13: Regression analyses between community phylogenetic structure metrics and elevation

Key: the black dots are actual measured values, the blue line is the fitted value, and the shading is the 95 % confidence interval; Chongoni forest= 1600-1770m, Dzalanyama forest= 1150-1295m, Kaning'ina forest= 1250-1370m, Malosa forest= 850-950m, Mangochi forest= 700-800m, and Perekezi forest= 1500-1600m

Correlations between phylogenetic diversity indices and environmental variables were analyzed (Figure 14). For the Faith_PD index, strong and statistically significant positive correlations were observed with variables BIO03 ($r = 0.934$; $p = 0.0065$), BIO16 ($r = 0.892$; $p = 0.0170$) and BIO18 ($r = 0.861$; $p = 0.0275$). Other positive but non-significant correlations were found with BIO12 ($r = 0.729$; $p = 0.1003$), BIO05 ($r = 0.696$; $p = 0.1250$), and BIO11 ($r = 0.614$; $p = 0.1944$). Moderate negative correlations were found with HWSD ($r = -0.670$; $p = 0.1454$) and altitude ($r = -0.455$; $p = 0.3643$). The observed MPD index showed a positive correlation with BIO19 ($r = 0.737$; $p =$

0.0947), while moderate positive correlations were noted with Phosphorus ($r = 0.659$; $p = 0.1542$) and SOIL_DEPTH ($r = 0.612$; $p = 0.1969$). The other variables showed weak and insignificant correlations. For the Net Relatedness Index (NRI), moderate to strong negative correlations were recorded with BIO03 ($r = -0.768$; $p = 0.0746$), BIO16 ($r = -0.686$; $p = 0.1323$), and BIO18 ($r = -0.626$; $p = 0.1835$).

A positive correlation was observed with BIO19 ($r = 0.758$; $p = 0.0806$). The Nearest Taxon Index (NTI) showed a strong negative correlation with BIO12 ($r = -0.799$; $p = 0.0564$), followed by BIO18 ($r = -0.633$; $p = 0.1775$) and Phosphorus ($r = -0.657$; $p = 0.1566$). The other variables showed weak correlations. The observed MNTD index showed moderate negative correlations with Aridity ($r = -0.685$; $p = 0.1329$), Nitrogen ($r = -0.637$; $p = 0.1741$), and BIO04 ($r = -0.567$; $p = 0.2406$), while altitude showed a moderate positive correlation ($r = 0.432$; $p = 0.3926$). For SES_MNTD, the strongest correlations were observed with Nitrogen ($r = -0.648$; $p = 0.1639$) and BIO19 ($r = -0.594$; $p = 0.2135$), but did not reach statistical significance. For SES_MPD, a strong negative correlation was found with BIO19 ($r = -0.895$; $p = 0.0159$). Significant negative correlations were also found with SOIL_DEPTH ($r = -0.770$; $p = 0.0732$) and Phosphorus ($r = -0.769$; $p = 0.0738$). Finally, for SES_PD, no significant correlation was detected. The highest coefficients were observed with HWSD ($r = 0.579$; $p = 0.2287$), BIO12 ($r = -0.531$; $p = 0.2783$), and BIO04 ($r = -0.520$; $p = 0.2904$), all of which were non-significant.

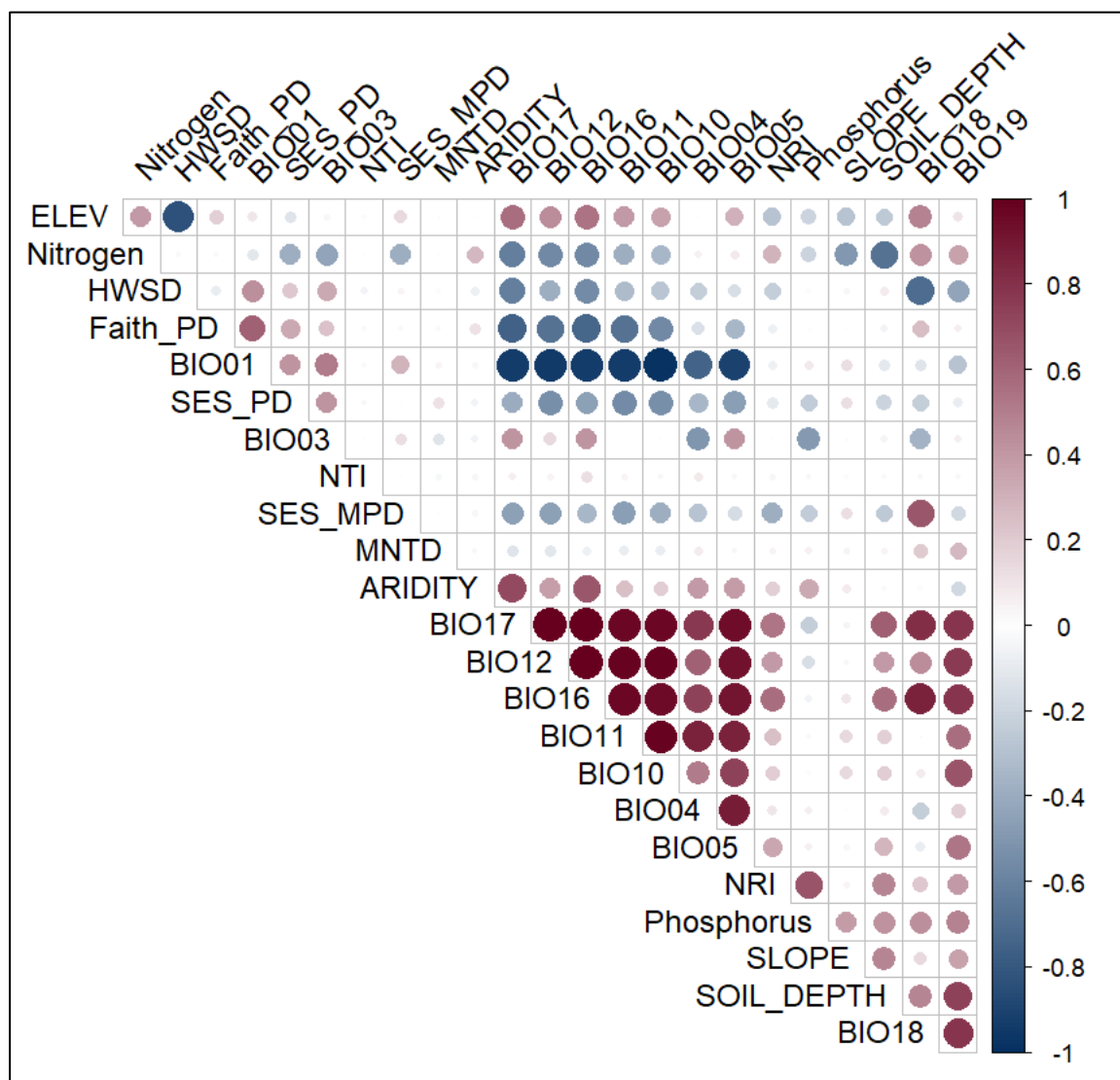


Figure 14: Correlations between phylogenetic diversity indices and environmental variables across the ecological gradient

Key: Faith_PD = Faith's Phylogenetic Diversity; MPD = Mean Pairwise Distance; SES_MPD = Standardized Effect Size of MPD; NRI = Net Relatedness Index; MNTD = Mean Nearest Taxon Distance; SES_MNTD = Standardized Effect Size of MNTD; NTI = Nearest Taxon Index; Aridity = Aridity index; BIO01 = Annual Mean Temperature; BIO03 = Isothermality; BIO04 = Temperature Seasonality; BIO05 = Max Temperature of Warmest Month; BIO10 = Mean Temperature of Warmest Quarter; BIO11 = Mean Temperature of Coldest Quarter; BIO12 = Annual Precipitation; BIO16 = Precipitation of Wettest Quarter; BIO18 = Precipitation of Warmest Quarter; BIO19 = Precipitation of Coldest Quarter; Elev = Elevation; HWSD = Harmonized World Soil Database

The circular phylogenetic tree, Figure 15 illustrates the evolutionary relationships among the 89 woody species recorded across all sampling plots. These species belong to multiple families and genera and are organized according to their phylogenetic positions. Branch lengths correspond to evolutionary divergence based on the underlying phylogenetic dataset. Several distinct clades were

4.3 Functional trait variation of *Uapaca kirkiana* across eco-geographical regions

4.3.1 Morphological variability of *U. kirkiana* among geographical region

U. kirkiana showed a considerable variability in morphological and functional traits across the three geographical regions studied (Table 22). Many traits, which included fruit shape (CV = 138.13%), seed weight (CV = 34.64%) and mass loss by desiccation (CV = 30.04%), showed significant dispersion (CV > 30%) in the Central region, which showed the highest variability (Table 22). Regional differences in fruit traits, including fruit weight and seed weight, were significant ($p < 0.05$), with the Central region recording lower average values than the North and South (Table 22). Fruit width, length, and number of seeds, on the other hand, were not significantly different ($p > 0.05$). The North had higher mean values for fresh leaf weight and leaf water content than the other regions. On the one hand, in an argument that precedes it, there was a regional variation in the mean leaf shape (1.75 ± 0.15) and the mass loss by desiccation was intermediate in the South. Total height and canopy height were the growth-related morphological traits that varied significantly ($p < 0.05$), with individuals from the Central region being shorter than those from the North and South. Additional traits such as canopy diameter, basal diameter and diameter at breast height (DBH) showed high coefficients of variation (CV > 50%), especially in the South (Table 22).

Table 22: Variation of the morphological traits of *U. kirkiana* among geographical regions

Traits	Statistics	North	Central	South
Fruit traits				
Shape fruit	Mean $\pm$ std	1 $\pm$ 0.07 ^a	1.39 $\pm$ 1.92 ^a	0.98 $\pm$ 0.04 ^a
	CV (%)	7	138.13	4.08
Fruit weight	Mean $\pm$ std	20.16 $\pm$ 5.28 ^a	15.25 $\pm$ 5.21 ^b	18.47 $\pm$ 4.19 ^a
	CV (%)	26.19	34.16	10.5
Fruit length	Mean $\pm$ std	31.72 $\pm$ 2.77 ^a	31.19 $\pm$ 2.17 ^a	31.23 $\pm$ 2.76 ^a
	CV (%)	8.73	6.95	8.83
Fruit width	Mean $\pm$ std	32.18 $\pm$ 2.91 ^a	31.09 $\pm$ 2.14 ^a	31.45 $\pm$ 2.81 ^a
	CV (%)	9.04	6.88	7.41
Seed traits				
Number of seed	Mean $\pm$ std	3.67 $\pm$ 0.28 ^a	3.49 $\pm$ 0.28 ^a	3.57 $\pm$ 0.26 ^a
	CV (%)	7.63	8.02	7.28
Seed weight	Mean $\pm$ std	6.95 $\pm$ 2.08 ^a	4.59 $\pm$ 1.59 ^b	6.61 $\pm$ 1.69 ^a

	CV (%)	29.92	34.64	25.56
Leaf morphological traits				
Leaf length	Mean $\pm$ std	16.49 $\pm$ 4.43 ^a	17.44 $\pm$ 1.99 ^a	17.69 $\pm$ 1.99 ^a
	CV (%)	26.86	11.41	11.24
Leaf width	Mean $\pm$ std	10.97 $\pm$ 1.63 ^a	11.07 $\pm$ 0.94 ^a	10.25 $\pm$ 1.40 ^a
	CV (%)	14.85	8.49	13.65
Leaf shape	Mean $\pm$ std	1.51 $\pm$ 0.34 ^b	1.59 $\pm$ 0.12 ^b	1.75 $\pm$ 0.15 ^a
	CV (%)	22.07	7.55	8.57
Leaf functional traits				
Fresh leaf weight	Mean $\pm$ std	6.12 $\pm$ 1.34 ^a	4.39 $\pm$ 1.00 ^b	4.68 $\pm$ 1.01 ^b
	CV (%)	21.9	22.78	21.58
Dry leaf weight	Mean $\pm$ std	2.17 $\pm$ 0.60 ^a	1.96 $\pm$ 0.47 ^a	1.52 $\pm$ 0.33 ^b
	CV (%)	27.64	23.97	21.71
Mass loss by desiccation	Mean $\pm$ std	3.95 $\pm$ 0.83 ^a	2.43 $\pm$ 0.73 ^b	3.17 $\pm$ 0.77 ^c
	CV (%)	21.01	30.04	24.29
Leaf water content	Mean $\pm$ std	64.40 $\pm$ 4.52 ^a	54.73 $\pm$ 7.20 ^b	67.03 $\pm$ 5.53 ^a
	CV (%)	6.91	13.15	8.25
Growth-related morphological traits				
Basal Diameter	Mean $\pm$ std	21.67 $\pm$ 5.99 ^a	26.28 $\pm$ 9.54 ^a	27.73 $\pm$ 14.63 ^a
	CV (%)	27.64	36.3	52.75
Diameter at Breast Height	Mean $\pm$ std	19.64 $\pm$ 4.98 ^a	22.80 $\pm$ 8.23 ^a	24.96 $\pm$ 12.57 ^a
	CV (%)	25.36	36.09	50.36
Total height	Mean $\pm$ std	9.47 $\pm$ 4.17 ^a	6.54 $\pm$ 2.17 ^b	8.58 $\pm$ 2.31 ^a
	CV (%)	44.03	33.18	26.92
Bole height	Mean $\pm$ std	2.98 $\pm$ 1.61 ^a	3.11 $\pm$ 1.78 ^a	3.41 $\pm$ 1.50 ^a
	CV (%)	50.03	57.23	43.99
Height of canopy	Mean $\pm$ std	6.49 $\pm$ 3.76 ^a	3.43 $\pm$ 2.51 ^b	5.17 $\pm$ 2.12 ^a
	CV (%)	57.93	73.17	41
Mean diameter of the canopy	Mean $\pm$ std	7.95 $\pm$ 2.33 ^a	7.43 $\pm$ 2.35 ^a	6.94 $\pm$ 2.66 ^a
	CV (%)	29.3	31.62	38.32
Canopy shape	Mean $\pm$ std	0.87 $\pm$ 0.50 ^a	0.48 $\pm$ 0.37 ^b	0.77 $\pm$ 0.26 ^a
	CV (%)	54.47	77.08	33.77
Number of branches	Mean $\pm$ std	3.71 $\pm$ 1.33 ^a	3.75 $\pm$ 1.32 ^a	3.17 $\pm$ 1.40 ^a
	CV (%)	35.85	35.2	44.16

Key: CV: Coefficient of variation, std: standard error of mean. For each trait, means followed by the same letters are not significantly different (p-value > 0.05) according to Tukey's post hoc test

4.3.2 Pairwise correlation between morphological traits

We found a significant and positive correlation ($r > 0.5$; $p < 0.001$) between the diameter at breast height (DBH) and the basal diameter (BD) ($r = 0.97$), as well as between the total height (TH) and the basal diameter ($r = 0.52$) and the DBH ($r = 0.42$). Significant correlations were also observed

between fruit width (FW) and its diameter (FWID) ($r = 0.69$; $p < 0.001$), as well as between fresh leaf weight (FLW) and its width (LW) ($r = 0.53$; $p < 0.001$). Canopy shape (CS) showed a significant correlation with canopy height (CH) ($r = 0.81$; $p < 0.001$) and total height (TH) ($r = 0.65$; $p < 0.001$) (Figure 16). Moreover, CS was also positively correlated with the leaf dehydration mass (MLD) ($r = 0.33$; $p < 0.01$). Among the significant negative relationships, there was an inverse correlation between leaf length (LL) and leaf dry mass (LWC) ($r = -0.36$; $p < 0.01$). Moreover, the height of the canopy was negatively correlated with leaf length (LL; $r = -0.30$; $p < 0.01$) and leaf dry mass (LWC; $r = -0.44$; $p < 0.001$). Finally, moderate correlations were observed between the number of seeds (NS) and the seed mass (SW) ($r = 0.34$; $p < 0.01$).

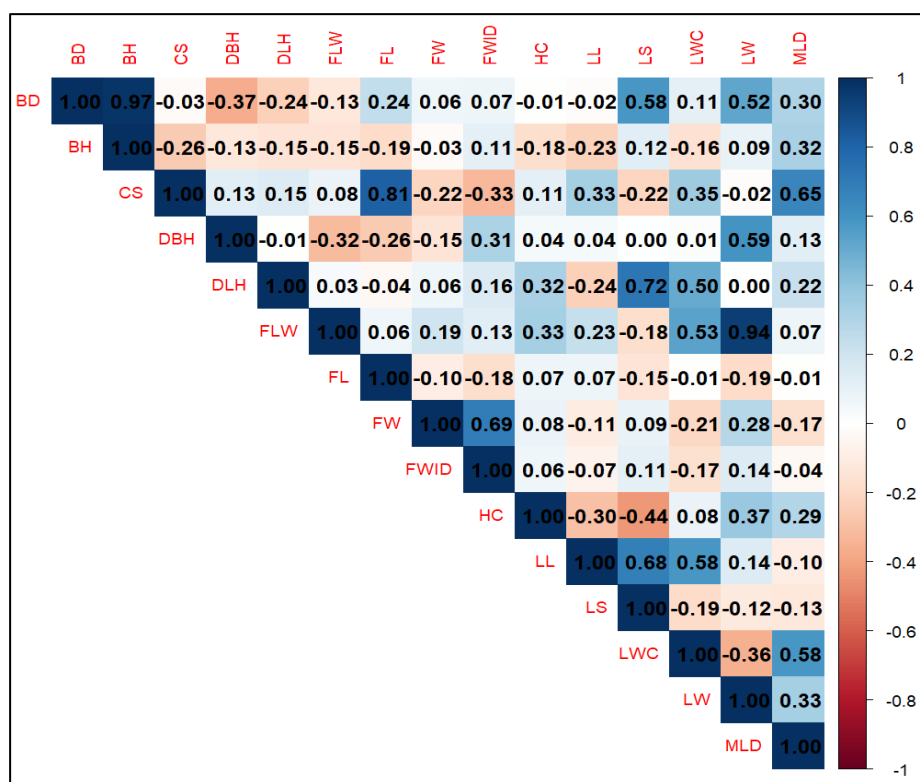


Figure 16: Pairwise correlation of morphological traits

Key: SH = Shape fruit; FW=Fruit weight; FL=Fruit length; FWi=Fruit width; NS=Number of seed; SW=Seed weight; LL=Leaf length; LW=Leaf width; LS=Leaf shape, FLW=Fresh leaf weight; DLW=Dry leaf weight; MLD=Mass loss by desiccation, LWC=Leaf water content; BD=Basal Diameter; DBH=Diameter at Breast Height; TH=Total height; BH=Bole height; HC=Height of canopy; MDC=Mean diameter of canopy; CS=Canopy shape, and NB=Number of branches. The colors used in a correlation matrix provide a powerful visual representation of two key aspects of the Pearson correlation coefficient (r): its direction (sign) and its magnitude (strength). The standard diverging color scheme employs blue and red to indicate the sign of the relationship. Specifically, blue indicates a positive correlation ($r > 0$), meaning that as one variable increases, the other variable also tends to increase. Conversely, red indicates a negative correlation ($r < 0$), meaning that as one variable increases, the other tends to decrease. The intensity of these colors denotes the strength of the relationship: a darker, more saturated color (deep blue or vivid red) signifies a strong correlation, with $|r|$ approaching 1, indicating a tight linear relationship. Conversely, a paler or lighter color (often near white or light grey) signifies a weak correlation, where r is close to 0, meaning the variables are largely unrelated. Therefore, the matrix allows the viewer to instantly identify the strongest positive relationships (darkest blue) and the strongest negative relationships (most vivid red).

4.3.3 Discriminant morphological and functional traits of *U. kirkiana* according to the region

According to the results of the CDA, the morphological and functional traits that significantly discriminated various *U. kirkiana* trees included LWC, MLD, LL, CS, SF, NB, BD, SW, MDC (Table 23).

Table 23: Results of the selection of explanatory variables using a multivariate procedure based on Wilks' Lambda and F-tests

Variable	Wilks' Lambda	Overall F-statistic	Overall p-value	F-statistic difference
LWC	0.54	29.29	6.16	29.29
MLD	0.38	20.85	2.01	13.86
LL	0.32	17.04	1.43	6.51
CS	0.27	15.13	1.32	6.01
SF	0.24	13.34	6.88	3.81
NB	0.22	12.04	5.02	3.30
BD	0.19	11.29	2.19	3.82
SW	0.17	10.53	1.92	2.94
MDC	0.16	9.89	1.99	2.67

Key: CS=canopy shape; MDC=mean diameter of canopy; SW=seed weight; BD=basal diameter; NB=number of branches; SF=shape fruit; LL=leaf length; LWC=leaf water content; MLD=mass loss by desiccation

These traits significantly discriminated trees based on their regions of provenance (Table 24). Mass loss by desiccation (MLD) was higher in the North (estimate = 1.52, $p < 0.001$) and the South (estimate = 0.73, $p = 0.002$) compared to the Central region. Leaf water content (LWC) also exhibited strong regional variation, with increases of 9.66 units in the North and 12.29 units in the South ($p < 0.001$). Seed weight (SW) was significantly greater in both the North (estimate = 2.26, $p < 0.001$) and South (estimate = 2.22, $p < 0.001$), while canopy shape (CS) was more developed in these two regions (North = 0.38, $p = 0.001$; South = 0.29, $p = 0.014$). In contrast, traits such as

leaf length, fruit shape, and number of branches, basal diameter, and mean canopy diameter did not differ significantly among regions.

Table 24: Results of linear models evaluating the effect of the region on different morpho-functional variables of *U. kirkiana*

Variable	Coefficient	Estimate	Std. Error	t value	p-value	Adj. R ²	Model global p-value
MLD	(Intercept)	2.43	0.159	15.28	< 2e-16 ***	0.3811	2.42e-08 ***
	Region North	1.52	0.22	6.76	3.61e-09 ***		
	Region South	0.73	0.22	3.27	0.00168 **		
LWC	(Intercept)	54.73	1.19	45.76	< 2e-16 ***	0.4435	6.16e-10 ***
	Region North	9.66	1.69	5.715	2.56e-07 ***		
	Region South	12.29	1.69	7.267	4.35e-10 ***		
LL	(Intercept)	17.43	0.61	28.13	< 2e-16 ***	0.0012	0.358 (ns)
	Region North	-0.94	0.87	-1.07	0.286 (ns)		
	Region South	0.25	0.87	0.29	0.769 (ns)		
SF	(Intercept)	1.39	0.22	6.15	4.4e-08 ***	0.0014	0.356 (ns)
	Region North	-0.39	0.32	-1.23	0.221 (ns)		
	Region South	-0.40	0.32	-1.27	0.208 (ns)		
NB	(Intercept)	3.75	0.27	13.55	< 2e-16 ***	0.0107	0.258 (ns)
	Region North	-0.04	0.39	-0.10	0.916 (ns)		
	Region South	-0.58	0.39	-1.49	0.141 (ns)		
BD	(Intercept)	26.28	2.17	12.07	< 2e-16 ***	0.0305	0.128 (ns)
	Region North	-4.61	3.07	-1.49	0.138 (ns)		
	Region South	1.44	3.07	0.47	0.639 (ns)		
SW	(Intercept)	4.59	0.37	12.17	< 2e-16 ***	0.2335	3.86e-05 ***
	Region North	2.26	0.53	4.25	6.50e-05 ***		
	Region South	2.22	0.53	4.16	8.84e-05 ***		
MDC	(Intercept)	7.42	0.50	14.81	< 2e-16 ***	0.0005	0.367 (ns)
	Region North	0.52	0.70	0.742	0.460 (ns)		
	Region South	-0.4846	0.709	-0.683	0.497 (ns)		
CS	(Intercept)	0.4842	0.0803	6.033	7.13e-08 ***	0.1264	0.00353 **
	Region North	0.3819	0.1135	3.365	0.00125 **		
	Region South	0.2867	0.1135	2.526	0.0138 *		

Key: CS=canopy shape; MDC=mean diameter of canopy; SW=seed weight; BD=basal diameter; NB=number of branches; SF=shape fruit; LL=leaf length; LWC=leaf water content; MLD=mass loss by desiccation

The two canonical axes explained 100% of the total variability in the morphological and functional traits (Figure 17). The first canonical function (Can1) had an eigenvalue of 1.716 and explained 58.26% of the total variation, while the second canonical function (Can2) accounted for 41.74% of the variation, with an eigenvalue of 1.229. LWC, MLD, SW, and CS showed higher values in the north and south region compared to central. However, the trees from central region showed distinct traits from those in north and south, particularly evident in SF, LWC, NB, MDC and BD, which best discriminated central region individuals from the other two regions (Figure 17). LWC and MLD were the two traits most strongly associated with the main axis of inter-regional variation (Can1). High positive correlations between LWC, MLD, and SW were primarily linked to the first canonical axis (Can1) (Table 25).

Table 25: Correlations between functional traits and canonical axes from discriminant analysis

Variables	Can1	Can2
MLD (Mean Leaf Diameter)	0.65	0.48
LWC (Leaf Water Content)	0.84	-0.14
LL (Leaf Length)	-0.05	-0.22
SF (Shape fruit)	-0.21	-0.01
NB (Number of Branches)	-0.14	0.21
BD (Basal Diameter)	-0.07	-0.31
SW (Seed Weight)	0.63	0.05
MDC (Mean Diameter of Capsules)	-0.01	0.23
CS (Conservation Score)	0.46	0.15

Key: an1 and Can2 correspond to the first two canonical axes from a canonical analysis. Values indicate the relative contribution of each variable to the respective axis.

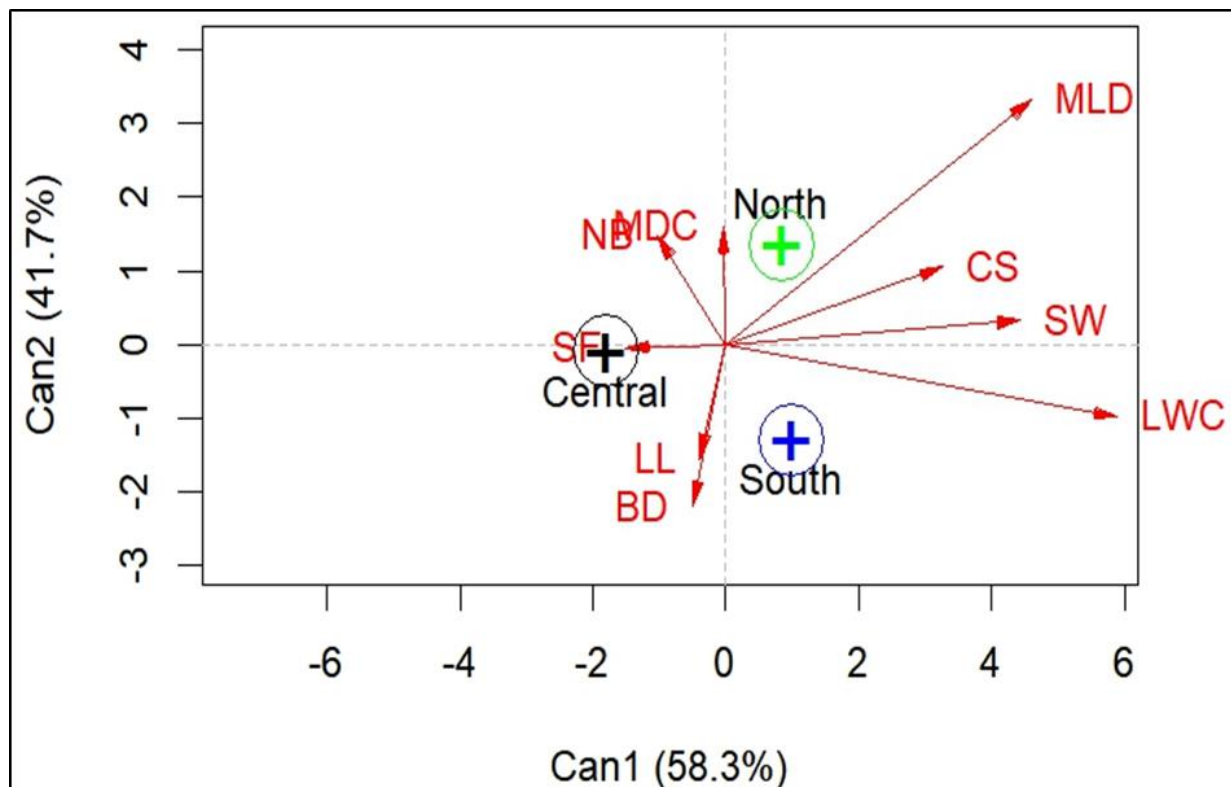


Figure 17: Discrimination of the 72 individuals of *U. kirkiana* according to region of provenances

Key: Projection of the traits and geographical regions into the system defined by the first two axes from the canonical discriminant analysis (CDA). Each geographical region was represented by the centroid of all trees in the region. Abbreviations are described in Table 26. This specific chromatic (+) encoding where green, blue, and black signify the North, South and Center regions respectively is employed for spatial stratification of the variables within the analysis. This technique of geographical categorization integrates the territorial dimension into the interpretation of statistical results.

4.3.4 Relationships between environmental variables and discriminant morphological and functional traits of *U. kirkiana* trees

The redundancy analysis (RDA) showed that two axes (RDA1 and RDA2) together explain 87.1% of the constrained inertia (Table 26). The RDA1 and RDA2 axis were statistically significant ($p < 0.001$). Among the environmental variables, the aridity index, types of soil (HWSD), and altitude (ELEV) have a significant effect on trait distribution (Table 27). On the first axis (RDA1), ELEV was positively related to the discriminant morphological traits such as BD, DBH, LWC, and SW. In contrast, they negatively affected FW. Conversely, the FW (-0.20) had a strongly negative relationship with RDA2 (-1.45). Furthermore, specific canopy height (-0.66) was more sensitive to variations along the RDA2 axis (Table 27).

Table 26: Significance and scores of environmental variables influencing the discriminant morphological and functional traits of *U. kirkiana* trees

Environmental variables	Permutation ANOVA				Scores on axes	
	Df	Variance	F	Pr (>F)	RDA1 (59.4%)	RDA2 (27.7%)
Elev (altitude)	1	25.00	5.08	0.005	0.13	0.34
HWSD (soil type)	1	40.00	8.13	0.001	-0.26	-0.09
Aridity index	1	52.67	10.71	0.001	-0.80	-0.19
Residual	63	309.80				
Axis						
RDA1 (59.4%)	1	76.86	15.20	0.001		
RDA2 (27.7%)	1	36.37	7.19	0.001		
Residual	67	338.91				

Key: RDA = axes from the redundancy analysis; DF = degrees of freedom, F = Fisher statistics related to the test; Pr (>F) = probability of the significance. Bold values indicate the variables with the largest contribution to the RDA axes.

Table 27: Loadings of the discriminating morphological and functional traits on the axes of the redundancy analysis (RDA1 and RDA2)

Traits	RDA1 (59.4%)	RDA2 (27.7%)
Fruit trait		
Fruit weight	-0.20	-1.45
Seed weight	1.81	-1.24
Leaf functional traits		
Leaf water content	0.96	-3.20
Growth-related morphological traits		
Basal Diameter	4.19	0.93
Diameter at Breast Height	3.499	0.47
Total height	0.522	-0.59
Height of canopy	0.449	-0.66

Key: RDA1 and RDA2 correspond to the first and second axes from a Redundancy Analysis (RDA), explaining 59.4% and 27.7% of the total variation, respectively.

4.3.5 Discriminant morphological and functional traits of *U. kirkiana* and their relationships with the least correlated bioclimatic variables

The PCA describing the relationship between the most discriminant morphological traits of *U. kirkiana* and the environmental variables indicated that the first two PCA axes explained 43.9% of the total variation (Figure 18). We funded three groups, such as central, north, and south, illustrated by confidence ellipses (Figure 19). Group 1 comprising populations from the central region, associated with high values of temperature-related variables Annual Mean Temperature (BIO1),

Max Temperature of Warmest Month (BIO5), Mean Temperature of Warmest Quarter (BIO10), Mean Temperature of Coldest Quarter (BIO11) and some seasonal precipitation variables (BIO16=Precipitation of Wettest Quarter, BIO18=Precipitation of Warmest Quarter). Morphologically, this group was characterized by fruit length, width, and shape, and annual precipitation (BIO12). In contrast, the North group was strongly correlated by higher elevation (elev), slope, tree basal diameter and diameter at breast height (bd, dbh), and environmental variables such as soil depth and aridity index. The second axis (Dim 2) relates leaf morphological variables (ll, lwi, lsh, flw, dlw, lwc) and fruit traits (fw, sw) to pedological factors such as soil nitrogen and phosphorus content, in association with the regional groups. Group three, composed of the populations of south region, were most strongly associated with morphological and environmental traits associated with higher rainfall and better soil fertility, whereas the central group was more influenced by temperature-related climatic variables. In addition, the bioclimatic variables positively correlated with the first axis (BIO5: BIO8; BIO10: 7.86; BIO01: 7.42; BIO11: 7.62; BIO16: 6.98) and negatively correlated with elevation (-5.49), soil type (HWSD: -8.19), and slope (-2.12) were well represented on Dim1 (Table 28). Dim 2 described a gradient of soil depth (9.12) and aridity (aridity index: 7.30), and was positively associated with canopy traits (canopy height: 4.94; canopy shape: 3.74) and leaf water content (4.72). In contrast, diameter at breast height (DBH: 14.35), basal diameter (BD: 15.74), and seed weight (SW: 4.91) were well loaded on Dim 3 (Table 28).

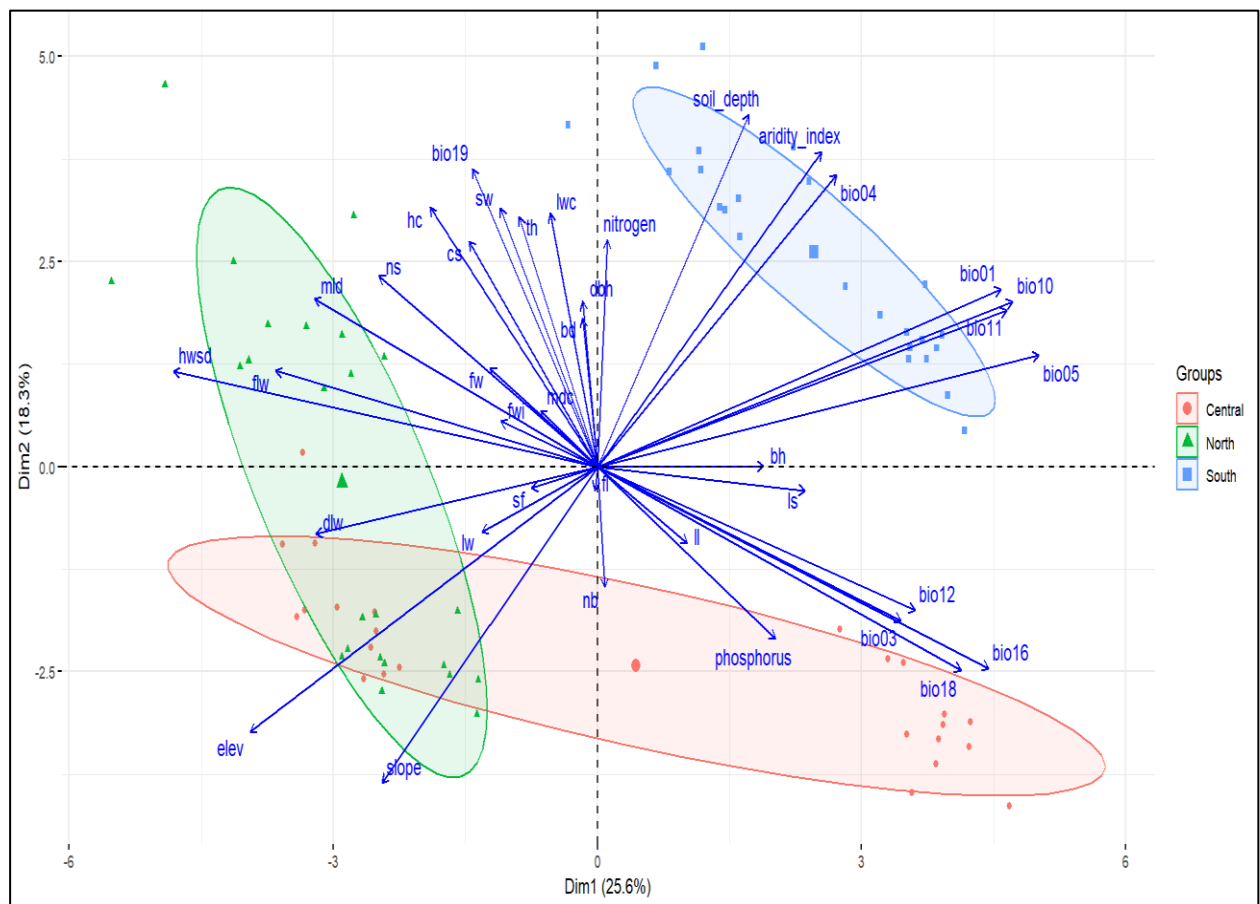


Figure 18: Principal Component Analysis (PCA) plot of morphological and functional traits, discriminant environment variable describing the variation of those traits according to different regions (Dim 1 and 2)

Key: sf = Shape fruit, fw = Fruit weight, fl = Fruit length, fwi = Fruit width, ns = Number of seed, sw = Seed weight, ll = Leaf length, lwi = Leaf width, lsh = Leaf shape, flw = Fresh leaf weight, dlw = Dry leaf weight, mld = Mass loss by desiccation, lwc = Leaf water content, bd = Basal Diameter, dbh = Diameter at Breast Height, th = Total height, bh = Bole height, hc = Height of canopy, mdc = Mean diameter of canopy, csh = Canopy shape, nb = Number of branches, bio01 = Annual mean temperature, bio03 = Isothermality, bio04 = Temperature seasonality, bio05 = Max temperature of warmest month, bio10 = Mean temperature of warmest quarter, bio11 = Mean temperature of coldest quarter, bio12 = Annual precipitation, bio16 = Precipitation of wettest quarter, bio18 = Precipitation of warmest quarter, bio19 = Precipitation of driest quarter, elev = Elevation, hwsd = Harmonized World Soil Database, Aridity index = aridity index, soil_depth = Soil depth, slope = Slope, nitrogen = Nitrogen content, phosphorus = Phosphorus content, potassium = Potassium content.

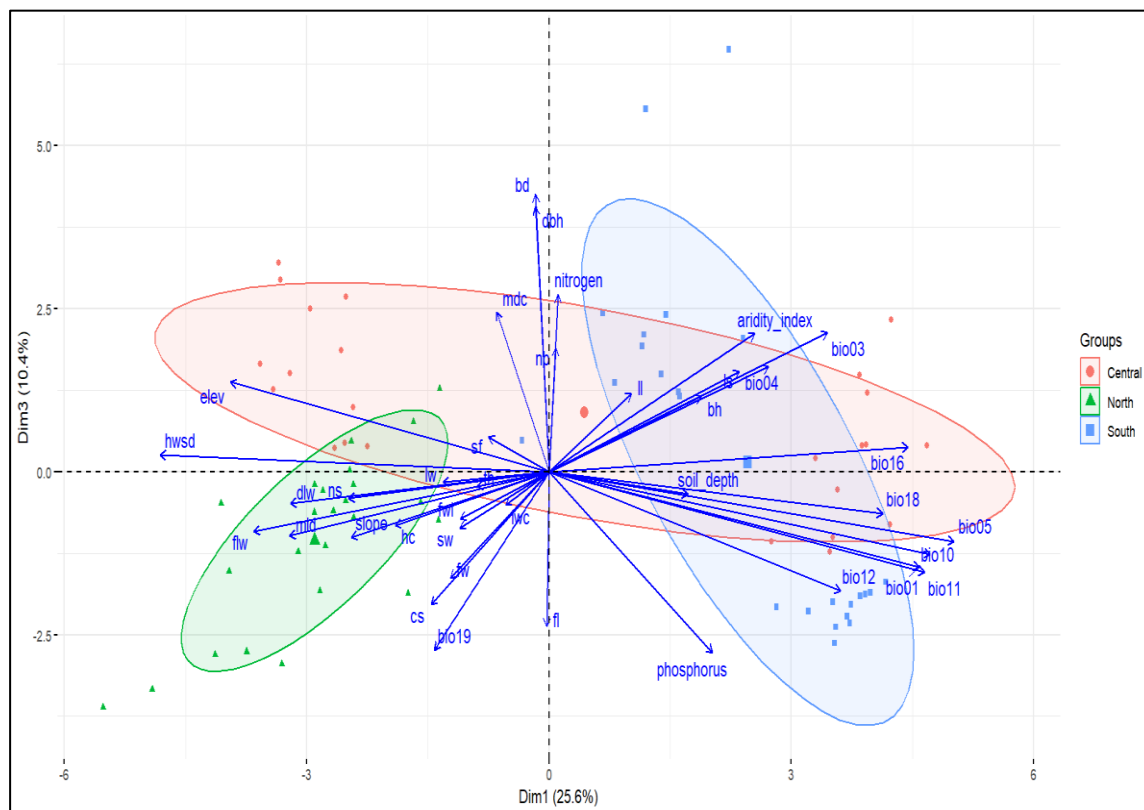


Figure 19: Principal Component Analysis (PCA) plot of morphological traits, discriminant environment variable describing the variation of those traits according to different regions (Dim 1 and Dim 3)

Table 28: Correlation matrix between the first three principal components and the most discriminating morphological traits and significant environmental variable

Variables	Dim1	Dim2	Dim3
sf	0.20	0.03	0.25
fw	0.53	0.71	2.31
fl	0.00	0.04	4.89
fwi	0.43	0.15	0.45
ns	2.17	2.66	0.15
sw	0.43	4.91	0.65
ll	0.37	0.43	1.25
lw	0.61	0.31	0.02
ls	1.96	0.04	2.04
flw	4.71	0.68	0.73
dlw	3.61	0.34	0.20
ml	3.65	2.08	0.84
lwc	0.10	4.72	0.22
bd	0.01	1.63	15.74
dbh	0.01	2.02	14.35

th	0.28	4.59	0.04
bh	1.26	0.00	1.15
hc	1.28	4.94	0.60
mdc	0.15	0.23	5.21
cs	0.75	3.74	3.61
nb	0.00	1.07	3.14
bio01	7.42	2.32	1.86
bio03	4.21	1.73	3.95
bio04	2.61	6.25	2.24
bio05	8.88	0.92	1.00
bio10	7.86	2.00	1.40
bio11	7.62	1.80	2.06
bio12	4.60	1.52	2.93
bio16	6.98	2.98	0.13
bio18	6.02	3.04	0.36
bio19	0.71	6.52	6.52
elev	5.49	5.16	1.64
hwsd	8.19	0.67	0.06
aridity_index	2.29	7.30	3.89
soil_depth	1.04	9.12	0.10
slope	2.12	7.36	0.88
nitrogen	0.00	3.79	6.42
phosphorus	1.44	2.19	6.71

Key: sf = Shape fruit, fw = Fruit weight, fl = Fruit length, fwi = Fruit width, ns = Number of seed, sw = Seed weight, ll = Leaf length, lwi = Leaf width, lsh = Leaf shape, flw = Fresh leaf weight, dlw = Dry leaf weight, mld = Mass loss by desiccation, lwc = Leaf water content, bd = Basal Diameter, dbh = Diameter at Breast Height, th = Total height, bh = Bole height, hc = Height of canopy, mdc = Mean diameter of canopy, csh = Canopy shape, nb = Number of branches, bio01 = Annual mean temperature, bio03 = Isothermality, bio04 = Temperature seasonality, bio05 = Max temperature of warmest month, bio10 = Mean temperature of warmest quarter, bio11 = Mean temperature of coldest quarter, bio12 = Annual precipitation, bio16 = Precipitation of wettest quarter, bio18 = Precipitation of warmest quarter, bio19 = Precipitation of driest quarter, elev = Elevation, hwsd = Harmonized World Soil Database, Aridity index = aridity index, soil_depth = Soil depth, slope = Slope, nitrogen = Nitrogen content, phosphorus = Phosphorus content, potassium = Potassium content.

4.3.6 Morphotypes identified across geographical region in Malawi

The result showed four morphotypes (Figure 20). Morphotype 1 includes individuals from Kaning'ina forest (North region), characterized by NB (3.83 ± 1.27) with a large, basal shape fruit (1.40 ± 1.93). Morphotype 2 was made of individuals from Chongoni forest (Central region) and Perekezi forest (North region), which characterised by the lowest values of fresh leaf weight

(4.08 ± 0.78 g) and dry weight (1.62 ± 0.38 g), coupled with a reduced mass loss due to desiccation (2.45 ± 0.74 g). However, this morphotype showed a relatively high bole height (3.59 ± 1.76 m). Morphotype 3 includes individuals from Malosa forest (South region), which stood out particularly for its high values of fruit characteristics, specifically the fruit weight (19.77 ± 3.22 g), the fruit width (32.14 ± 2.88 mm), and NS (3.90 ± 0.15). This cluster also exhibits a high FLW ($63.25 \pm 5.27\%$) and a more pronounced mass loss by desiccation (4.12 ± 0.83 g). Morphotype 4 was made of individuals from Dzalanyama (Central region) and Mangochi forest (South region) (Figure 20), showing the highest value of BD (36.31 ± 16.70 cm), BH (3.74 ± 1.67 cm), and DBH (32.07 ± 14.60 cm). Additionally, this cluster has a notable mean CS (8.24 ± 3.24 m) and an average of TH (9.88 ± 2.63 m). However, the FLW was at its highest ($68.22 \pm 3.24\%$) (Table 29).

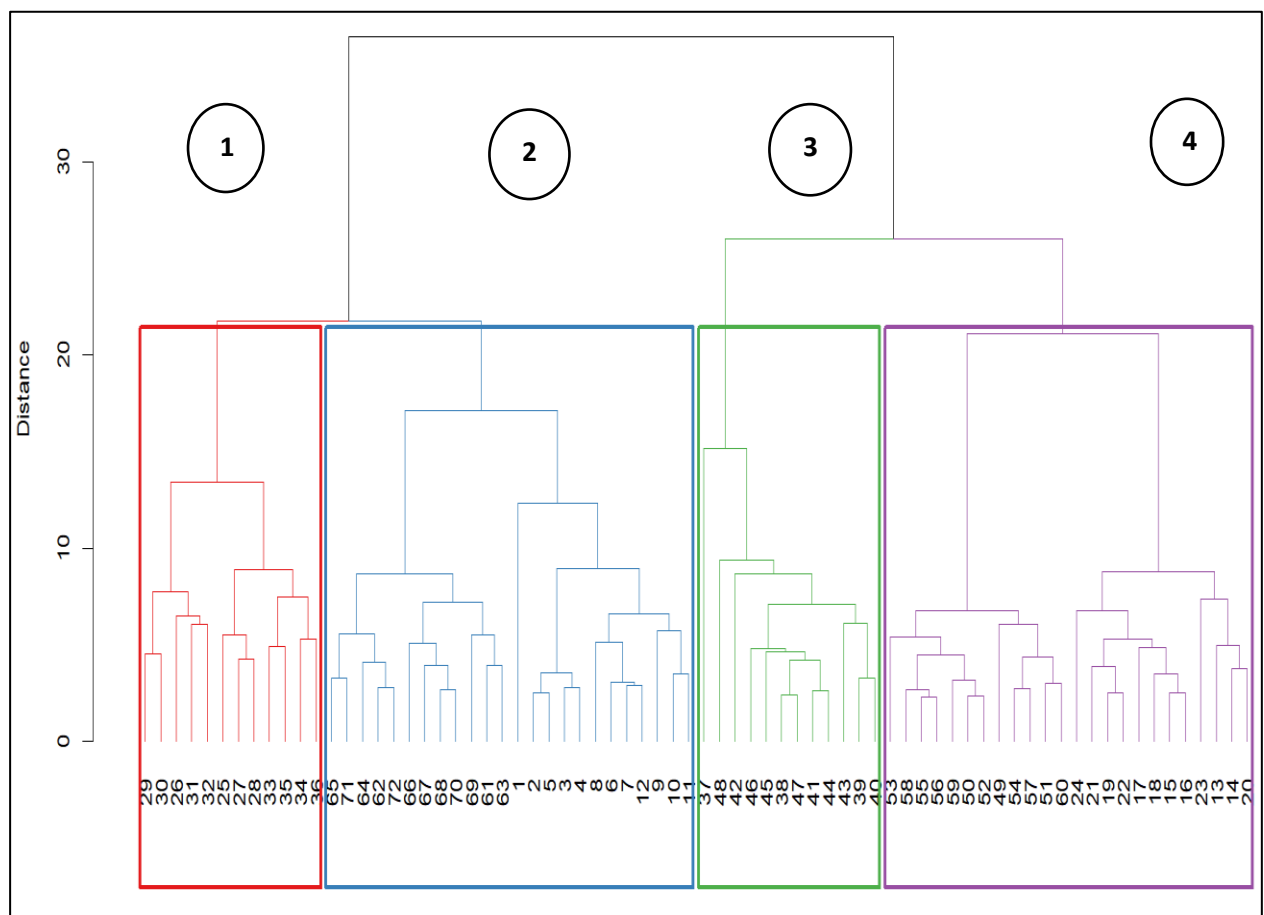


Figure 20: Dendrogram showing clusters of *U. kirkiana* individuals based on morphological traits

Key: Morphotype 1=Red color (Kaning'ina forest), morphotype 2=blue color (Chongoni forest (Central region) and Perekezi forest (North region)), morphotype 3=green color (Chongoni forest (Central region) and Perekezi forest (North region)) and morphotype 4=purple color (individuals from Dzalanyama (Central region) and Mangochi forest (South region)).

Table 29: Variability of *U. kirkiana* trees, fruits, leaves and seeds traits according to cluster

Parameters	Statistics	Cluster			
		1	2	3	4
Shape fruit		1.40 ± 1.93	0.99 ± 0.05	1.00 ± 0.09	0.98 ± 0.04
Fruit weight (g)		18.29 ± 6.81	16.14 ± 4.37	19.77 ± 3.22	19.15 ± 4.41
Fruit length (mm)		31.17 ± 2.58	31.87 ± 2.47	31.89 ± 2.77	30.33 ± 2.45
Fruit width (mm)		31.77 ± 2.46	30.74 ± 2.64	32.14 ± 2.88	32.32 ± 2.69
Number of seeds		3.55 ± 0.24	3.42 ± 0.22	3.90 ± 0.15	3.64 ± 0.31
Seed weight (g)		5.16 ± 2.10	5.15 ± 1.43	7.96 ± 1.35	14.78 ± 24.30
Leaf length		17.44 ± 1.97	17.73 ± 1.94	14.89 ± 5.67	18.03 ± 2.04
Leaf width		10.80 ± 1.11	10.64 ± 1.18	11.37 ± 2.00	10.32 ± 1.53
Leaf shape		1.63 ± 0.14	1.68 ± 0.13	1.30 ± 0.38	1.78 ± 0.19
Fresh leaf weight (g)		5.40 ± 1.04	4.08 ± 0.78	6.50 ± 1.46	4.93 ± 1.20
Dry leaf weight (g)	Mean ± SD	2.06 ± 0.42	1.62 ± 0.38	2.38 ± 0.71	1.55 ± 0.40
Mass loss by desiccation (g)		3.34 ± 0.86	2.45 ± 0.74	4.12 ± 0.83	3.38 ± 0.84
Leaf water content (%)		61.33 ± 6.96	59.09 ± 9.67	63.25 ± 5.27	68.22 ± 3.24
Basal Diameter		24.05 ± 9.50	21.28 ± 6.23	24.40 ± 6.17	36.31 ± 16.70
DBH		21.26 ± 7.86	19.19 ± 5.25	21.85 ± 5.18	32.07 ± 14.60
Total height (m)		6.51 ± 2.63	7.31 ± 1.16	11.68 ± 4.35	9.88 ± 2.63
Bole height (m)		2.62 ± 1.35	3.59 ± 1.76	2.83 ± 1.54	3.74 ± 1.67
Height of canopy (m)		3.90 ± 1.85	3.72 ± 2.17	8.84 ± 3.93	6.13 ± 2.51
Mean canopy diameter (m)		7.01 ± 1.53	6.77 ± 2.45	8.84 ± 2.60	8.24 ± 3.24
Canopy shape		0.58 ± 0.28	0.60 ± 0.38	1.10 ± 0.57	0.80 ± 0.34
Number of branches		3.83 ± 1.27	3.42 ± 1.47	3.17 ± 0.94	3.58 1.68

4.3.7 Phenotypic plasticity of *U. kirkiana* trees in Malawi

The results showed differences in the phenotypic plasticity index (PPI) value of *U. kirkiana* tree among the geographical regions. In particular, the PPI values of CS and HC were higher for central vs. north and central vs. south population compared to north vs. south (Figure 21). We also observed that the morphological and functional traits associated with growth-related traits, such as DBH, BD, and TH, exhibited the highest levels of phenotypic plasticity (> 0.2). In contrast, NB, MDC, and BH showed the lowest levels of plasticity (Figure 21). Moreover, the range of

phenotypic plasticity varied by regions. The highest plasticity values for BH and MDC were observed between north and south populations. The same trends were observed between central and north populations for NB. Conversely, the lowest degree of phenotypic plasticity was recorded between central and north populations, except for BD, CS, HC, TH, and DBH (Figure 21).

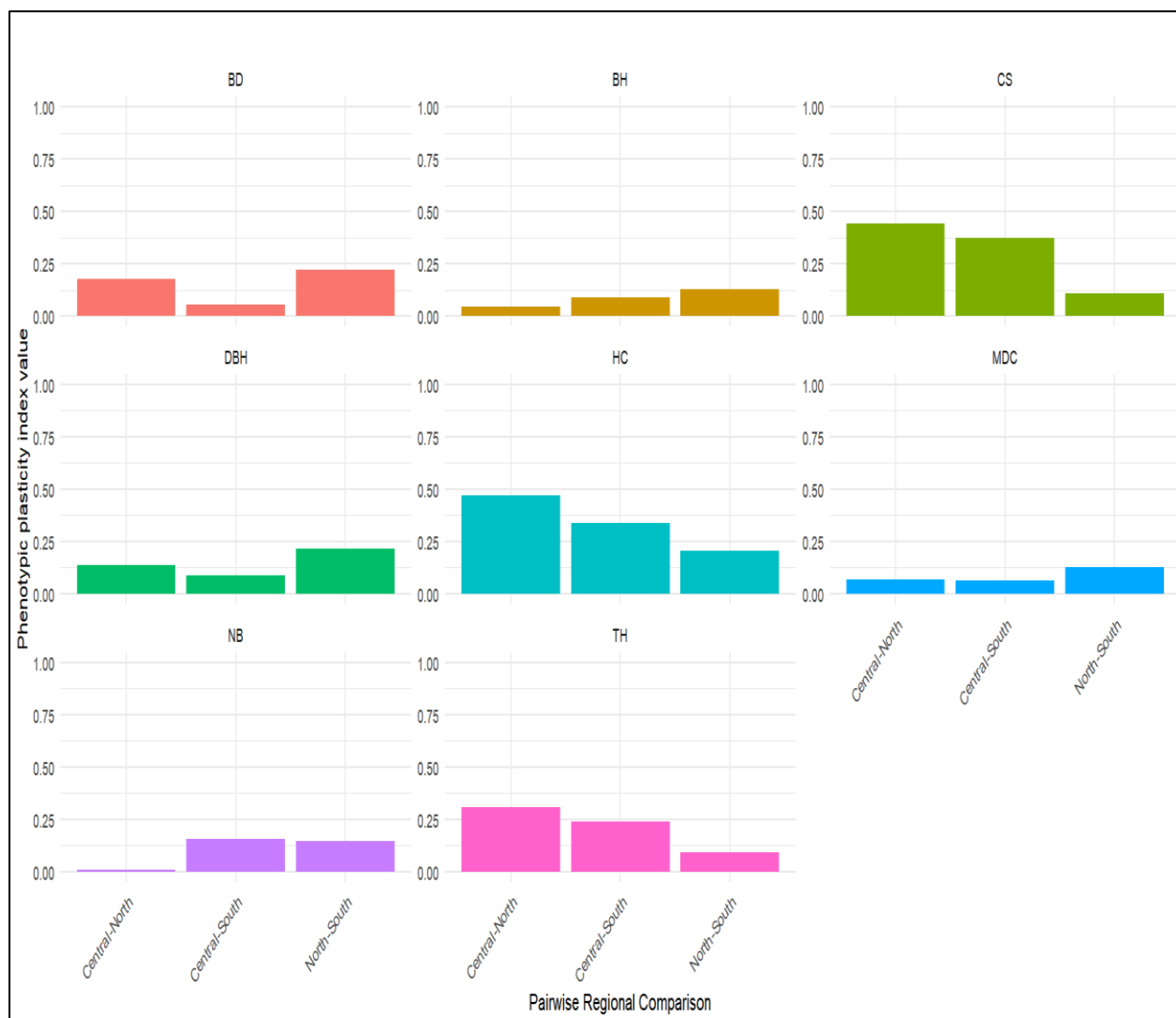


Figure 21: Variation of the phenotypic plasticity of the discriminant morphological and functional traits of *U. kirkiana* among the geographical regions in Malawi

Key: The index varies between 0 and 1, with values closer to 1 indicating greater phenotypic plasticity. BD=Basal Diameter, DBH=Diameter at Breast Height, TH=Total height, BH=Bole height, HC=Height of canopy, MDC=Mean diameter of canopy, CS=Canopy shape, NB=Number of branches.

4.4 Population ecology and carbon storage of *Uapaca kirkiana* Müll. Arg. across regions

4.4.1. Floristic composition and diversity pattern

A total of 5706 individuals belonging to 124 species distributed in 89 genera and 39 botanical families were inventoried (Appendix 5). The most representative families were Fabaceae (42 spp.), Phyllanthaceae (9 spp.), Rubiaceae (8 spp.) and Anacardiaceae (5 spp.), accounting for 51.61 % of the total (Figure 22, and Appendix 6). Specific frequencies revealed that the vegetation of *U. kirkiana* habitats was predominantly dominated by *Uapaca sansibarica* Pax (12.49%), followed by *Brachystegia spiciformis* Benth. (6.98%), *Brachystegia taxifolia* Harms (6.84%), *Parinari curatellifolia* Planch. ex Benth. (5.63%), *Julbernardia paniculata* (Benth.) Troupin (4.14%), *Combretum molle* R. Br. ex G. Don (3.56%), *Brachystegia longifolia* Benth. (3.20%), *Brachystegia floribunda* Benth. (3.17%), and *Syzygium guineense* (Willd.) DC. (3.01%) (Appendix 6). According to the IUCN categories, five species are considered vulnerable (*Afzelia quanzensis* Welw., *Albizia tanganyicensis* Baker f., *Khaya anthotheca* (Welw.) C. DC., *Ozoroa reticulata* (Baker f.) R. Fern. & A. Fern., and *Pterocarpus angolensis* DC.), and two are classified as near threatened (Figure 22). Twenty-five have not yet been evaluated, ninety-one are of least concern, and one species is listed as data deficient (Appendix 7).

Analysis of the importance value indices (IVI) in the six forests studied shows a marked predominance of *U. kirkiana* (Table 30). In Zomba Forest, the species has the highest IVI (220.73), indicating absolute dominance in the forest structure. It is followed by its strong representation in Mangochi Forest (IVI = 209.85), where it far surpasses the other species present. In Chongoni Forest, *U. kirkiana* remains the dominant species (IVI = 191.4), although *Brachystegia floribunda* also has a high value (IVI = 154.6), reflecting floristic co-dominance. In Kaning'ina Forest, *U. kirkiana* retains a central position (IVI = 173.31), followed by *U. sansibarica* (119.09) and *B. spiciformis* (92.08), highlighting a more diverse composition. In Perekezi Forest, the species also dominates with an IVI of 151.96, but it is closely followed by *B. taxifolia* (124.23) and *B. spiciformis* (115.39), revealing a high species richness. Finally, in Dzalanyama Forest has a

moderate IVI (147.1), competing with *U. sansibarica* (123.9) and *Julbernardia paniculata* (105.8), reflecting a balance in the floristic composition.

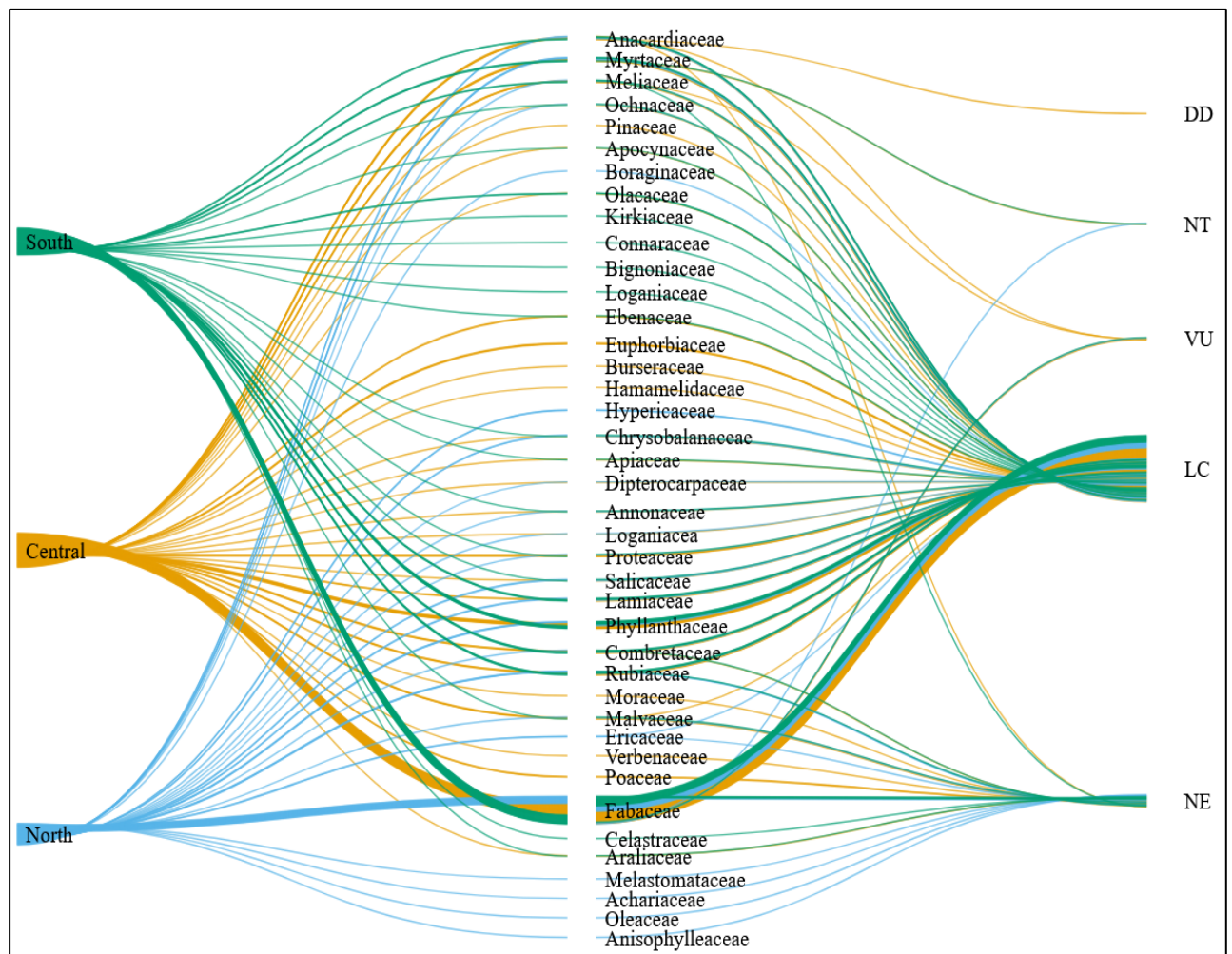


Figure 22: Distribution of species families across the phytogeographic regions in Malawi

Key: Least concern (LC); Near threatened (NT); Vulnerable (VU); Data deficient (DD); and not evaluated (NE); International Union for Conservation of Nature (IUCN).

Table 30: Importance Value Index

Regions	Forests	Species	RD	RDo	RF	IVI
Central	Chongoni	<i>Uapaca kirkiana</i>	59.6	31.8	100	191.4
		<i>Brachystegia floribunda</i>	22.4	32.2	100	154.6
		<i>Bridelia micrantha</i>	7.1	4.3	56	67.4
		<i>Brachystegia taxifolia</i>	5.7	14.6	76	96.3
		<i>Brachystegia spiciformis</i>	5.3	17.1	68	90.4
	Dzalanyama	<i>Uapaca kirkiana</i>	33.4	13.7	100	147.1
		<i>Uapaca sansibarica</i>	14.3	21.6	88	123.9
		<i>Julbernardia paniculata</i>	7.8	50	48	105.8
		<i>Parinari curatellifolia</i>	4.1	12.7	32	48.8
		<i>Pericopsis angolensis</i>	3.3	2	28	33.3
North	Kan'ingnina	<i>Uapaca kirkiana</i>	33.41	39.9	100	173.31
		<i>Uapaca sansibarica</i>	20.89	30.2	68	119.09
		<i>Brachystegia spiciformis</i>	5.33	10.75	76	92.08
		<i>Syzygium guineense</i>	5.93	9.6	68	83.53
		<i>Parinari curatellifolia</i>	5.48	9.54	60	75.02
	Perekezi	<i>Uapaca kirkiana</i>	29.73	22.23	100	151.96
		<i>Brachystegia spiciformis</i>	11.63	23.76	80	115.39
		<i>Brachystegia taxifolia</i>	13.12	19.11	92	124.23
		<i>Brachystegia longifolia</i>	8.56	18.94	68	95.5
		<i>Combretum molle</i>	7.81	15.95	56	79.76
South	Mangochi	<i>Uapaca kirkiana</i>	46.99	62.86	100	209.85
		<i>Parinari curatellifolia</i>	3.41	13.53	72	88.94
		<i>Brachystegia utilis</i>	6.35	12.46	68	86.81
		<i>Uapaca nitida</i>	3.29	7.88	60	71.17
		<i>Pseudolachnostylis maprouneifolia</i>	3.29	3.24	52	58.53
	Zomba	<i>Uapaca kirkiana</i>	36.75	83.98	100	220.73
		<i>Annona senegalensis</i>	7.45	4.73	79.17	91.35
		<i>Burkea africana</i>	3.15	6.21	62.5	71.86
		<i>Lannea discolor</i>	3.97	2.23	54.17	60.37
		<i>Eucalyptus camaldulensis</i>	4.8	2.85	37.5	45.15

Key: RDo, relative dominance, RF, Relative frequency, RD relative density, IVI importance value index; the completed name of species is showing in (Appendix 6).

The Tukey post hoc test for the Species Richness, Shannon Index, Simpson Index and Hill Index, in Table 31, reveal notable differences among the communities. The central region community exhibits a significantly higher mean Species Richness (82 ± 1.37) compared to northern and southern regions. Central region community exhibits a significantly higher mean Shannon diversity (2.96 ± 0.04) compared to the northern region. The southern region community also showed a significantly higher Shannon diversity (2.80 ± 0.09) compared to the northern region. We found that north region community has the lowest Shannon diversity (2.63 ± 0.02). For the Simpson Index, significant differences were observed among the regions (Table 31). The northern community has a significantly higher Simpson diversity (0.86 ± 0.004) than the southern region and the central. Central region (0.84 ± 0.01) shows significantly higher Simpson diversity than southern region, but is not significantly different from the northern region. The Southern region has the lowest Simpson diversity (0.81 ± 0.01), significantly lower than the other two regions (Table 31). The Pielou Evenness indicated no significant differences in variations between regions (Table 31). Jaccard similarity index between the northern and the southern regions (0.73 ± 0.08) has shown significantly higher dominance than central - north and central - south.

Table 31: Variation in diversity indices among *U. kirkiana* habitats across the regions in Malawi

Index					Jaccard Similarity Index		
Regions	Species			Pielou's Evenness Index (J')	Hill (Nq) index		
	Richness (S)	Shannon Index (H')	Simpson Index (D)		Hill (q=0)	Hill (q=1)	Hill (q=2)
Central	82 ± 1.37	2.96 ± 0.04	0.84 ± 0.01	0.67 ± 0.01	4.41 ± 0.04	2.94 ± 0.02	1.84 ± 0.08
North	54 ± 1.12	2.63 ± 0.02	0.86 ± 0.004	0.66 ± 0.00	3.99 ± 0.02	2.63 ± 0.02	1.98 ± 0.01
South	66 ± 1.05	2.80 ± 0.09	0.81 ± 0.01	0.67 ± 0.00	4.19 ± 0.18	2.79 ± 0.04	1.64 ± 0.02
Central - North					0.65 ± 0.02		
Central - South					0.56 ± 0.01		
Comparison	North - South				0.73 ± 0.08		

4.4.2 Structural, demographic, and dendrometric characteristics of *U. kirkiana* populations along Malawi regions

An increasing relative frequency of higher mingling classes ($M_i = 0.50$ and 0.75) was observed in all three regions (Figure 23). The high proportions in mingling ($M_i = 0.5$) were found in the southern region (44%). In contrast, extreme mingling classes ($M_i = 0.00$ or 1.00) were rare across all sites. Although diameter differentiation did not differ significantly between regions (Table 32). The mean distance between trees (D_i) was significantly shorter in the southern region (3.44 ± 0.94 m) compared to the central (4.27 ± 0.90 m) and northern regions (4.09 ± 1.16 m). This spatial arrangement in the south may reflect land-use pressure and selective retention of mature individuals, which is consistent with the larger average DBH in that region (18.79 ± 5.95 cm), despite lower regeneration rates. Pruning intensity (P_i) was highest in the central region (41.63 ± 30.28), with a low density of adult trees ($300 \pm 97/\text{ha}$). In contrast, the northern region exhibited the highest adult tree density ($400 \pm 100/\text{ha}$) and significantly greater regeneration ($30.59 \pm 16.25\%$), even though average tree size was small. These patterns may result from favorable climatic conditions (higher humidity and rain) and lower anthropogenic pressures.

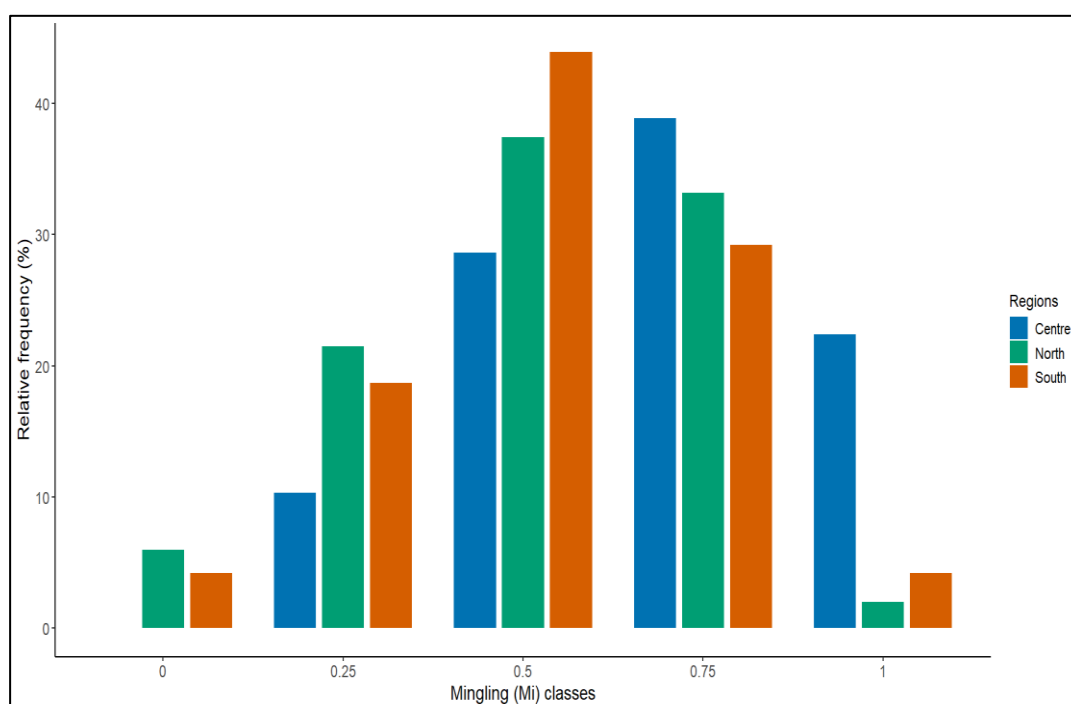


Figure 23: Mingling of *U. kirkiana* with neighbouring trees across the regions in Malawi

Table 32: Demographic, structural and dendrometric parameters of *U. kirkiana* populations according to Malawian regions

Structural parameters	Regions		
	Central	North	South
Diameter differentiation	-1.00 ^a (0.76)	-0.99 ^a (0.95)	-1.40 ^a (0.93)
Tree to tree distance (Di) (m)	4.27 ^a (0.90)	4.09 ^a (1.16)	3.44 ^b (0.94)
Pruning intensity of <i>U. kirkiana</i> (Pi) (%)	41.63 ^a (30.28)	28.2 ^b (16.99)	28.97 ^b (24.71)
Density of <i>U. kirkiana</i>	300 ^a (97)	400 ^b (100)	300 ^a (97)
Regeneration ratio (Rr) of <i>U. kirkiana</i> (%)	21.00 ^a (22.18)	30.59 ^b (16.25)	18.06 ^a (15.25)
Mean diameter (Dg)	15.80 ^a (4.71)	16.78 ^a (4.96)	18.79 ^b (5.95)

Key: Within the same row, values with different letters significantly differ at $\alpha = 5\%$

Pearson's correlation analysis highlighted significant relationships among structural, demographic and dendrometric variables. Across all regions, diameter at breast height (DBH) displayed strong positive correlations with the species quotient (Qs) and the average distance between trees (Di) in the northern (a) and southern (b) regions (Figure 24a-c). Conversely, DBH showed a significant negative correlation with the diameter differentiation index. Specifically, the diameter differentiation index exhibited a significant negative correlation with the average tree-to-tree distance (Di) in both the northern (Figure 24a) and southern (Figure 24c) regions. In these same regions, the density of adult of *U. kirkiana* individuals showed a low positive correlation with DDi, and a stronger positive correlation with the mean diameter (Dg) in the southern region (Figure 24c). This result showed that, population with high densities of *U. kirkiana* tend to be associated with greater structural heterogeneity, moderate levels of pruning, and larger average tree size. In the southern region (Figure 24c), Dg showed significant negative correlations with Di, DBH, and the quotients (Qs). In contrast, the opposite trend was observed in the northern region (Figure 24a). This contrast suggested regional differences in how mean tree diameter relates to spacing and dominance. Across all regions, Qs was consistently and significantly positively correlated with Di (Figure 24a-c).

Across most altitudinal ranges, DBH exhibited a strong positive correlation with the quotient (Qs, Figure 25a-f). Conversely, DBH showed a consistent negative correlation with the DDI across all altitude classes (Figure 25a-f). At the altitudinal ranges [1150-1295[, and [700-880[, DDi was negatively correlated with Di (Figure 25a, f). In contrast, Mi displayed negative correlations with DDi, NPE, and Dg in some mid and low altitude classes (Figure 25b, e, f), while it showed a positive correlation with DDi at [1250-1370[(Figure 25c). Furthermore, NPE was negatively correlated with Dg (Figure 25c) and Di (Figure 25d). Lastly, Pi was positively correlated with Qs and negatively correlated with DDi at [1150-1295[, and [850-950[, (Figure 25a, e).

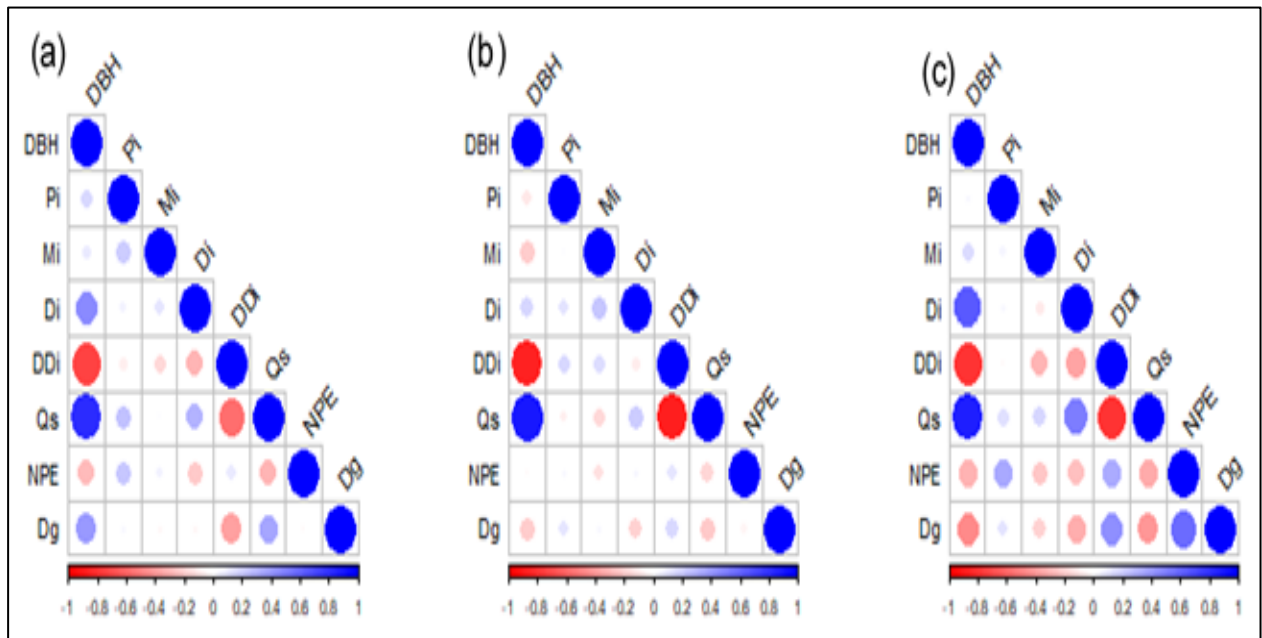


Figure 24: Correlation matrix between structural, demographic, and dendrometric parameters of *U. kirkiana* populations in Malawi

Key: (a) Central region, (b) Northern region, and (c) Southern region. The size of the circles denotes the strength of the correlation, where larger circles represent higher correlations, and smaller circles demonstrate weaker correlations. Blue colour indicates positive correlations and red colour indicates negative ones. NPE: *U. kirkiana* adult density; Dg: Mean diameter; Di: Tree-to-tree distance; DDi: DBH differentiation; Mi: Mingling; Pi: Pruning intensity of *U. kirkiana*; Qs: Quotient. Chongoni forest= 1600-1770m, Dzalanyama forest= 1150-1295m, Kaning'ina forest= 1250-1370m, Malosa forest= 850-950m, Mangochi forest= 700-800m, and Perekezi forest= 1500-1600m

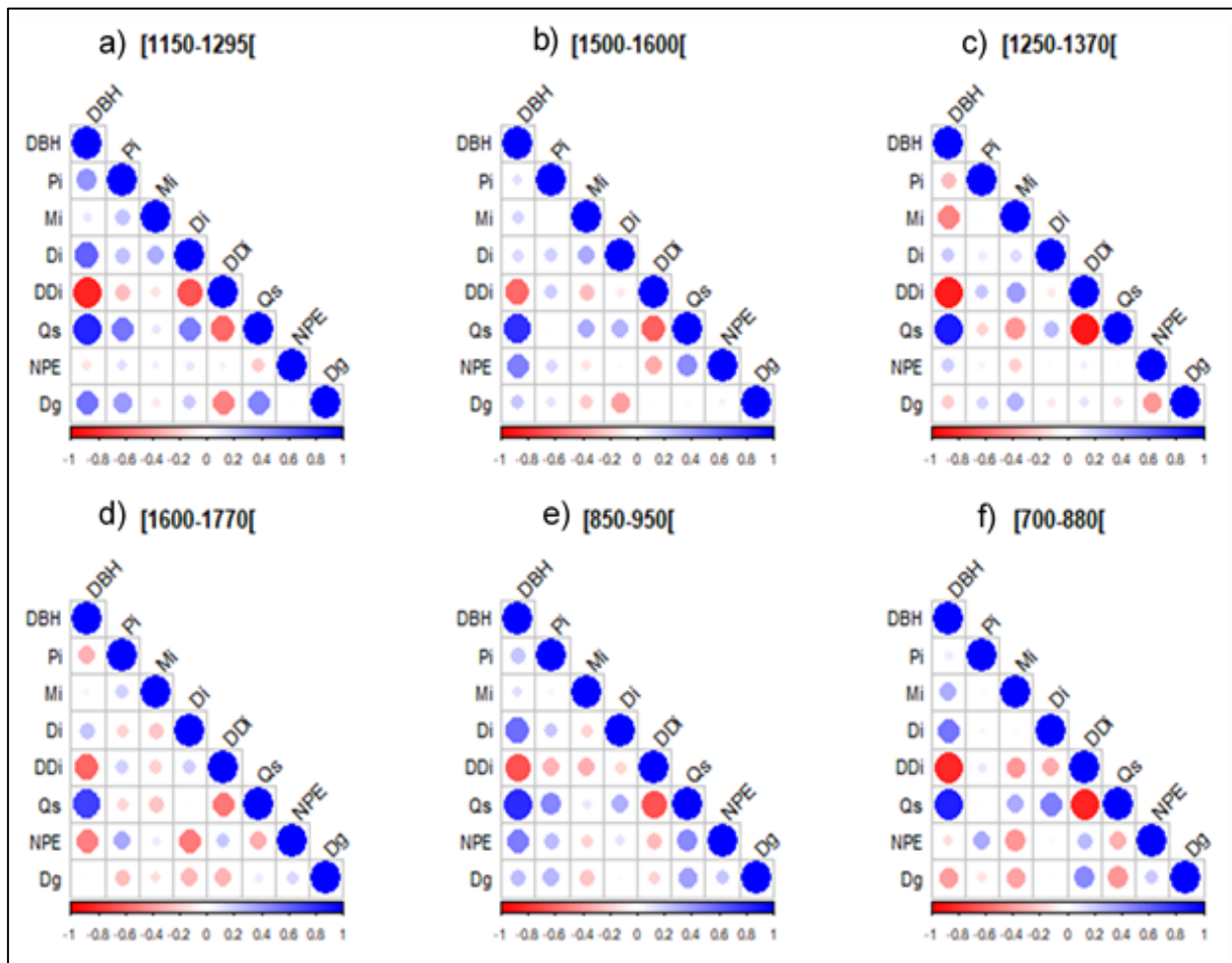


Figure 25: Correlation matrix between structural, demographic, and dendrometric parameters of *U. kirkiana* populations in Malawi across altitude.

Key: The size of the circles denotes the strength of the correlation, where larger circles represent higher correlations, and smaller circles demonstrate weaker correlations. Blue colour indicates positive correlations and red colour indicates negative ones. NPE: *U. kirkiana* adult density; Dg: Mean diameter; Di: Tree-to-tree distance; DDi: bdh differentiation; Mi: Mingling; Pi: Pruning intensity of *U. kirkiana*; Qs: Quotient. Chongoni forest= 1600-1770m, Dzalanyama forest= 1150-1295m, Kaning'ina forest= 1250-1370m, Malosa forest= 850-950m, Mangochi forest= 700-800m, and Perekezi forest= 1500-1600m

Population structures of *U. kirkiana* varied significantly among the different regions ($F = 7.30$; $p < 0.001$). In the Central Region (Figure 26a), the DBH class distribution showed a positively skewed pattern (Skewness = 1.28), dominated by individuals in the small size (10-20 cm) classes. Large individuals in the > 45 cm classes were largely missing. In the northern region (Figure 26b), the size classes distribution was also positively skewed (Skewness = 1.36), with a pronounced accumulation in the 10-20 cm classes, moderate presence in the 20-30 cm classes, and a near absence of individuals beyond 50 cm. Conversely, the southern region (Figure 26c) exhibited a less

pronounced skewness (Skewness = 0.86), showing a slightly more balanced distribution. Although the 10-20 cm classes remained dominant, larger individuals (> 50 cm) were marginally more present than in the other regions. The individuals in the 5-20 cm classes dominated the size-class distribution. The populations in the northern region had more small-size individuals than those in the central and southern regions. In contrast, the populations in the north and south had more large-size individuals compared to the populations in the central region (Figure 26). Overall, the permutation index for the whole population as well as for the populations in the different regions were greater than zero. The highest PI was observed in the central region (Figure 26a).

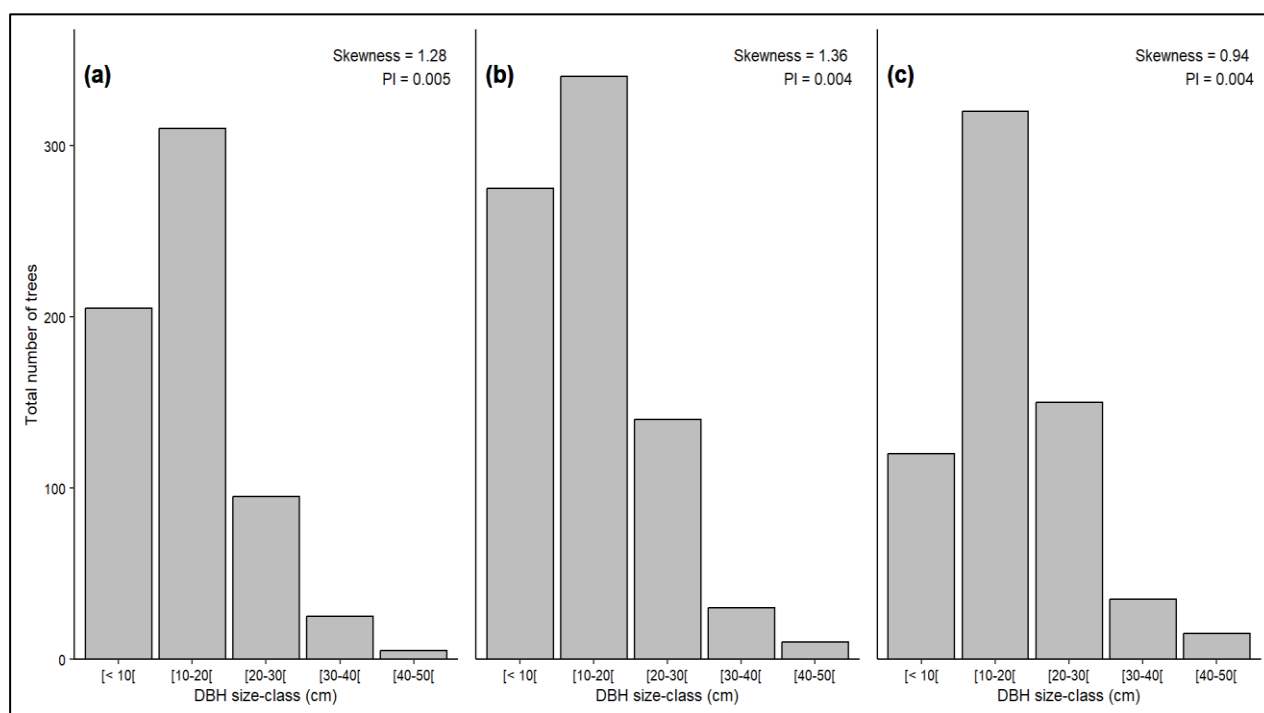


Figure 26: Size (dbh) class distribution of *U. kirkiana* populations in each region in Malawi

Key: (a): Central Region; (b): Northern Region; (c): Southern Region; PI: Permutation Index

Additionally, the DBH size-class distribution of *U. kirkiana* varied across different altitudinal gradients (Figure 27). Small-sized individuals (10-20 cm) (Figure 27a-e) dominated most populations' structures. Conversely, the altitude (850-959) was characterized by populations with a bell-shaped structure, dominated by individuals in the 20-30 cm DBH size classes (Figure 27f).

Large trees (>40 cm) were rare in all altitudes. The altitudes (Figure 27a-c) had the highest numbers of small trees.

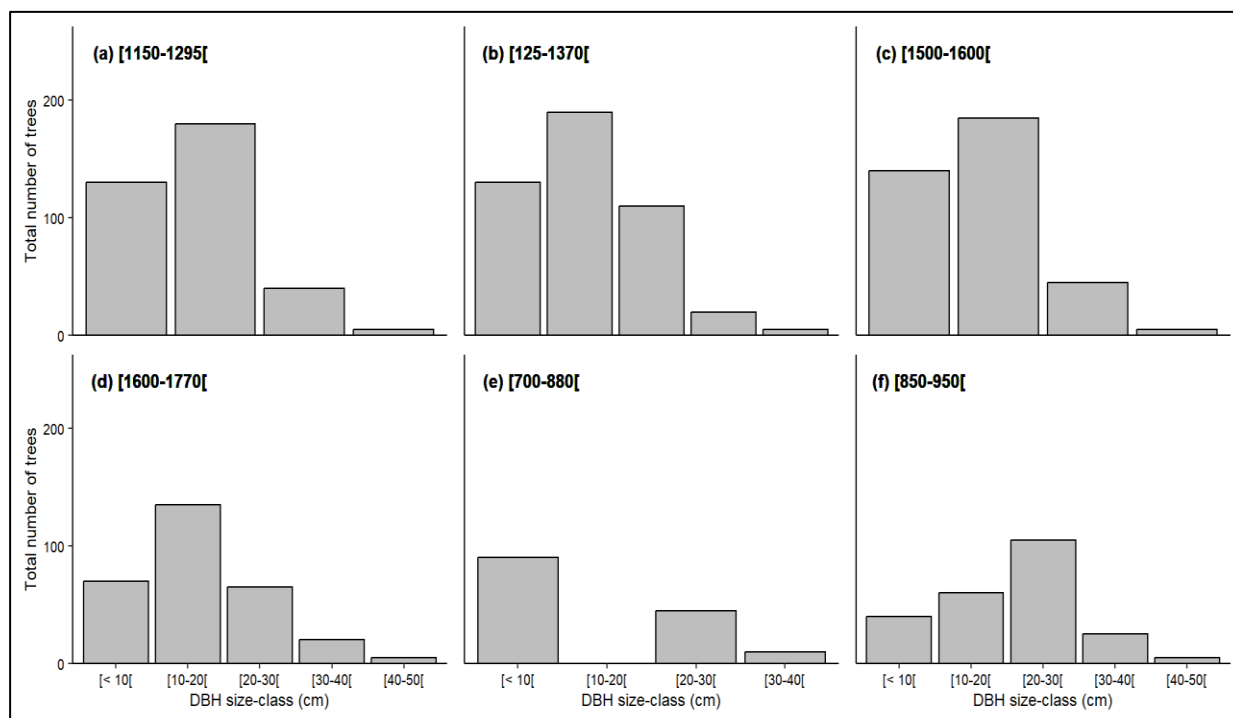


Figure 27: Size (dbh) class distribution of *U. kirkiana* populations across altitude in Malawi

Key: Chongoni forest= 1600-1770m, Dzalanyama forest= 1150-1295m, Kaning'ina forest= 1250-1370m, Malosa forest= 850-950m, Mangochi forest= 700-800m, and Perekezi forest= 1500-1600m

The quotient (Q_s) indicated that the species populations of *U. kirkiana* were not uniformly distributed, across DBH classes, with marked fluctuations between size classes, regardless of the region (Figure 28). However, *U. kirkiana* trees were more uniformly distributed in the smaller size classes than in the large size classes where large fluctuations indicating uneven distribution observed across regions (Figure 28). In contrast, the greatest fluctuation of large size individuals was observed in the central region (30-40 cm) class populations (Figure 28a). Additionally, the quotient (Q_s) across altitude indicated that the species populations of *U. kirkiana* were not uniformly distributed, across DBH classes, with marked fluctuations between size classes, regardless of altitude (Figure 28b). However, across altitude, *U. kirkiana* trees were more uniformly distributed in the smaller size classes than in the large size classes where large fluctuations were

observed, indicating uneven distribution (Figure 28b). In contrast, the greatest fluctuation of large size individuals was observed in the altitude (1600-1770m) (30-40) class populations (Figure 28b).

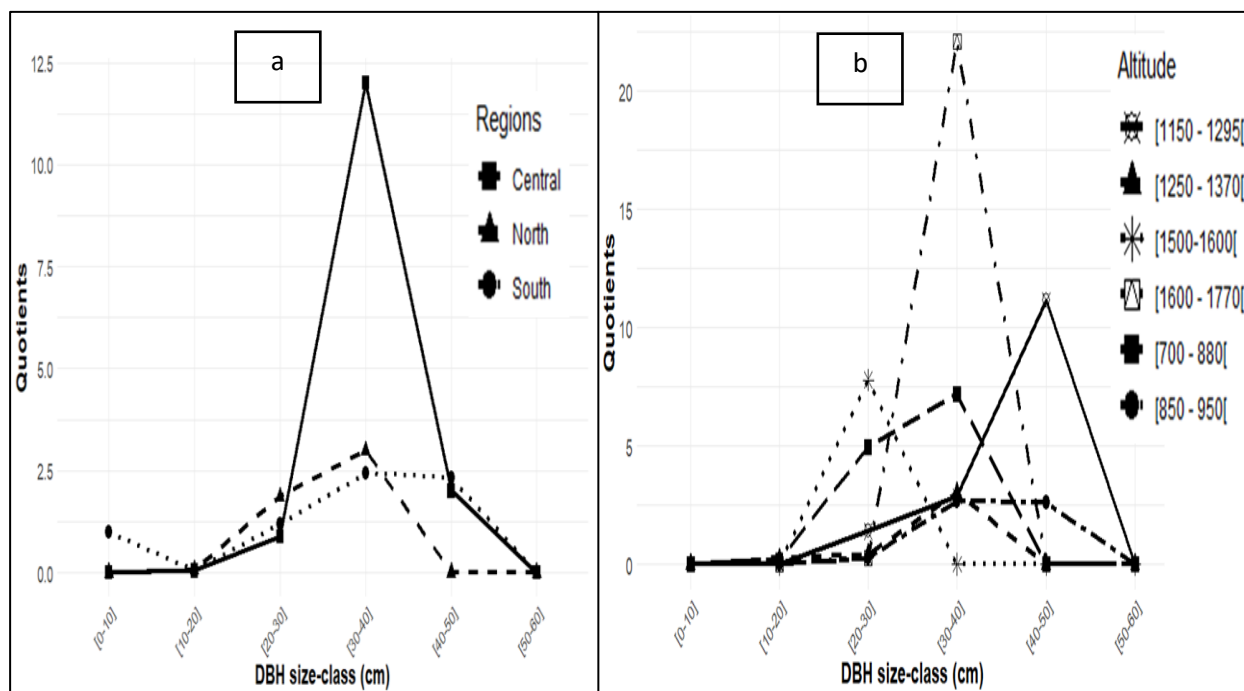


Figure 28: Quotients between *U. kirkiana* density in successive dbh size-classes (in 10 cm intervals)

Key: for each region in Malawi (a), and (b) for each altitude in Malawi. Chongoni forest= 1600-1770m, Dzalanyama forest= 1150-1295m, Kaning'ina forest= 1250-1370m, Malosa forest= 850-950m, Mangochi forest= 700-800m, and Perekezi forest= 1500-1600m

4.4.3 Natural regeneration and tree branches of *U. kirkiana* across the region

Overall, there was a variation in the number of regenerations based on the DBH of adult trees. In the Central Region (Figure 29A), a notable concentration of *U. kirkiana* regeneration was recorded under trees belonging to the diameter class (30-40 cm), while the extreme classes, namely (0-10 cm), (40-60 cm), showed very little regeneration. In the northern region (Figure 29B), the distribution of *U. kirkiana* regeneration appears more balanced, with a notable density under trees in the size (20-40 cm) and (50-60 cm) classes, while the (40-50 cm) class was almost absent. Unlike the central and northern regions, the southern region (Figure 29C) exhibited a decreasing distribution of *U. kirkiana* regenerations with increasing tree diameter. The highest densities of regeneration were observed under small trees (0-10 cm). Finally, apart from the northern region,

where significant regeneration was observed under large diameter trees (50-60 cm), the other regions showed almost an absence of regeneration in this class.

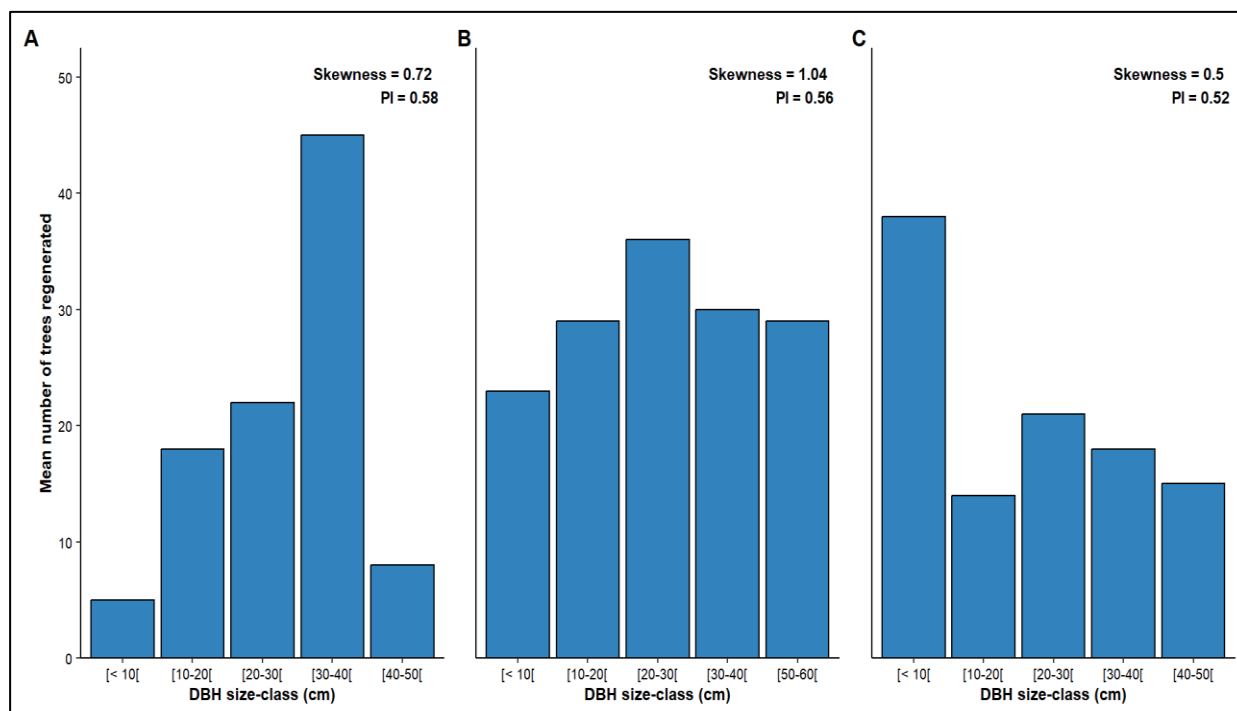


Figure 29: Number of trees regenerated distribution of *U. kirkiana* populations in each region in Malawi.

Key: (A): Central Region; (B): Northern Region; (C): Southern Region

Regarding the average number of branches per tree, a general trend of increase was observed with the growth of the tree diameter, and this was consistent across all the studied regions (Figure 30). This positive relationship indicated that trees with larger diameters tend to develop more branches. In the central and southern regions, the highest average number of branches was recorded in trees with a diameter between 30 and 40 cm. Conversely, in the northern region, the peak branching was observed in trees with a diameter between 50 and 60 cm. We also observed that the highest number of branches is shown in the north region (Figure 30b) and the smallest number of branches was observed in the central region.

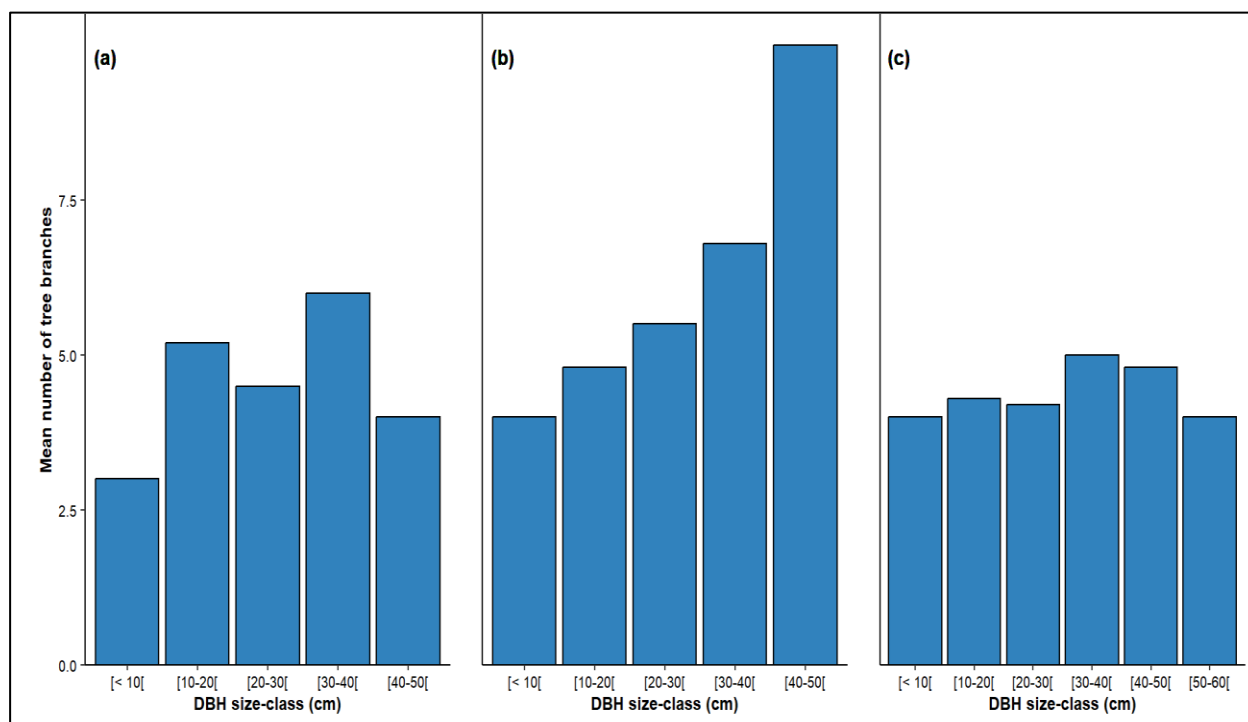


Figure 30: Number of tree branches distribution of *U. kirkiana* populations in each region in Malawi

Key: (a): Central Region; (b): Northern Region; (c): Southern Region

4.4.4 Biomass, carbon potential and ecological value of carbon storage by *U. kirkiana* across regions in Malawi

The biomass and carbon sequestered by *U. kirkiana* per hectare in the Central, Northern, and Southern regions of Malawi highlighted variation in carbon storage potential (Table 33). The Northern Region exhibited the highest total biomass (31,496.13 kg/ha), representing a living carbon stock of 15,748.07 kgC/ha, approximately 57.80 tons of CO₂ sequestered per hectare. The Southern region followed with 27,929.11 kg/ha of biomass and 51.25 tCO₂/ha, while the Central region recorded the lowest values (23,871.78 kg/ha, 43.80 tCO₂/ha), although statistically significant ($p < 0.05$). From an economic perspective, the valuation of sequestered carbon was estimated in Malawian kwacha, using a benchmark rate based on voluntary carbon markets. Thus, the northern region displayed an average economic value of 1,011,997.57 MKW/ha, followed by the Southern Region (897,385.99 MKW/ha) and the Central Region (767,020.44 MKW/ha).

Table 33: Estimation per hectare of living biomass, sequestered carbon, and the ecological value of carbon storage by *U. kirkiana* across regions in Malawi

Regions	Aboveground biomass (KG)	Below ground carbon (KG)	Total living biomass (KG)	Total living carbon (KG)	Carbon dioxide (CO ₂) (ton)	Economic Value of Sequestered Carbon (MKW)	Pvalue
Central	19759.16	4112.61	23871.78	11935.89	43.80	767 020.44	
North	26095.20	5400.94	31496.13	15748.07	57.80	1 011 997.57	
South	23168.94	4760.17	27929.11	13964.55	51.25	897 385.99	< 0.05 ***

Key: MKW = Malawian kwacha; 1 Dollars = 1751Mkw

4.5 Shifts in suitable habitats of *U. kirkiana* under climate change in Malawi

4.5.1. Model performance and relative importance of environmental variables

The Area Under Curve value was 0.93 (Figure 31). Indicating that the model had an excellent performance.

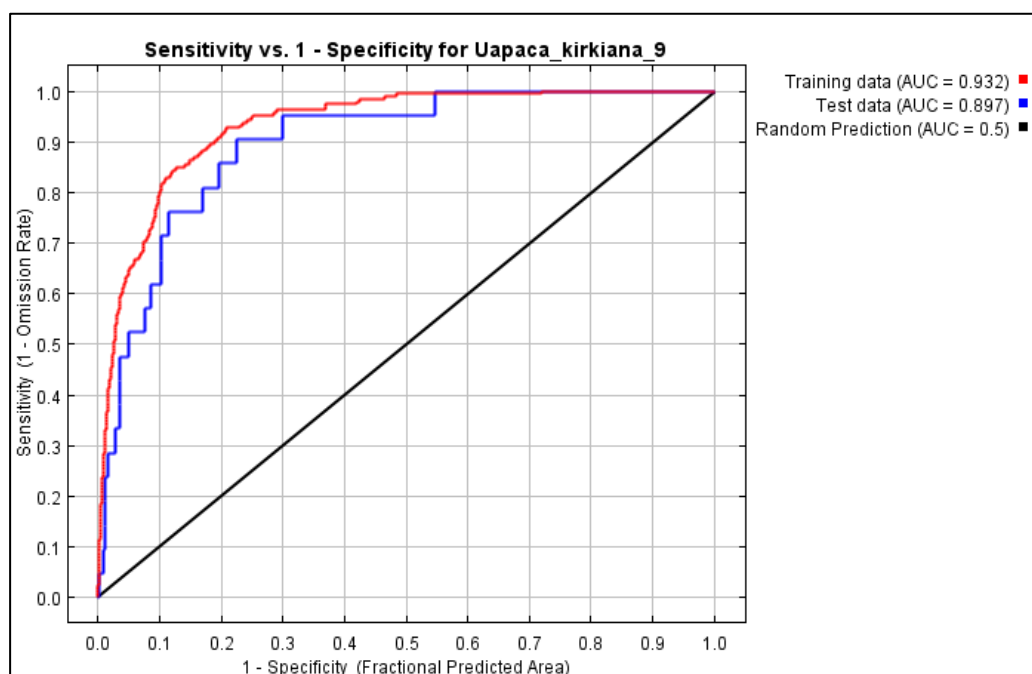


Figure 31: Area Under Curve showing the performance of *U. kirkiana* distribution model based on the training and test data

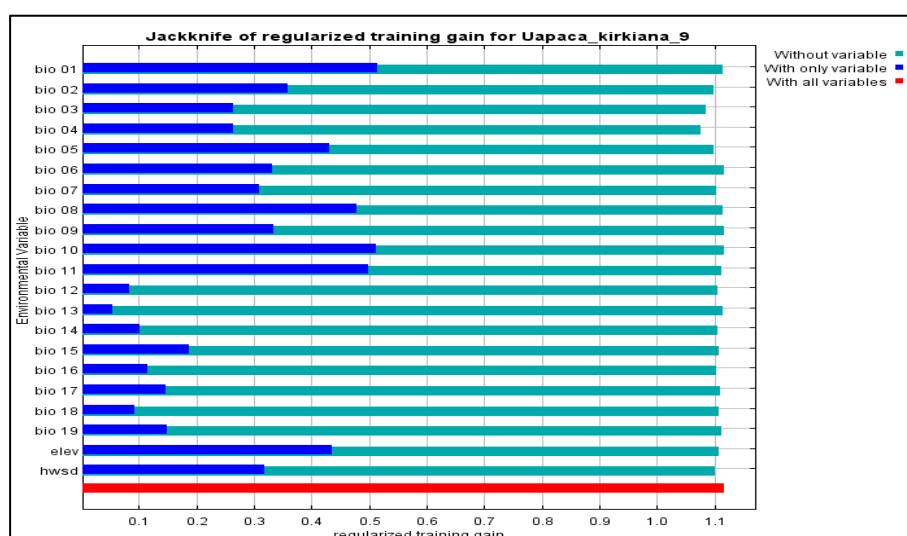
Similarly, the mean values of TSS and SEDI were 0.86 and 0.95 respectively (Table 34), indicating a very good predictive capability of the model.

Table 34: Performance statistics of *U. kirkiana* distribution model

Performance Index	Value
T	0.32
AUC	0.93
Omission rate	0.05
H	0.95
S	0.91
F	0.09
TSS	0.86
K	0.77
SEDI	0.95

Key: T = Threshold, AUC = Area Under Curve, H = sensitivity, S = specificity, F = False positive rate, TSS = True Skill Statistic, K = Kappa, SEDI = Symmetric Extremal Dependence Index

Based on the permutation importance (Figure 32), the jackknife test (Figure 32) and the partial dependence curves (Figure 33), Isothermally (BIO3) was the most important bioclimatic variable owing to its substantial contribution to the current potential distribution of the species. The highest probability of occurrence for *U. kirkiana* occurred around a BIO3 value of approximately 5.5% (Figure 33). The mean temperature of the coldest quarter (BIO11) and the mean temperature of the driest quarter (BIO10) displayed the second and third largest contribution to the potential distribution of the species with peaks of species occurrence at around 28°C and 27.5°C, respectively (Figure 33).

**Figure 32:** Receiver Operating Characteristic (ROC) curve showing the performance of *U. kirkiana* distribution model based on the training and test data

Key: For a given predictor variable, the corresponding green bar (without variable) shows how much the total gain is decreased if this specific variable is excluded from the model. The blue bar (with only variable) shows the obtained gain if the considered variable is used in isolation and the others are excluded from the model.

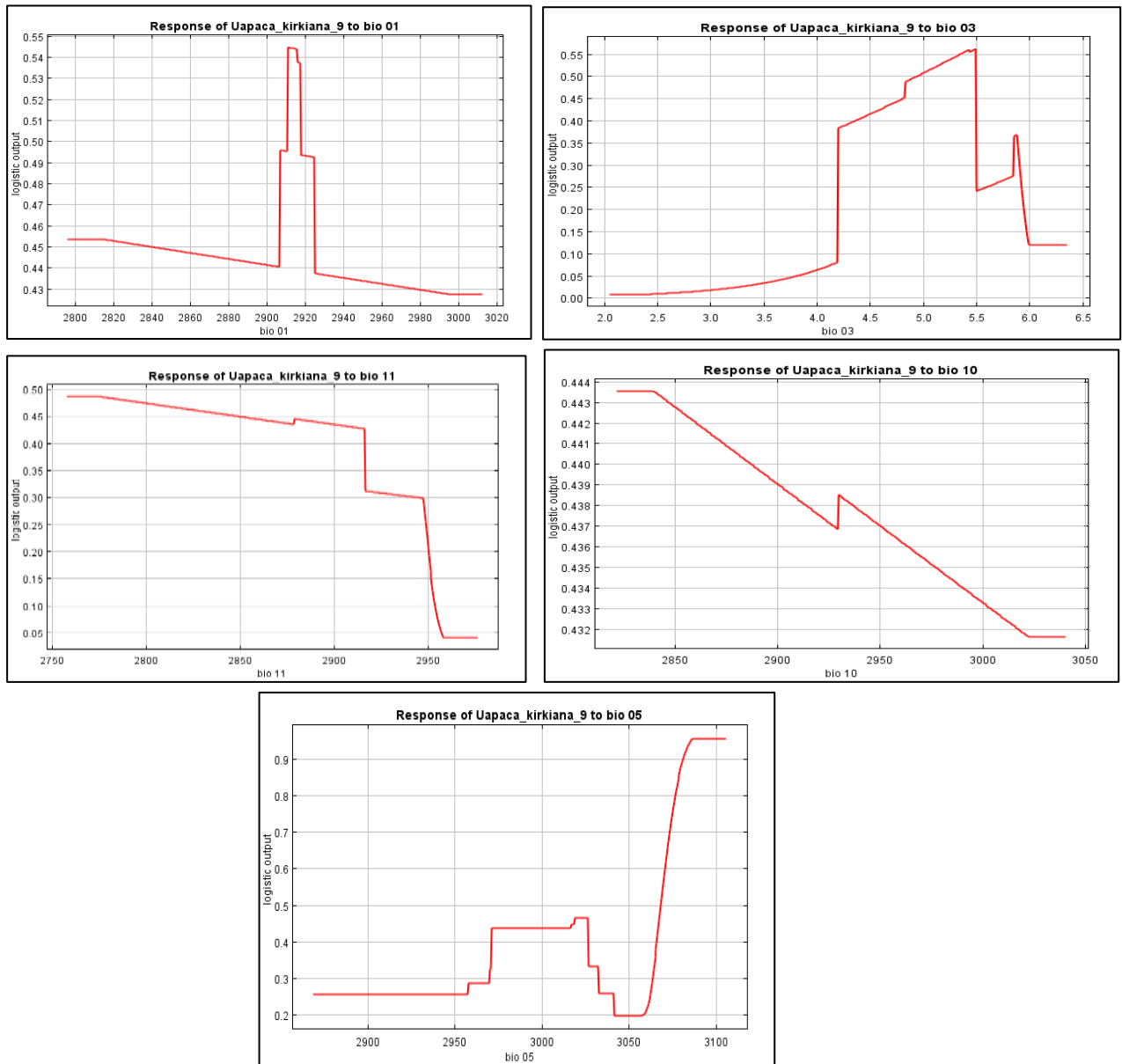


Figure 33: Response curves showing the effects of environmental variable on the predicted habitat suitability for *U. kirkiana*.

Key: The values of BIO11 and BIO10 in bioclimatic datasets like CHELSA (Climatology's at High resolution for the Earth's Land Surface Areas) are typically in hundredths of degrees Celsius. To prevent decimal points, the values are multiplied by 100. This is a standard procedure in raster datasets to reduce file size and preserve accuracy. *U. kirkiana* was sensitive to changes in the climatic variables BIO1, BIO3, BIO5, BIO10, and BIO11, as shown by the response curves in Fig. S3. The species occurrence probability decreased gradually with increasing BIO1 values but peaked in the middle range of BIO1 values (highest peak at around 29°C), suggesting a preference of the species for moderately warm climatic conditions. The species' response to BIO3 (isothermality) showed a gradual increase, peaking at around 6.5 before abruptly declining afterward, suggesting that relatively high levels of isothermality are favorable for the species occurrence. The BIO5 rose to a maximum before declining, with a peak in the probability of occurrence at around 30.7°C. A gradual and consistent decline of probability of occurrence was observed with increasing BIO10, suggesting that lower values of BIO10 are the most suitable for the species survival. A trend similar to that of BIO10 was observed for BIO11, with low suitability at higher BIO11 values. These variations highlighted how *U. kirkiana* responded to temperature and seasonality changes.

The mean maximum temperature of the warmest month (BIO5) and the annual mean temperature (BIO1) also contributed significantly to the species distribution. *U. kirkiana* had the highest probability of occurrence at high BIO5 values around 31°C, with moderately favorable and fluctuating conditions between 29.5°C and 30.5°C. The highest probability of occurrence was observed around 29.1°C for BIO1. Elevation (percent contribution of 5.8%) was also considered as an important contribution given its high importance in predicting the species distribution when used in isolation in the jackknife test. The contribution of the remaining variables was minimal (Figure 34).

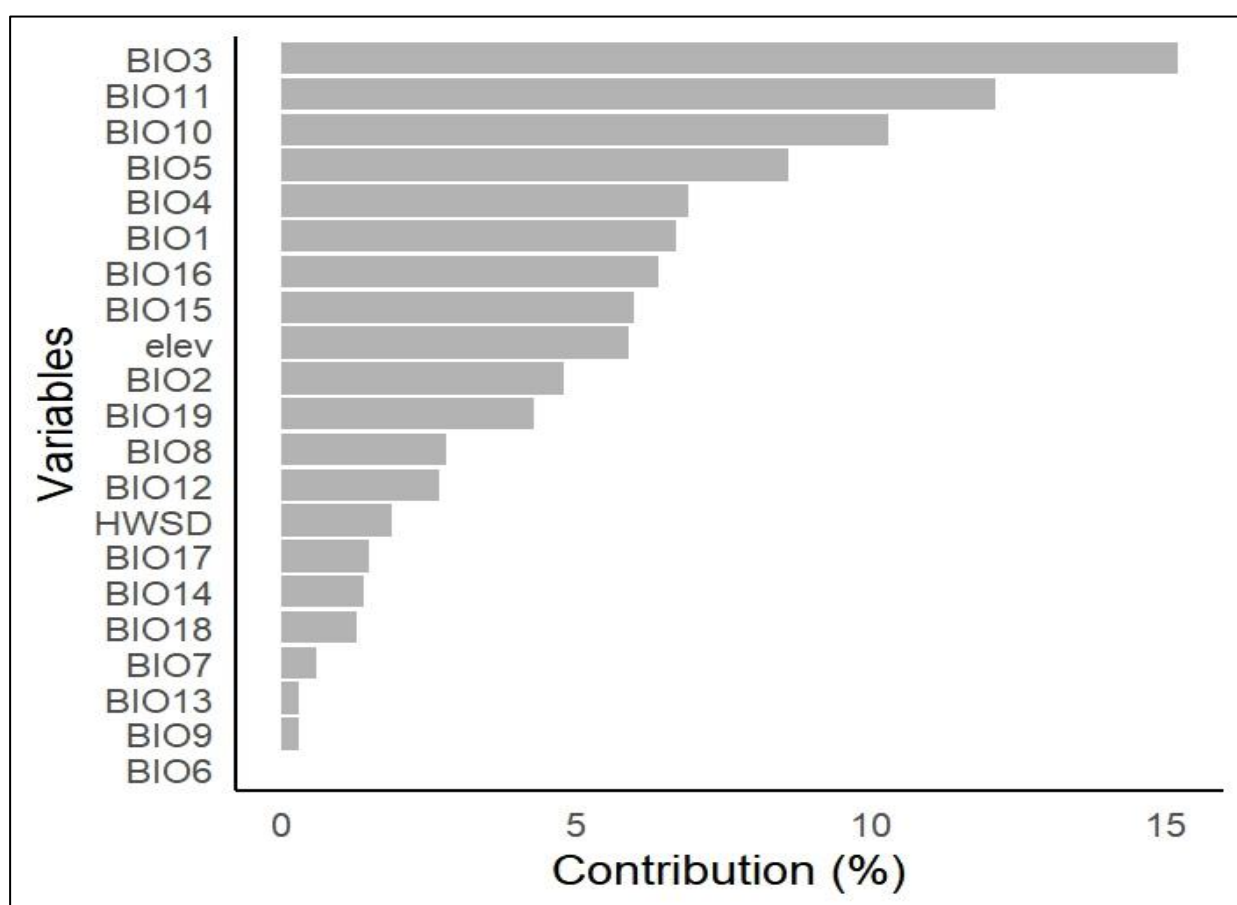


Figure 34: Contribution (%) of the environmental variables to the potential distribution of *U. kirkiana* in Malawi

Key: HWSD = Soil types; BIO1 = annual mean temperature; BIO2 = mean diurnal range; BIO3 = isothermality; BIO4 = temperature seasonality; BIO5 = maximum temperature of warmest month; BIO6 = minimum temperature of coldest month; BIO7 = Temperature Annual Range (BIO5 - BIO6); BIO8 = Mean Temperature of the Wettest Quarter; BIO9 = Mean Temperature of the Warmest Quarter; BIO10 = Mean Temperature of the Driest Quarter; BIO11 = Mean Temperature of the Coldest Quarter; BIO12 = Annual Precipitation; BIO13 = Precipitation of Wettest Month; BIO14 = Precipitation of the Driest Month; BIO15 = Precipitation Seasonality (Coefficient of Variation); BIO16 = Precipitation of Wettest Quarter; BIO17 = Precipitation of the Driest Quarter; BIO18 = Precipitation of the Warmest Quarter; BIO19 = Precipitation of the Coldest Quarter.

4.5.2. Suitable habitats for *U. kirkiana* in Malawi

The predicted suitable area for the species occurrence under the three scenarios (i.e., current, SSP3-7.0 and SSP5-8.5) is shown in Figure 35 and 36. Under the current climate, 9.29% of Malawi's land was classified as very suitable, 17.39% moderately suitable, 25.20% poorly suitable and around 48.12% of the land was predicted as unsuitable (Figure 35). There was a reduction in highly suitable areas in the future climate scenarios, decreasing from 9.29% under the current conditions to 8.01% under the SSP3-7.0 scenario and to 6.21% under the SSP5-8.5 scenario. A similar trend was observed for the moderately suitable areas, which declined from 17.39% to 16.83% under SSP3-7.0. Conversely, the moderately suitable areas slightly increased from 17.39% to 17.73% under the SSP5-8.5 scenario. The poorly suitable areas increased under all future scenarios (from 25.20% to 26.97% under SSP3-7.0 and from 25.20% to 29.73% under SSP5-8.5). Consequently, the percentage of unsuitable land increased from 48.12% under the current climate to 48.19% under the SSP3-7.0 scenario but decreased to 46.33% under the SSP5-8.5 scenario (Figure 35).

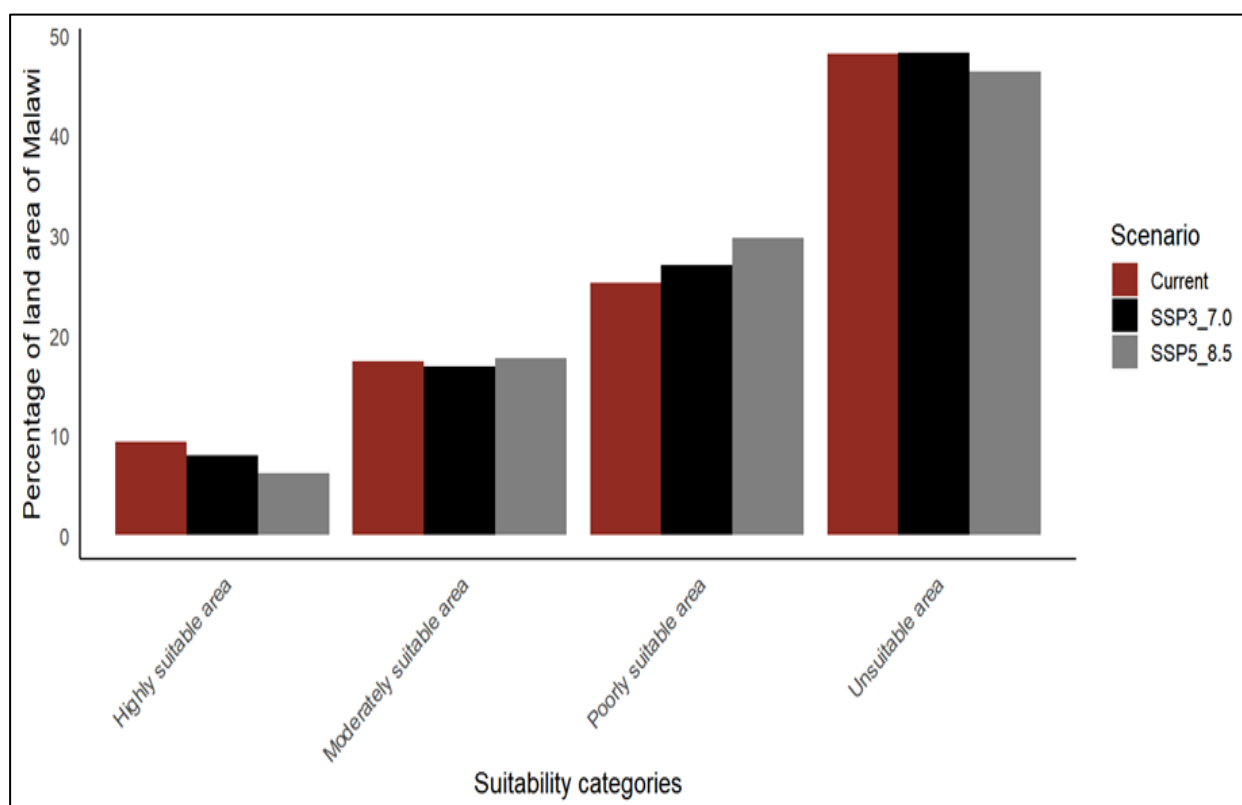


Figure 35: Area (% of the Malawi's total land area) covered by *U. kirkiana* suitable and unsuitable habitats under the current and future climates

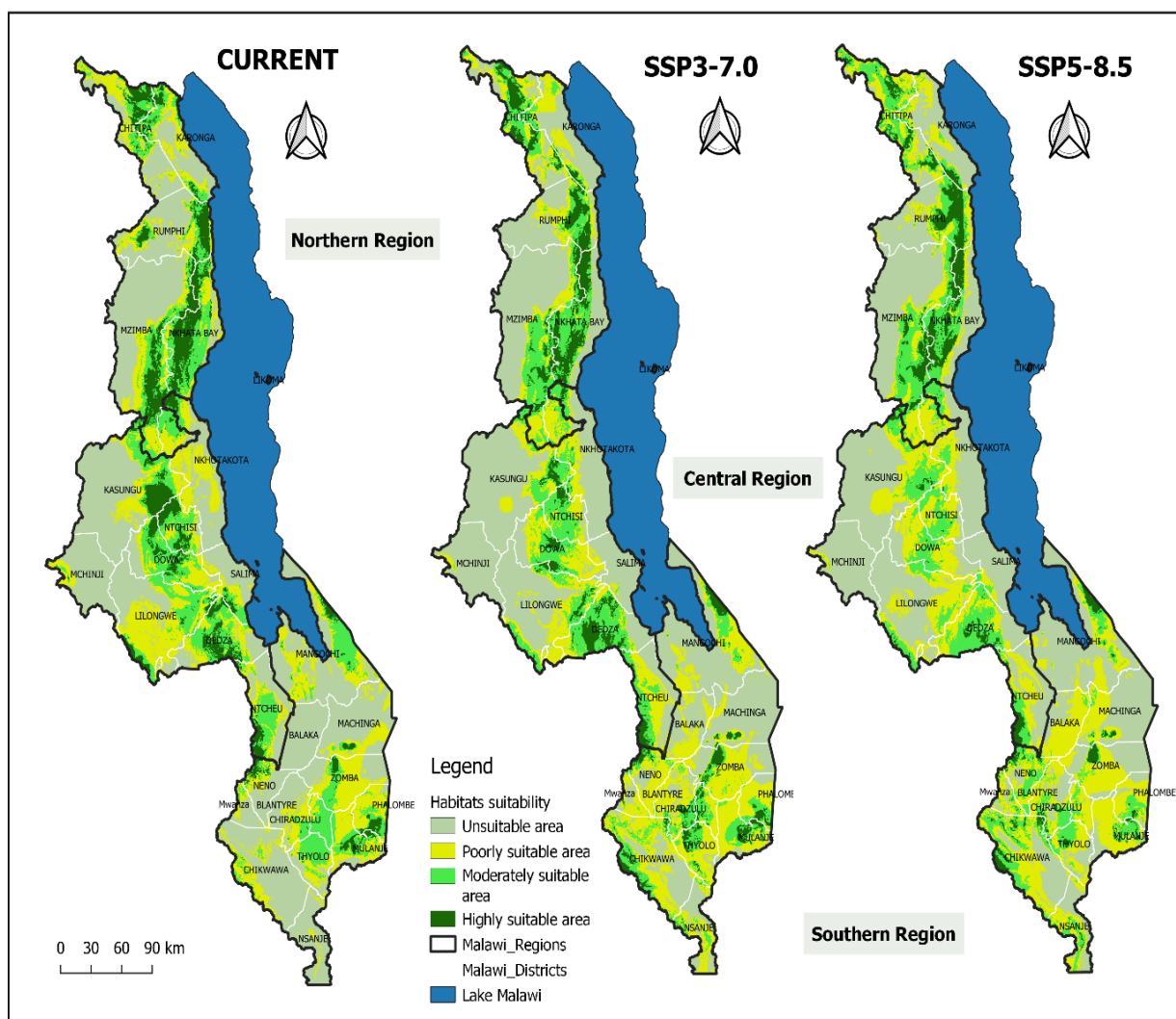


Figure 36: Predicted distribution of *U. kirkiana* under the current climate and the future climate scenarios (SSP 3-7.0 and SSP 4-8.5)

Key: Future projections was projected to 2040-2060. SSP3-7.0: Socioeconomic Pathway, characterize by High emissions, difficult mitigation & adaptation. SSP4-8.5: Socioeconomic Pathway, characterize by Very high emissions, extreme warming, severe impacts

These results were confirmed by the patterns of the rate of changes observed across the future scenarios (Figure 37). Notably, a higher decrease rate in highly suitable areas was observed for SSP5-8.5 (-1.80%) compared to SSP3-7.0 (-1.28%). A large rate of decrease in unsuitable areas was predicted under SSP5-8.5 whereas a positive rate of change was recorded for unsuitable areas under SSP3-7.0 (Figure 37).

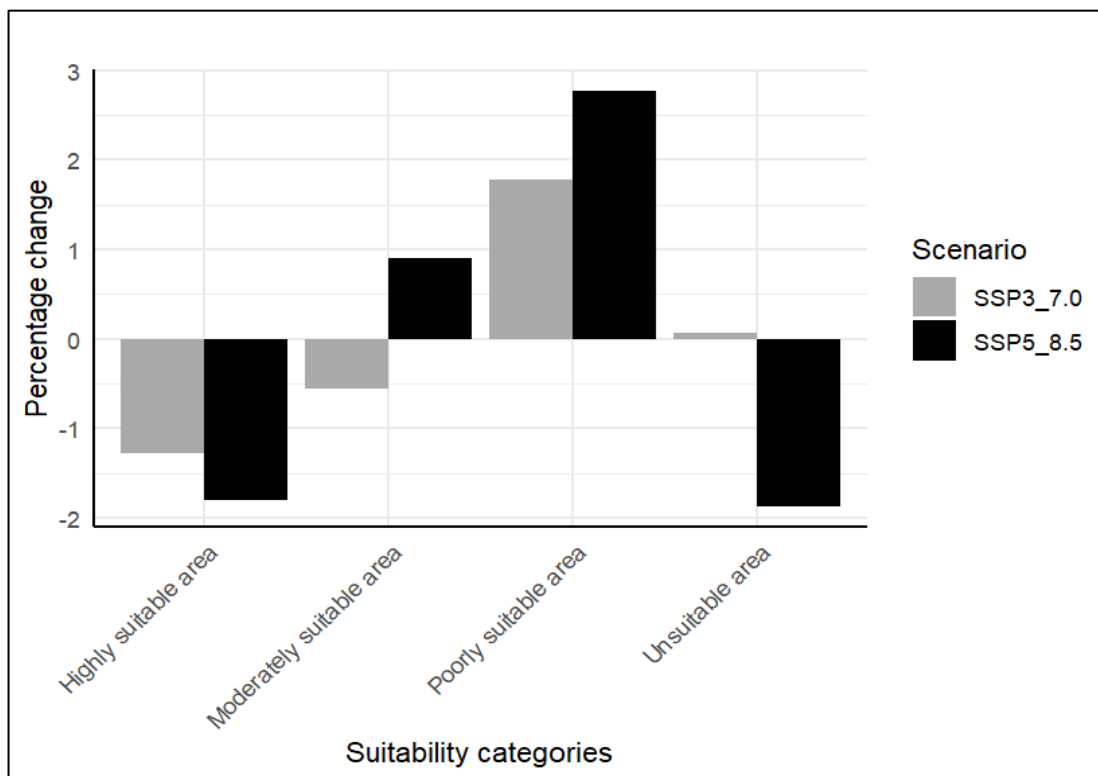


Figure 37: Rate of change in potential habitats of *U. kirkiana* in Malawi under SSP3-7.0 and SSP5-8.5 scenarios

The findings on habitat projection of change dynamics of *U. kirkiana* under SSP3-7.0 and SSP5-8.5 scenarios is presented in Figure 38. In-depth analyses of habitat range shifts indicated different change dynamics for *U. kirkiana* in terms of habitat loss (areas that transitioned from a more suitable category e.g., highly or moderately suitable under the current scenario to a less suitable category e.g., poorly suitable or unsuitable in the future scenarios), stability (areas where the suitability category remains unchanged across scenarios), and gain (areas that transitioned from a less suitable category e.g. unsuitable or poorly suitable under the current scenario to a more suitable category e.g., moderately or highly suitable in the future scenarios) under future scenarios (Figure 38). In the SSP3-7.0 scenario, there was a moderate gain (12.09%) and a slight loss (13.85%) in 74.06% of the habitats. Under the current climate, unsuitable areas comprised 61.58% of stable areas. As opposed to this, the SSP5-8.5 scenario resulted in habitat gain of 18.18% and habitat loss of 53.88% with more noticeable losses in poorly suitable (9.77%) and moderately suitable (2%) areas (Figure 38).

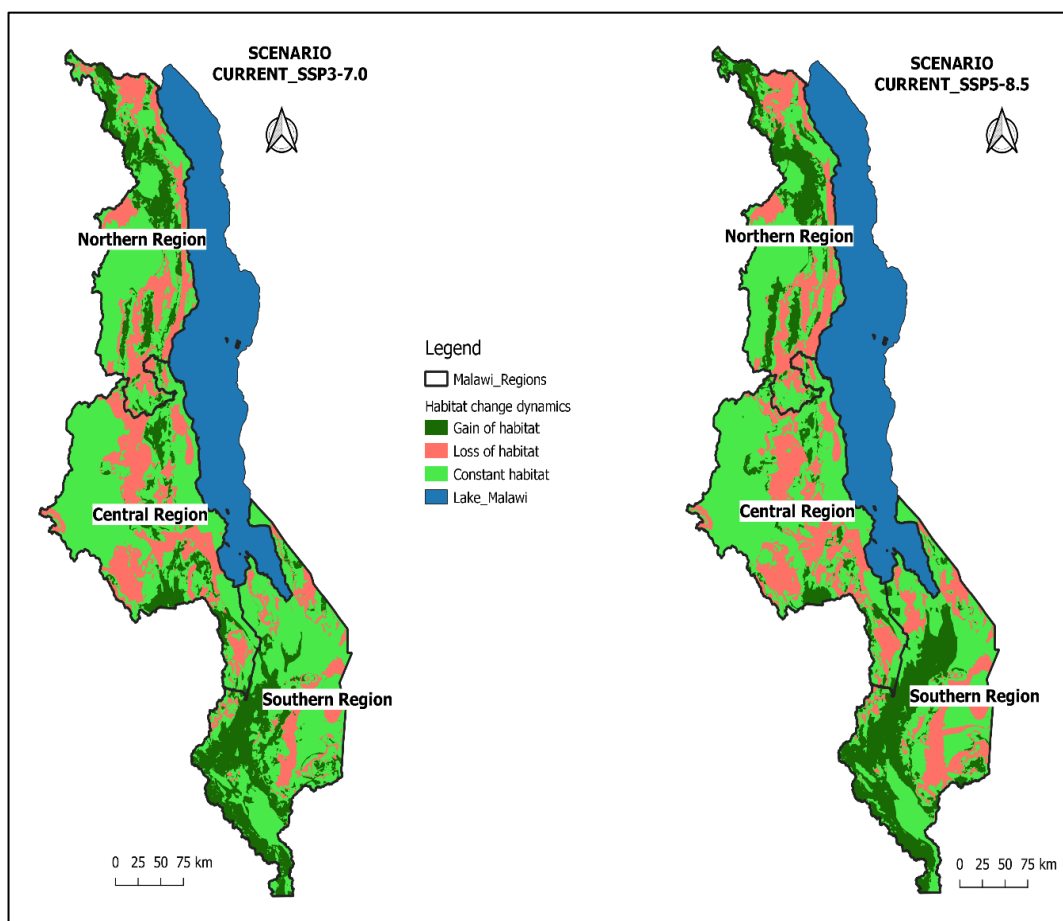


Figure 38: Projection of habitat change dynamics for *U. kirkiana* under SSP3-7.0 and SSP5-8.5 scenarios

Key: The categorical color scheme directly maps these expected dynamics: Dark Green represents areas of Projected Habitat Gain, indicating regions where future climatic conditions are anticipated to become significantly more suitable for the species' survival and expansion. Conversely, Red denotes Projected Habitat Loss, identifying current suitable areas that are expected to become climatically unfavorable, marking regions highly vulnerable to extirpation under these severe future conditions. Finally, Light Green signifies Constant Habitat, representing those areas projected to maintain long-term climatic stability and suitability for the species, which are crucial for establishing conservation strongholds against climate change impacts.

4.5.3. Priority conservation and cultivation area of *U. kirkiana* in Malawi

The geographical distribution of priority areas for the protection and cultivation of *U. kirkiana* along Malawi's three economic Regions is shown in Table 36. Notably, the very higher priority classes (>75%) exhibited a higher proportion of priority areas in the Northern and Central regions (Figure 39). With 35.64% of its territory falling within the 75-100% priority class, the Northern region emerged as a very important region for the conservation of *U. kirkiana*. The Southern region only contributed 16.39% to the very high priority areas, despite having a considerable share in the

middle priority areas (20-75%). Furthermore, the proportion of high priority areas (20-75%) was higher than that of very high priority habitats (75-100%).

Table 36: Regional variation in priority levels (%) for *U. kirkiana* in Malawi

Priority level (%)		0 – 20%	20 – 50%	50 – 75%	75 – 100%
Regions	Northern	21.99	21.84	20.53	35.64
	Central	25.06	19.04	27.45	28.45
	Southern	25.69	30.84	27.08	16.39

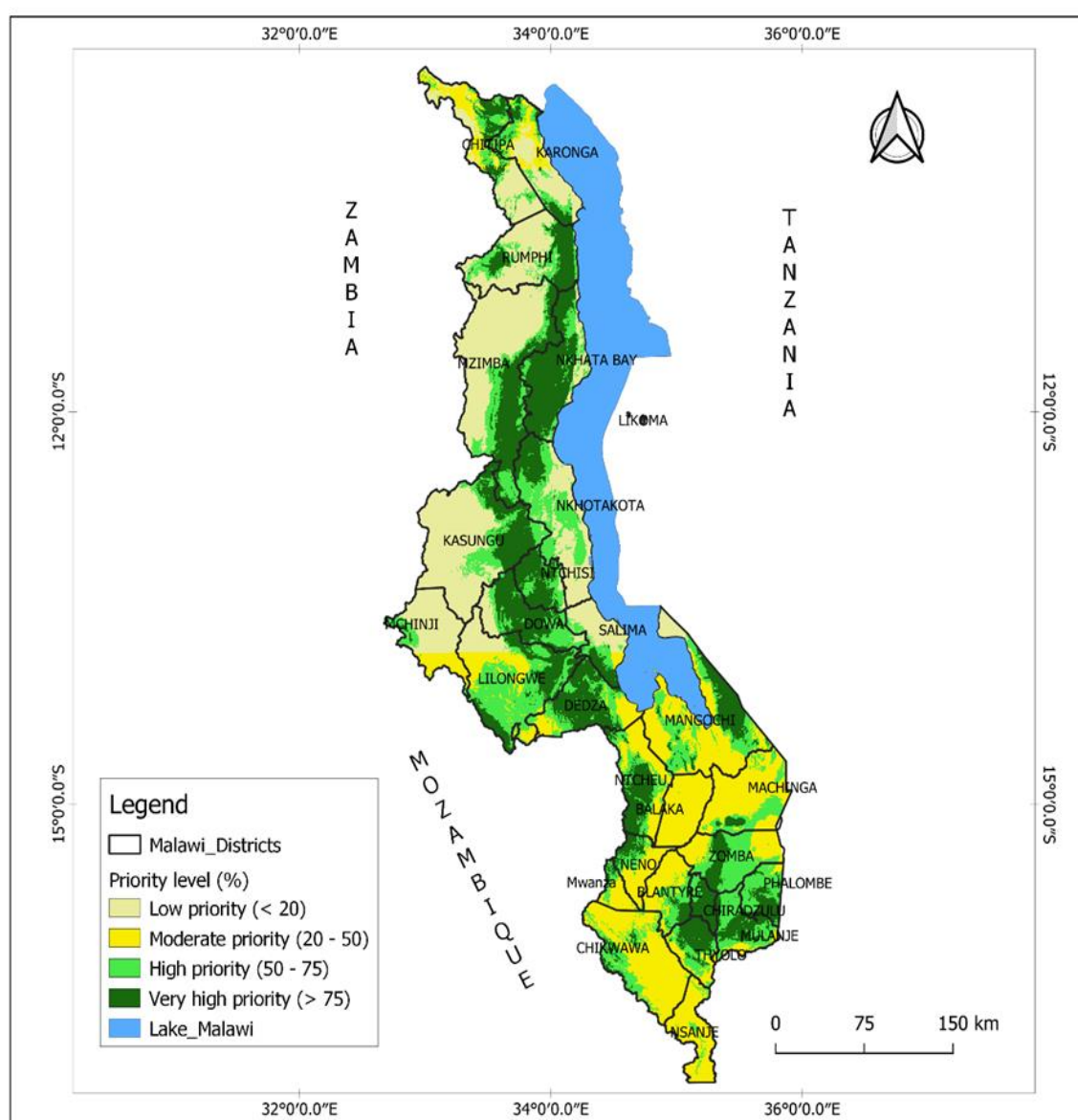


Figure 39: Priority areas for the conservation of *U. kirkiana* in Malawi

CHAPTER 5: DISCUSSION

5.0 Introduction

This chapter discusses the findings presented in Chapter four, integrating insights on local ecological knowledge, ethnobotanical uses, and community-based conservation strategies of *U. kirkiana* in Malawi. The discussion situates these results within the broader literature on the species' ecology, functional traits, population dynamics, and climate-driven distribution shifts. It highlights points of convergence and divergence with previous studies and explores the implications for sustainable management, conservation, and the livelihoods of local communities.

5.1 A Combined Socio-Ecological Perspective on *U. kirkiana* Health and Productivity

5.1.1 Local perception on the dynamics of *U. kirkiana* Population: Insights for awareness raising

The study revealed that local communities are aware of the declining *U. kirkiana* populations in all regions of Malawi (Figure 3). This result indicates a high level of ecological knowledge among community members regarding species status, which can be leveraged for conservation and management initiative. The majority of elderly and adult individuals reporting declining in the species (Table 11) suggest that they have personally experienced declining populations over time. This trend highlights the significant ecological knowledge held by local communities, which is crucial for developing effective conservation and management strategies. Interestingly, younger respondents also recognized the decline, suggesting that environmental education and awareness initiatives have enhanced the understanding of natural resource dynamics among the youth. Regional differences in perception were evident. Participants from the Northern regions reported higher species abundance, reflecting more favorable pedoclimatic conditions for *U. kirkiana*. In contrast, conservation efforts in agroforestry systems were more commonly reported in the Southern Region, despite lower species availability. This pattern may indicate that scarcity in certain areas stimulates local efforts to manage and conserve the species.

The study also identified key human and environmental factors contributing to population decline. Activities such as deforestation, charcoal production, population growth, and agricultural expansion were recognized as primary drivers, alongside climate change and weak enforcement of forestry laws. The recognition of both anthropogenic and climatic threats by respondents suggests a nuanced understanding of the pressures affecting *U. kirkiana*, which can inform targeted conservation interventions. These results have significant implications for conservation and sustainable management. The awareness of species decline across all age groups underscores the potential for engaging entire communities in participatory decision-making and ecological restoration. Moreover, the observed regional variation in perceptions points to the need for locally tailored strategies that consider differences in species abundance and environmental conditions. When compared with other studies, these findings are largely consistent with previous research in Sub-Saharan Africa. Ntupanyama et al. (2008), reported that anthropogenic pressures on customary lands contribute to declines in *U. kirkiana* populations. Similar perceptions of resource decline were noted for *Tamarindus indica* in Togo (Samarou et al. (2021) and other natural plant resources (Lokonon et al. 2021; Zon et al. 2022; Tiétiambou et al. 2020; Rabiou et al. 2017). The regional differences in conservation effort reflect patterns observed for *Pseudocedrela kotschy* in Benin, where species abundance influenced local management practices (Deguenonvo et al. 2023).

In contrast, Biaou et al. (2023b), showed that respondents in Benin had limited awareness of climate change impacts on *Pterocarpus erinaceus*, suggesting that knowledge gaps can constrain the adoption of sustainable management practices. This is consistent with earlier studies indicating that climate change perception varies significantly across African regions, influenced by education level, livelihood dependence, and the frequency of climate-related disruptions (Deressa et al. 2011). Compared to these contexts, the relatively high climate-change awareness observed among Malawian communities may stem from repeated climate-related shocks such as floods, droughts, and erratic rainfall, which have intensified over the past decade (McSweeney et al. 2010). Several studies indicate that populations experiencing recurrent climate stresses often develop a stronger

understanding of environmental change and its impacts on local resources (Nkomwa et al. 2014). Additionally, Malawi has benefited from multiple climate adaptation programs and community-based natural resource management (CBNRM) initiatives that enhance public knowledge about climate risks and ecosystem conservation (Kamoto et al. 2013). This institutional exposure may explain why local communities engaged in the management of *U. kirkiana* demonstrate comparatively higher awareness of both species decline and climate-change impacts.

5.2 Local conservation practices of *U. kirkiana*: an opportunity for capacity building

The findings indicate that, *U. kirkiana* conservation is actively supported by local communities throughout Malawi (Figure 4a and b), primarily through measures like field conservation in agroforestry systems, preservation of natural regeneration, prevention of cutting, and control against excessive trimming. According to these metrics, communities are motivated to preserve and protect the species because they believe it to be socially and economically significant. The close socioeconomic ties between the species and local livelihoods probably explain the high degree of involvement seen. These practices have two implications: firstly, they directly support biodiversity conservation by lessening the strain on natural populations; secondly, they enhance local communities' quality of life by ensuring that ecosystem services are continuously available. These results are consistent with the argument that local knowledge plays a central role in biodiversity management and rural well-being (Galluzzi et al. 2010). The involvement of local communities in the conservation efforts for *U. kirkiana* in all regions of Malawi is likely due to its socio-economic importance. This aligns with Sawchuk et al. (2015) who support the idea that local community engagement in wild plant conservation increases when people have greater knowledge about these plants, which also fosters more positive attitudes toward their protection.

Despite these positive practices, techniques such as deliberate planting and participants rarely mentioned assisted natural regeneration. This limited adoption may be due to gaps in knowledge or lack of awareness regarding propagation and management of the species. The absence of active planting practices suggests that without external interventions, communities tend to rely primarily

on passive forms of conservation. To address this, policies that formally recognize the ecological and economic value of native species, coupled with training programs on propagation and management, could encourage stronger community engagement. Such interventions would not only enhance local conservation efforts but also shift perceptions towards proactive preservation and restoration of the species. These findings align with others studies conducted on neglected indigenous trees. For instance, *Vitellaria Paradoxa* C.F. Gaertn., *Parkia. biglobosa* (Jacq.) R.Br. ex G.Don and *Adansonia. digitata* L. have been conserved by communities using similar measures of on-farm protection, natural regeneration, and cutting restrictions (Okiror et al. 2012; Teklehaimanot 2004; Chawafambira et al. 2020). Furthermore, Sawchuk et al. (2015) emphasised that when communities have greater knowledge about wild plants, their willingness to engage in conservation increases, and their attitudes toward species protection become more favorable. This confirms that awareness and knowledge enhancement are central drivers of conservation behavior.

Age and profession have an impact on the adoption of conservation measures for *U. kirkiana* (Table 12). Professional organisations that have demonstrated limited involvement in conservation efforts include hunters, state authorities, and dealers. Given that, their primary professions are unrelated; this might be the result of their ignorance of how their actions affect the species' ability to survive. To help *U. kirkiana* conservation in Malawi, our research emphasises the necessity of concentrated ecological education on how different uses affect the species' dynamics. The seniors, the majority of whom work as farmers, thought that these measures were suitable for conservation. Conservation practices may be more likely to be adopted by those who depend on natural resources or are directly involved in their management, such as farmers. This finding was supported by the fact that respondents who are not involved in managing natural resources tended to have lower conservation attitudes than farmers. Through their delayed interactions with agricultural landscapes and ecosystems, as well as their cultural or traditional attachment to natural resources, farmers often have strong ties to nature (Gouwakinnou et al. 2019; Biauou et al. 2023b). Their understanding of the importance of protecting ecosystems for their livelihoods, cultural heritage, and the

sustainability of their farming practices can be enhanced through this hands-on experience (Gilbert 2018).

The study revealed that participants recognised a broad spectrum of ecosystem services provided by *U. kirkiana* and its habitats. Specifically, three provisioning services were emphasised food, energy, timber, and medicine along with two supporting services, namely pollination and water cycling, and one cultural service, represented by the perceived importance of landscapes for shade and tranquility (Figure 5). These results highlight the multifunctional role of *U. kirkiana* in sustaining rural livelihoods. The implications of these findings are significant. The prominence of provisioning services in local perceptions underscores the direct dependence of rural households on natural resources for daily subsistence. Food, fuelwood and medicinal uses contribute to both nutritional security and household health, while timber provides essential material for construction. Supporting services such as pollination and water cycling illustrate that communities also recognize the ecological functions that maintain agricultural productivity and ecosystem resilience. Meanwhile, the cultural value attributed to shade and tranquility reflects the species' role in human well-being beyond material benefits. These perceptions reveal an important difference between rural and urban communities. Whereas urban populations often prioritize cultural, recreational, and aesthetic aspects of landscapes (Martín-López et al. 2012; Hartel et al. 2014), rural communities attach greater importance to the direct provisioning benefits. This divergence reflects the socioeconomic context: in rural Malawi, households remain highly reliant on ecosystem services to meet basic needs, as also emphasised by (Hartel et al. 2014; Fischer et al. 2012). The continued reliance on these services at the household level illustrates both their irreplaceable role in sustaining livelihoods and the potential vulnerability of communities to resource degradation.

5.2.1 Uses of plant parts of *U. kirkiana* and ecological vulnerability

The findings indicates that species plant parts are more valued for food, therapeutic, fodder, artisanal, energy, and timber purposes (Figure 6). The fruits are the parts of the *U. kirkiana* most familiar to almost all respondents. The valorization of the plant parts of *U. kirkiana* could contribute

to the improvement of human livelihood and provide a different perspective for the sustainable management of the species. These findings were consistent with those reported by Samarou et al. (2021) and Garba et al. (2019) on *T. indica* trees in the West African sub-region. However, the cosmetic uses reported by (Garba et al. 2019) were unimportant in the present study.

Differences in the use of the species by ethnicity could be due to cultural heritage (Table 16), where knowledge is passed down from generation to generation within the same ethnic group (Garba et al. 2019; Samarou et al. 2021). Diversity in plant parts of use, the type of use, and the specific uses were found to explain ethnic differences. The convergence of use knowledge between the Mang'anja and the Yao (IS = 0.55) indicates that each ethnic group knows more than half of the uses known by the other ethnic group. These results are similar to those reported by Samarou et al. (2021) in Togo and Garba et al. (2019) in Niger.

The reported use of *U. kirkiana* by men and women is close (Table 17), which may be due to the frequent and daily consumption of *U. kirkiana* fruits. However, the usage score is significantly different, showing that men have more knowledge of use than women do. Similar studies by Avocèvou-Ayisso et al. (2012) conducted on *Pentadesma butyracea* in Benin and by Atakpama et al. (2012) on *Sterculia setigera* in the Sudanese zone of Togo, as well as by Samarou et al. (2023) in the northern region of Togo, confirm that men have a better knowledge of uses than women. This result contrasts with studies conducted on *P. biglobosa* in Benin and on *Adansonia digitata* L. in Togo, where the authors reported that usage values were not statistically influenced by gender (Kébenzikato et al. 2015; Koura et al. 2011; Padakale et al. 2018). Similarly, the study by Garba et al. (2019) on *T. indica* in Niger reports that the use of plant parts was not influenced by gender. Although the use of *U. kirkiana* was not significantly different according to age (Table 16), participants under 30 years, old have less knowledge than those over 30 years old. Conversely, Ayantunde et al. (2008) demonstrated that older individuals have more knowledge than the young. Age is a factor of knowledge, as the experience of using plants increases with age and frequency of use (Atakpama et al. 2021).

The study revealed significant variation in local knowledge of *U. kirkiana* according to the level of education attained by participants (Table 18). This result suggests that education plays an important role in shaping the depth and transmission of ethnobotanical knowledge within communities. The implication of this finding is twofold: first, it indicates that formal education may enhance the ability of individuals to acquire, interpret, and retain knowledge about plant uses; second, it highlights the potential of integrating local ecological knowledge into educational curricula to strengthen conservation awareness among future generations. This pattern points to the fact that education provides broader exposure to information sources and can improve awareness of the ecological and socio-economic value of native species. At the same time, formal education may contribute to changes in perceptions and attitudes towards biodiversity, influencing how individuals engage with conservation initiatives. When compared with previous studies, these results present both similarities and contradictions. Unlike Issifou et al. (2018), who reported no significant effect of education level on local knowledge on *Khaya senegalensis* in Togo, our findings demonstrate a clear link between educational attainment and ethnobotanical knowledge. However, the results are consistent with those of Samarou et al. (2021), who found that education level significantly influenced local knowledge of plant species in Togo. This comparison suggests that the influence of education may vary depending on the species studied, the socio-cultural context, and the type of knowledge being assessed.

The results of this study indicate that the use of *U. kirkiana* strongly influences its level of vulnerability (Figure 8). The relatively high demand for various plant parts reflects the species' socio-economic importance for local communities, confirming its status as a multipurpose plant (Chawafambira et al. 2020). This multifunctionality, while beneficial for livelihoods, also places considerable pressure on the species, particularly in areas where natural populations are already declining. The vulnerability index of *U. kirkiana* was estimated at 2.25, suggesting that the species is moderately vulnerable. This finding implies that although the species is still present across Malawi, the combined pressures of intensive use, habitat degradation, and the lack of formal

conservation strategies (Muluneh 2021), could accelerate its decline in the absence of intervention. The recognition of this moderate vulnerability underscores the urgent need for proactive management measures to safeguard the species and ensure its sustainable use. Interpreting these results further, the moderate vulnerability score highlights a precarious balance: while *U. kirkiana* continues to provide essential ecosystem services and socio-economic benefits, ongoing anthropogenic pressures threaten its long-term viability. The absence of structured conservation policies, coupled with habitat conversion, suggests that vulnerability could increase over time if no action is taken. When compared with other studies, the present findings partially contradict those of Samarou et al. (2021), who reported a higher vulnerability index (2.5) for *Tamarindus indica* in Togo, classifying it as vulnerable. This discrepancy may be explained by differences in ecological distribution, regeneration capacity, and cultural use between the two species. Nevertheless, the vulnerability index reported here is consistent with the broader literature indicating that *U. kirkiana* populations are undergoing significant decline across their range.

5.3 Woody species composition and phylogenetic structure along elevation gradients

5.3.1 Floristic composition and demographic structure in different elevation areas

The results demonstrate that *U. kirkiana* habitats across the elevational gradient in Malawi support a remarkable floristic richness, with a particularly strong representation of Fabaceae (42 species) (Table 19; Appendix 5). This highlights the ecological significance of these habitats, since Fabaceae are widely recognized for their symbiotic role in nitrogen fixation, which enhances soil fertility and sustains woodland productivity. Such patterns are consistent with other studies in African savanna ecosystems, where Fabaceae dominance is often linked to ecosystem resilience and nutrient cycling (Swap et al. 2023). Beyond Fabaceae, the consistent presence of Phyllanthaceae, Rubiaceae, and Anacardiaceae in the study area underscores the multifunctional role of these forests as reservoirs of biodiversity. These families not only provide ecological stability, but they also support diverse fauna, thus reinforcing the notion that *U. kirkiana* habitats function as biodiversity hotspots.

Similar trends have been reported in other miombo landscapes, where tree community assemblages exhibit a convergence around these families. This trend reflects their adaptive success under semi-arid and seasonal climates (Shorrocks and Bates 2015; Moura et al. 2017). The dominance of genera such as *Brachystegia*, *Julbernardia*, *Uapaca*, and *Parinari* further characterises these ecosystems as typical miombo woodlands. This observation aligns with the findings of Campbell et al. (2007) and Frost (1996), who emphasise that the prevalence of Caesalpinioideae in miombo is a defining feature of these ecosystems, although their relative abundance may fluctuate across sites due to differences in disturbance regimes, soil conditions, and climatic variability. The variability observed in this study between and within stands therefore suggests that local environmental filters and anthropogenic pressures play a crucial role in shaping demographic structure and floristic assemblages. From an ecological perspective, the co-occurrence of *U. kirkiana* with indicator species of savanna woodlands suggests niche complementarity and potential facilitation processes. Such associations may enhance natural regeneration by creating microhabitats favorable for seedling establishment and by maintaining functional diversity. This finding resonates with the interpretations of Chidumayo and Gumbo (2010), who showed that species interactions in miombo woodlands underpin regeneration dynamics and contribute to woodland persistence under both natural and disturbed conditions.

Vegetation Importance Frequencies (VIF) across the sites also highlight the dominance of Fabaceae and Phyllanthaceae (Table 19), both families known for broad ecological tolerance. Fabaceae, with nitrogen-fixing capacity, thrive in degraded or secondary forests (Reid et al. 2024), while Phyllanthaceae are well-adapted to semi-arid zones and poor soils (Trotter et al., 2022). This pattern aligns with findings from Tanzania and Angola, where these families exhibit strong structural roles in Miombo woodland (Shirima et al. 2011; Ryan et al. 2011). These results affirm *U. kirkiana*'s dual ecological and socio-economic importance as a keystone species for forest structure and as a provisioning species through its fruit, crucial for rural livelihoods (Ngulube 2002; Ngulube 2000;

Dewees et al. 2010). However, its elevation-dependent variability in abundance highlights the need for site-specific conservation strategies, particularly in zones subject to intense land-use pressure.

The observed structural values highlight-differentiated states of forest development according to the studied sites (Table 20). The positive skewness (skewness > 1) observed in all forests can reflect a dominance of juvenile or small-diameter individuals, a typical signature of stands in regeneration or in equilibrium, where the distribution has not yet reached a stable structure (Sharma et al. 2020). This is often a sign of recent disturbances, whether natural or anthropogenic, or of active forest dynamics. The high kurtosis, particularly in Perekezi (10.30), indicates a significant concentration around a central diameter, with a low representation of individuals with large diameters. This revealed a lack of adult strata, possibly caused by selective harvesting or forest poaching (Laurance et al. 2014).

The Gini index, although moderate across sites, may reflect disparities in diameter distribution. The highest value observed at Malosa (0.32) suggests an uneven structure likely resulting from selective anthropogenic pressures such as timber extraction, similar to findings in tropical forests under logging regimes (Gadow et al. 2012; Metz et al. 2023). In contrast, lower Gini values in Mangochi and Perekezi forest (0.22) may indicate a more uniform structure; however, this could reflect the historical loss of large individuals due to overexploitation, a pattern also reported by (Zhang et al. 2024). The Shannon index, which captures structural diversity, was highest at Chongoni (1.11) and Kaning'ina (0.99) forest, suggesting a well-stratified and heterogeneous forest stand, conditions favorable to resilience and regeneration (Saha et al. 2016; Shell et al. 2021). Conversely, lower values at Mangochi (0.64) and Perekezi (0.73) point to structural homogeneity, often associated with degraded or recovering forests, as observed in secondary woodlands of East Africa (Ocholla et al. 2023). These results indicate that Chongoni and Kaning'ina maintain more complex and ecologically stable structures, whereas Mangochi and Perekezi show signs of past disturbances and reduced structural complexity.

The three-parameter Weibull function effectively described the diameter at breast height (DBH) distributions across six forested sites distributed along an altitudinal gradient in Malawi, ranging from 700-800m to 1600-1770m (Figure 9). This model captured site-specific variations in forest structure while enabling standardised comparisons. In all elevation bands, the DBH distributions were right-skewed, indicating a progressive decline in stem density across increasing diameter classes, a pattern consistent with tropical forests and miombo ecosystems under natural regeneration or disturbance (Kalaba 2013; Banda et al. 2006). Across the gradient, the Weibull shape parameter (c) remained consistently below two, signifying a structural dominance of small-diameter individuals and an absence of symmetry indicative of uneven-aged stands or disturbed conditions. Similar patterns were noted in the miombo regions of Mozambique and Tanzania, where anthropogenic pressures maintain forests in an early or mid-successional state (Ryan et al. 2011; Syampungani et al. 2016). The fact that c values remained low and similar across the altitudinal range suggests that elevation alone may not be the primary driver of forest structure; rather, disturbance regimes and land-use histories likely play a dominant role.

In contrast, differences emerged in the scale (b) and position (a) parameters across elevation classes. Sites at 1150-1370m and 1600-1770m showed higher b values, reflecting broader DBH size class distributions and potentially more complex structural layers. This may reflect local factors such as regeneration dynamics, site fertility, or legacy effects from past logging. These observations align with findings from tropical montane forests, where elevation interacts with environmental filtering and anthropogenic effects to shape stand composition (Doležal et al. 2022; Báez et al. 2022). Comparatively, (Liu et al. 2020) showed that forests with higher c values tend to be more mature and less disturbed, whereas those with low c values indicate early successional stages supporting the idea that the studied Malawian sites are largely recovering or managed woodlands. This is further supported by (Kalaba 2013), who linked DBH structural shifts in Zambian forests to fire frequency and land-use conversion, both of which are relevant across the

Malawian gradient especially in lower elevations like 700–950m, where pressures such as charcoal production and agricultural expansion are more intense.

5.3.2 Phylogenetic community composition in different elevation areas

The decline in Phylogenetic Diversity with increasing elevation supports a widely documented pattern in montane ecosystems, where harsher abiotic conditions such as reduced temperature, lower productivity, and shorter growing seasons lead to reduced species richness and evolutionary diversity (Qian et al. 2014; Jin and Qian 2022). Strong environmental filters may limit community assembly to species with similar traits and evolutionary histories at high elevations. This condition often results in phylogenetic clustering (Cisneros et al. 2021). In contrast, the non-linear trend observed in the Standardized Effect Size of Phylogenetic Diversity (SES.PD) along the elevation gradient (Figure 10), with high values at both low and high altitudes and a dip at mid-elevation, suggests variable community assembly processes. High SES.PD values at low and high elevations may reflect strong environmental filtering that favors distantly related yet ecologically similar species capable of surviving in extreme conditions. The mid-elevation dip, where SES.PD values are lower and this can be attributed to increased competition or neutral processes that promote the coexistence of closely related species (Swenson 2011). Comparable hump-shaped patterns of SES.PD have been observed in other mountainous tropical and subtropical regions, including the Andes (González-Caro et al. 2014), the Himalayas (Liu et al. 2020), and East African highlands (Onditi et al., 2022), where turnover in species and functional traits is pronounced over short elevational distances. These patterns highlight the complex interplay of biotic and abiotic drivers in shaping community structure. Notably, the increase in SES.PD at high elevations despite the overall decline in PD indicates that species present in these habitats are more phylogenetically overdispersed than expected by chance. This may be the result of historical dispersal events, local adaptation, or ecological niche differentiation under strong selection pressures (Tucker et al. 2017). Importantly, the divergence between raw PD and SES.PD underscores the need to use standardised metrics in community phylogenetic analyses, as raw metrics can obscure underlying patterns driven

by non-random processes. These results suggest that elevation acts not only as an environmental gradient but also as an evolutionary filter, shaping the phylogenetic structure of woody species communities through both deterministic and stochastic processes.

Our findings provide robust evidence that temperature-related climatic variables significantly structure the phylogenetic composition of woody plant communities along elevation gradients in Malawi (Table 21). Specifically, the dominant influence of mean annual temperature, isothermality and temperature seasonality is consistent with earlier studies demonstrating the central role of temperature in shaping community assembly and phylogenetic turnover across tropical ecosystems (Kraft et al. 2015; Ringelberg et al. 2023). Among these, temperature seasonality emerges as a particularly strong environmental filter, known to influence phenological patterns, trait divergence, and niche conservatism in montane forest systems (Padullés Cubino et al. 2022).

The PCoA ordination revealed clear segregation of communities across elevation bands (Figure 11), suggesting a gradual phylogenetic turnover associated with climatic variation. Such elevation-linked stratification of evolutionary lineages has been previously documented in Afromontane and tropical systems, where differences in climatic conditions across elevation are associated with shifts in dominant clades and trait assemblages (Siddique 2017; Jin et al. 2015; Romdal and Rahbek 2009). Phylogenetic niche conservatism in thermal tolerances likely underlies those patterns, explaining the restricted elevation ranges of certain evolutionary groups (Sunday et al. 2019). The findings support the emerging consensus that temperature, particularly metrics reflecting its variability and seasonality, plays an important role in driving phylogenetic differentiation at small spatial scales. This aligns with findings from other tropical and subtropical regions, where temperature regimes consistently emerge as key axes of environmental filtering and evolutionary structuring (González-Caro et al. 2014; Tucker et al. 2017; Chapman et al. 2016). Integrating environmental vectors into ordinations of phylogenetic community structure leads to a clearer understanding of how climate gradients influence biodiversity patterns. The significant associations between the three temperature-related variables and the major ordination axes

underscore their role in shaping the ecological and evolutionary assembly of plant communities, with implications for biodiversity responses under ongoing and projected climate change scenarios.

5.3.3 Phylogenetic community structure in different elevation areas

The observed variations in phylogenetic diversity indices along the elevational gradient (Figure 12) offer critical insights into the mechanisms shaping the assembly of woody plant communities in Malawi's forest ecosystems. Faith's Phylogenetic Diversity (Faith 1992), which quantifies the total evolutionary history represented by a community, exhibited higher values at both low and high elevations. This bimodal pattern supports previous hypotheses suggesting that environmental extremes either through niche differentiation, reduced competition, or historical biogeographic contingencies can harbor lineages with divergent evolutionary histories (Qian et al. 2014; González-Caro et al. 2014). In contrast, the relatively stable values of Mean Pairwise Distance (MPD) and Mean Nearest Taxon Distance (MNTD) across elevation suggest that average phylogenetic distances between co-occurring species remain consistent. This may indicate either ecological convergence on functional traits or a saturation of functional niches, resulting in apparent redundancy across different elevations (Swenson 2011). However, localised deviations such as a dip in MPD at mid-elevation could reflect selective environmental filtering or the presence of unique evolutionary lineages constrained to intermediate climatic conditions.

The analysis of phylogenetic structure metrics Net Relatedness Index (NRI) and Nearest Taxon Index (NTI) revealed divergent patterns of community assembly along the elevation gradient. At low elevations (700-950m), both NRI and NTI exhibited significantly negative values, indicating phylogenetic over dispersion. This pattern suggests that competitive exclusion or limiting similarity among distantly related species likely drives community assembly under relatively benign environmental conditions (Webb et al. 2002). In contrast, mid and high-elevation communities (above 1250m) showed positive NRI and NTI values, reflecting phylogenetic clustering. Such clustering are commonly interpreted as the result of strong environmental filtering, where only closely related, stress-tolerant taxa with similar ecological strategies can persist (Hu et al. 2024).

These patterns support the hypothesis that both deterministic and stochastic processes shape community assembly, but their relative importance shifts with elevation (Li et al. 2022). In lower-elevation zones, reduced abiotic stress may enhance interspecific competition, favoring niche differentiation among distantly related species. Conversely, in higher-elevation areas, increased environmental harshness (e.g., lower temperatures, limited resources) may intensify abiotic filtering, promoting convergence and the persistence of phylogenetically similar species (Ding et al. 2019; Domínguez-Amaya et al. 2025). Interestingly, contrary to findings of Liu et al. (2021), who reported a shift from phylogenetic clustering to over dispersion with increasing elevation, our study showed the opposite trend over dispersion at low elevation and clustering at higher elevations. This may be attributed to the relative strength of facilitative interactions at high elevations, where stress amelioration can promote the coexistence of ecologically similar taxa (Qian and Ricklefs 2016). The observed clustering of species at higher elevations could indeed be due to evolutionary convergence, where unrelated species independently evolve similar traits in response to comparable environmental pressures like cold or limited resources. This is a well-documented phenomenon in evolutionary biology (Losos 2011; Cadotte et al. 2008). Overall, our findings suggest that community assembly across the elevation gradient is governed by a balance between competition and facilitation, modulated by the degree of environmental stress, and further influenced by evolutionary processes such as niche conservatism and convergence (Bricca et al. 2022).

These interpretations are supported by the standardised effect size metrics (SES_MPD and SES_MNTD), which account for species richness differences and improve the detection of non-random phylogenetic patterns. The observed variation in SES values along the elevational gradient suggests that both deterministic and stochastic processes, including environmental filtering, biotic interactions, dispersal limitation, and historical legacies influence plant community assembly. This is consistent with the findings of Kraft et al. (2015), who show that both niche-based environmental filtering and neutral dispersal dynamics contribute significantly to ecological assembly in tropical

forests, and LI et al. (2014), who show that filtering plays an increasing role as elevation rises in montane ecosystems. Machac et al. (2011) found predictable shifts in phylogenetic structure in ant communities across elevational gradients, and Bañares-de-Dios et al. (2024) found similar trends in tropical tree assemblages in the Andes. By combining multiple phylogenetic diversity and structure metrics, this study reveals the intricate interplay between ecological processes and evolutionary history across environmental gradients, emphasising the importance of elevation in informing conservation strategies and biodiversity management in the face of ongoing climate change.

5.3.4 The relationship between phylogenetic community structure and the environmental factors

Analysis of the relationships between elevation and phylogenetic structure indices, namely the Net Relatedness Index (NRI) and the Nearest Taxon Index (NTI), revealed no significant structuring of woody communities along the altitudinal gradient in Malawi (Figure 13). The very low coefficients of determination ($R^2 = 0.01$ for NRI and $R^2 = 0$ for NTI) and non-significant p-values ($p = 0.3$ and $p = 0.4$, respectively) suggest that elevation alone does not have a marked influence on the phylogenetic assembly of plant communities. These results are comparable to those obtained by Zhang et al. (2016) in subtropical ecosystems, where no significant trend in phylogenetic structuring was observed in relation to altitude. Similarly, Qian et al. (2014) pointed out that, in some tropical regions, phylogenetic patterns are often shaped more by regional biogeographic history than by environmental gradients. However, these observations contrast with findings from mountainous regions such as the tropical Andes, where increasing elevation has been associated with stronger phylogenetic clustering due to intensified environmental filtering. For instance, Dehling et al. (2014) reported that frugivorous bird communities exhibited increased phylogenetic and functional clustering at higher elevations, suggesting that harsher abiotic conditions act as strong environmental filters, favoring closely related species with similar traits.

The absence of a significant signal in our study can be explained by several factors. First, the structural heterogeneity of landscapes in Malawi, including a mosaic of dry forests, wooded savannas, and rainforests, could favor the co-occurrence of species from highly diverse evolutionary lineages, diluting the effects of strict phylogenetic filtering. Second, widespread anthropogenic pressure (fires, agriculture and fragmentation) could lead to floristic homogenisation, masking natural assembly processes. Finally, it is possible that the altitudinal range studied (750-1750m) is not sufficient to generate abiotic variations strong enough to significantly filter certain lineages. It is therefore possible that, in Malawian ecosystems, edaphic factors act in synergy or compensation with climatic gradients, modulating assembly processes in a more complex way than is revealed by NRI and NTI indices alone. This soil-environment interaction could blur the expected phylogenetic trends, particularly in highly anthropised contexts where community resilience may rely on diversified functional strategies that are not necessarily phylogenetically related.

Phylogenetic diversity measured by the Faith_PD index was found to be positively correlated with certain seasonal climate variables, notably temperature variation (BIO03) and precipitation in wet and dry quarters (BIO16 and BIO18), indicating that intra-annual climate fluctuations strongly influence the evolutionary diversity of woody communities. These results are consistent with those of Jin and Qian (2022) and Qian and Sandel (2017), who highlighted the importance of thermal and water gradients in the phylogenetic structuring of regional flora. In contrast, the NRI and NTI indices showed no significant relationship with environmental variables, suggesting an absence of clear phylogenetic structuring, contrary to the observations of Luo et al. (2023) in temperate forests. The negative correlation between SES_MPD and precipitation in the coldest month (BIO19) indicates a loss of phylogenetic divergence under extreme climatic conditions, which is consistent with the results of Qian et al. (2021). The weak correlations between phylogenetic indices and edaphic variables (nitrogen, phosphorus, soil depth) suggest that seasonal climatic factors have a more decisive influence in this context. Thus, although seasonal climatic conditions appear to be

the main drivers of phylogenetic diversity, the lack of strong structuring of the NRI and NTI indices suggests the involvement of stochastic or historical mechanisms in community assembly, requiring further study.

5.3.5 Phylogenetic structure of plant communities

The phylogenetic tree constructed from data collected in Malawi reveals a non-random structure of woody communities, illustrated by the grouping of species belonging to the same clades such as *Uapaca*, *Brachystegia*, and *Parinari* (Figure 15). This grouping suggests environmental filtering, where only species sharing functional and ecological traits adapted to local conditions (soil, altitude, and climate) persist in a community (Webb et al. 2002; Kembel et al. 2010). This filtering tends to reduce local evolutionary diversity and promotes phylogenetic proximity among species. The dominance of the genera *Brachystegia*, *Julbernardia*, and *Uapaca* confirms their key role in the miombo ecosystems of southern Africa (Gondwe et al. 2021; Dewees et al. 2010; Akinnifesi et al. 2006; Prinzing et al. 2001).

However, the presence of certain phylogenetically distant taxa such as *Ficus spp.*, *Annona senegalensis*, and *Eucalyptus camaldulensis* also suggests trends of phylogenetic over dispersion at certain sites. This could reflect limiting competition processes or local environmental heterogeneity favoring the coexistence of ecologically divergent species (Cavender-Bares et al. 2009; Swenson 2011). Similar observations have been reported in the dry forests in Ghana (Parr et al., 2014), the Afromontane forests of Tanzania (Lyaru et al. 2000), and the forests of southern Africa (Ryan et al. 2011), where woody communities are structured by both abiotic constraints (climate, soil, altitude) and biotic interactions (competition, dispersal, disturbance). The phylogenetic approach adopted here, using a fully resolved tree, allows for a robust estimation of phylogenetic diversity, standardised indices such as SES.PD, and clustering or dispersion indices such as NRI and NTI (Swenson 2011; Tucker et al. 2017). These indices are essential for interpreting community structure from an evolutionary and ecological perspective and for identifying the dominant processes structuring plant diversity.

5.3.6 Conservation advice

Our study revealed that the phylogenetic structure of woody communities associated with *Uapaca kirkiana* varies considerably between natural forests along an altitudinal gradient in Malawi. This variation reflects the combined influence of evolutionary history, species interactions, and local environmental conditions. Forests located at higher altitudes (1600-1770m, and 1250-1370m) exhibited phylogenetic over dispersion, suggesting that coexisting species tend to be phylogenetically distant, likely due to environmental heterogeneity or competitive exclusion. In contrast, mid- to low-elevation forests (1150-1295m and 700-800m) showed phylogenetic clustering patterns, dominated by closely related species with similar ecological characteristics, likely due to strong habitat filtering. These results highlight the need to integrate evolutionary and ecological dimensions into conservation planning. Maintaining phylogenetically diverse communities can enhance ecosystem resilience and stability, particularly in the context of increasing climate pressures. Conservation and restoration strategies should therefore prioritise areas where *U. kirkiana* coexists with evolutionarily distinct taxa to ensure the protection of both the species and its broader ecological network. Furthermore, it is recognised that climatic variables such as temperature and precipitation structure species assemblages along altitudinal and spatial gradients (Rahbek et al. 2019). Functional traits, such as specific leaf area, wood density, and leaf nitrogen content, also influence plant responses to environmental stress and determine community assembly (Wang et al. 2022). Although our current study focused on phylogenetic structure at the local scale, future research should incorporate these functional and climatic dimensions to better predict how *U. kirkiana* and its associated woody communities might respond to environmental change. Furthermore, consideration of spatial scale is essential for understanding community assembly mechanisms (Pashirzad et al. 2018). Extending analyses to broader spatial gradients, incorporating functional trait data, will provide more comprehensive information for biodiversity conservation in Malawi's mid-canopy Miombo forests.

5.4 Intraspecific functional trait variation of *U. kirkiana* across eco-geographical regions

5.4.1 Morphological and functional traits variation across geographical regions

The results revealed a great variability of morphological and functional traits of the *U. kirkiana* tree across biogeographical regions (Table 23). Comparing the population from the Central region to the North and South, growth-related morphological traits like total height and canopy height were significantly lower. This comparison indicates that the conditions for vertical development may not be ideal for individuals in this area. This finding suggested that climatic conditions in central Malawi limited plant height development compared to northern and southern regions. Central Malawi experiences a prolonged dry season, lower rainfall (approximately 700-1,000 mm/year), and higher temperatures (FAO 2020), which may inhibit height growth. In contrast, the north has a more humid and mountainous climate, while the south benefits from a more stable climate. These disparities directly influence the morphological traits of plant species, particularly total height and canopy height. Significant variability in morphological characteristics was observed in the central and southern regions, particularly in terms of desiccation, seed weight, fruit shape, and structural size. This variability could result from a mix of the individuals' developmental stages and environmental differences (Kalinganire et al. 2008). Morphological traits such as fruit and seed weights showed significant regional variations concerning reproductive traits, with the Central region population showing lower average values than the North and South. This suggests that *U. kirkiana* in the Central region devotes less energy to fruit and seed development, perhaps as a means of adapting to local resource limitations (Dai et al. 2024). Leaf traits showed significant variations among geographic regions, with the highest value of fresh leaf weight and water content in Northern population, indicating improved water retention or more conducive leaf development conditions. Similarly, Chaffey (2009) found that tree populations in wetter or cooler environments exhibited greater leaf water content and biomass, suggesting that environmental conditions significantly influence leaf morphological traits.

However, the mean leaf shape differed by region, with the South recording intermediate values, which suggests that environmental variations influence leaf morphology. Leaf shape is often a response to climatic factors such as temperature, light intensity and water availability. Intermediate leaf shapes in southern populations may reflect a balance between extremes, perhaps an adaptation to moderate environmental pressures versus more stressful conditions in the North or more favorable conditions in the South. Studies by Yates et al. (2010) had shown that by characterising leaf morphology, leaf shape, and size of *Protea* species varied with climatic conditions, with intermediate leaf shapes in transitional climate regions reflecting adaptive strategies to optimize water use and temperature regulation in environments that are neither too dry nor too humid. Overall, the diversity of leaf morphology and functional among the regions could emanate from the adaptive response of the species to interactions between genotypic composition and environmental factors (Atkins and Travis 2010; Leakey et al. 2005; Perez-Harguindeguy et al. 2016).

5.4.2 Pairwise correlation between morphological traits

Our funding showed a positive correlation between basal diameter, diameter at breast height, and total height (Figure 16). This suggests that tree diameter can be used as an indicator of the growth in height of the tree. This confirms a typical morphological coordination of woody species, where vertical growth is generally accompanied by trunk widening to ensure mechanical stability and water conductivity (Brose et al. 2006; Díaz et al. 2016). This pattern is characteristic of resource acquisition strategies in environments where competition for light is intense (Demie et al. 2025). Similarly, the relationship between canopy shape and canopy height, as well as total height, may reflect a greater physiological efficiency in well-developed individuals, linked to enhanced resource use strategies.

The correlations between leaf water (LWC), leaf length (LL), and height showed functional trade-offs, particularly a differential allocation between leaf area and tissue density. A negative correlation between LL and LWC could indicate a tendency to produce longer but thinner leaves,

which is often observed in species adapted to dry conditions or low nutrient availability (Reich 2014). These trade-offs reflect the environmental pressures that constrain growth and survival strategies. Moreover, the significant relationships between reproductive traits such as seed number and seed mass illustrate a reproductive strategy where an increase in seed number also increases the total fruit mass. This link is often observed in animal-dispersed seed species, where fruit size can influence dispersal success (Moles and Westoby 2006). Additionally, non-significant relationships between certain traits (for example, between leaf width and height or between fruit length and basal diameter) also suggest that some characters are modulated independently, which is common in species with a wide ecological distribution and high functional plasticity (Valladares et al. 2007). This may reflect local adaptation or differentiated selective pressures according to the study area.

5.4.2 Discriminant morphological and functional traits and regional differentiation patterns of *U. kirkiana*

Our study highlights the significant role of morphological and functional traits in differentiating *U. kirkiana* populations across the distinct geographical and ecological regions of Malawi (Table 24). Traits such as leaf water content (LWC), mean leaf diameter (MLD), seed weight (SW), canopy shape (CS) and basal diameter (BD) emerged as the most discriminant variables, suggesting strong selective pressures linked to regional environmental conditions (McGill et al. 2006; Díaz et al. 2016). These findings are consistent with Díaz et al. (2016) and McGill et al. (2006), who emphasised the ecological relevance of functional traits in shaping plant responses to environmental heterogeneity. Individuals from the central region exhibited the most distinctive combinations of traits, including compact canopy structures and lower values of LWC and MDC. These patterns reflect possible adaptations to the region's harsher conditions, characterized by prolonged dry seasons, erratic rainfall, and poorer soils (FAO 2020). The lower vertical development observed here, compared to northern and southern populations, may indicate ecological constraints that inhibit full expression of growth potential. The strong association

between LWC and the first canonical axis (Can1) reinforces the role of foliar hydration as a key adaptive trait (Figure 17). Its co-variation with seed weight suggests a coordinated strategy between water use and reproductive investment, possibly driven by moisture stress and edaphic limitations (Violle et al. 2007; Albert et al. 2011). Similarly, differences in canopy shape and diameter between regions may reflect light competition and resource-use efficiency along environmental gradients (Valladares et al. 2007).

Individuals from the central region showed the most significant difference compared to those from the northern and southern regions (Table 25). Trees from the central region showed distinct combinations of traits, particularly SF, LWC, NB, MDC, and BD, which emerged as key discriminators. These patterns indicate that central populations may be subject to distinct ecological constraints or have unique genetic compositions that influence their phenotypic expression (Violle et al. 2007; Albert et al. 2011). Significantly, LWC and MLD were the traits most strongly associated with the first canonical axis (Can1) (Table 26), showing that foliar hydration and leaf dimensions were the primary drivers of inter-regional trait differentiation. This axis also showed positive SW loadings, suggesting that foliar water-use traits and reproductive investment vary in tandem. Such integration of physiological and reproductive characteristics may reflect adaptations to moisture availability and edaphic heterogeneity (Nicotra et al. 2010; Perez-Harguindeguy et al. 2016). Furthermore, CS and MDC contributed significantly to regional separation. Individuals from the north and south had higher CS and MLD values, whereas trees in the center had more compact canopy forms. These differences could be attributed to structural changes in regional gradients in light availability (Valladares et al. 2007).

Environmental drivers, particularly climate and soil, appear central in shaping this morphological diversity (Figure 18 and 19). For example, forests such as Chongoni and Perekezi, characterised by shallow soils, steeper slopes, and higher altitudes, exhibited traits indicative of water stress tolerance: thicker, heavier leaves and greater seed production. These findings align with (Chaves et al. 2003), who noted that in drought-prone environments, plants often develop morpho-

physiological traits that reduce dehydration and promote reproductive resilience (Linhart and Grant 1996). Conversely, forests like Dzalanyama showed strong associations with thermal and precipitation variables (BIO3, BIO12, BIO16), pointing to adaptations to warm, humid climates and confirming patterns of thermal plasticity reported by Nicotra et al. (2010). In southern regions like Malosa and Mangochi, deeper, nitrogen-rich soils combined with arid conditions were linked to greater height, canopy spread, and biomass accumulation, suggesting that soil fertility modulates the impact of climate stress on growth (Comita and Engelbrecht 2009).

These findings underscore *U. kirkiana*'s phenotypic plasticity and its capacity to adapt morphologically and functionally to a complex interplay of climatic and edaphic variables. Similar climatic effects on morphological variation have been reported in species like *Azelia africana* Sm., (Houehanou et al. 2019), *Uvaria chamae* P. Beauv., (Dai et al. 2024), and *Cynodon dactylon* L. Pers. (Wang et al. 2020) reinforcing the broader ecological principle that environmental heterogeneity drives trait variation and, ultimately, adaptation (Pigliucci et al. 2006).

5.4.3 Morphotypes identified across the geographic region in Malawi

Four morphotypes distinct from each other were identified from the *U. kirkiana* trees (Figure 20). This variability could result from a combination of environmental factors (edaphic, climatic conditions) and anthropogenic factors (selective harvesting, fires, agricultural practices) influencing the growth and reproduction of individuals (Boffa 2000; Kalinganire et al. 2008). Similar results were obtained by Padonou et al. (2013) on *A. Africana* and by Dai et al. (2024), on *U. chamae* shrubs in Benin. The identification of these four morphotypes and the difference in their distribution could have resulted from the adaptation of the species to local environmental conditions (Gandji et al. 2020). These observed morphotypes could reflect a high rate of polymorphism within the species in Malawi.

The first morphotype was composed of a high number of branches and larger, basal-shaped fruits and originates from Kaning'ina Forest in the northern region with an annual rainfall of 1100-2300

mm (Haghtalab et al. 2019) (Table 30). This indicates adaptation to potentially more competitive understory light environments, where higher branching may improve photosynthetic capture (Garnier et al. 2001). The larger fruit base might also indicate a locally selected trait for fruit persistence in that region. However, morphotype 2, consisting of trees from Chongoni (Central) and Perekezi (North), was composed of low fresh and dry leaf mass, as well as minimal water loss by desiccation. This may reflect an ecological strategy for drought tolerance, as lower leaf mass and reduced water loss are adaptive under water-limited conditions (Wright et al. 2004). Interestingly, this morphotype shows relatively tall boles, which may represent a growth strategy for light competition in forested ecosystems. Additionally, highest fruit traits, including weight, width, and seed number characterised Morphotype 3, from Malosa Forest (South).

These traits suggest that this morphotype might possess genotypes valuable for domestication and selection programs aimed at enhancing fruit yield, consistent with previous findings in other priority indigenous fruit species (Akinnesi et al. 2008). The high leaf water content and significant mass loss by desiccation further indicate high water uptake capacity, which may be associated with favorable soil and moisture conditions in Malosa. Moreover, Morphotype 4, formed by individuals from Dzalanyama (Central) and Mangochi (South), stands out with the largest basal diameter, DBH, and tallest mean canopy diameter. These traits imply vigorous growth, possibly linked to better soil fertility or reduced anthropogenic disturbance in these regions. This morphotype exhibited the highest leaf water content, underscoring its capacity for maintaining hydration and possibly enhanced photosynthetic efficiency under varying conditions (Chapin III et al. 1993). These observed differences between the morphological traits of the species would provide ecotypes as sources of genetic pool selection. Further research to distinguish the relative importance of edaphic factors and genetics on the observed variation of these four morphotypes would be an asset in the domestication and sustainable conservation of the species.

5.4.4 Interactions between environmental factors and *U. kirkiana* traits

The redundancy analysis indicated a strong link between environmental factors and morphological or functional trait variation in *U. kirkiana* individuals. The most important environmental factors influencing trait composition were altitude, aridity index, and soil type (Table 27). Altitude was found to be positively associated with key discriminant morphological traits such as BD, DBH, LWC, and SW (Table 28), indicating that individuals at higher elevations have larger stems, increased foliar hydration, and greater reproductive allocation (Binter et al. 2025).

These trait-environment relationships are consistent with previous findings, which show that higher altitudes frequently favor slower-growing individuals with increased investment in structural and storage traits due to colder temperatures and shorter growing seasons (Körner 2007; Fyllas et al. 2009). Fruit weight, on the other hand, showed a negative association along both axes, particularly on Leaf water content, Basal Diameter and Diameter at Breast Height, suggesting that this reproductive trait responds differently to environmental variation, possibly due to trade-offs between fruit size and other fitness-related traits (Zhang-Zheng et al. 2024). Specific canopy height (CH), with a negative loading on Leaf water content, Basal Diameter, and Diameter at Breast Height, appears to be more sensitive to unmeasured environmental variation or microclimatic factors. This pattern could indicate adaptive canopy architecture in response to localised light availability or competitive interactions (Valladares and Niinemets 2008).

5.4.5 Plasticity in the morphological and functional traits of *U. kirkiana*

The results showed distinct variation in phenotypic plasticity (PPI) across the regions, highlighting the species' ability to adapt to environmental aridity. The highest PPI value observed for growth-related traits, such as DBH, BD, and TH, indicating that these traits are particularly sensitive to environmental variations, allowing individuals to modulate their development according to local conditions (Sultan 2000; Anderson-Teixeira et al. 2022). Species with a widespread distribution demonstrate adjustments in their performance in response to changes induced by climatic variations (Nicotra et al. 2010; Valladares Ros and Araújo 2014). One strategy often adopted by these species

to cope with these environmental changes is phenotypic plasticity (Liu and El-Kassaby 2019). In contrast, traits such as the NB, MDC, and BH exhibited low plasticity, suggesting that they may be more strongly canalised genetically or subject to functional constraints that limit their phenotypic variation (Bradshaw 1965; Schlichting 1986).

The regional distribution of plasticity, particularly the marked values of BH and MDC between the north and the south, as well as the variation in NB between the center and the north, reflects differential adaptations to local environmental gradients, particularly climatic and edaphic (Jump and Peñuelas 2005). The low plasticity between the center and the north for the majority of traits, except for BD, CS, HC, TH, and DBH, suggests a relative environmental homogeneity or stabilising selection in these areas (Ghalambor et al. 2007). This differentiated plasticity reflects *U. kirkiana*'s ability to adjust certain functional traits in response to local variability, a key factor for its resilience to climate change (Nicotra et al. 2010; Valladares Ros and Araújo 2014). Genetic diversity, physiological adaptations and environmental conditions may play a crucial role in shaping the observed PPI variations. Further research into the molecular and physiological mechanisms underlying phenotypic plasticity may provide valuable insights into the species' resilience to aridity-related stresses.

5.4.6 Implications of the findings for *U. kirkiana* conservation and domestication

Understanding the relationships between environmental conditions and plant traits can inform conservation policies and strategies aimed at species' domestication (Avakoudjo et al. 2021; Balima et al. 2018; Shin et al. 2019). The variation in morphological and functional traits within populations of *U. kirkiana* across different regions underscores that there is, to some extent, genetic diversity that needs conservation efforts. These efforts should focus on maintaining populations across various regions, since each population may harbor unique adaptive traits that contribute to the species' resilience and survival in specific environments (Quintero-Galvis et al. 2024). In addition, the observed correlations between the climatic variables and specific traits can serve as a basis for selecting a genetic diversity pool for conservation and potential domestication efforts. For

example, Jump et al. (2009) demonstrated that populations of *Fagus sylvatica* (European beech) located at the ecological margins (drier southern populations) expressed distinct physiological and morphological adaptations that were absent in core populations.

Preserving this regional variation is critical for the species' long-term adaptability under changing climates. In addition, the observed correlations between climatic variables and specific traits can guide the selection of populations with desirable characteristics for conservation or domestication. This approach aligns with findings by Alberto et al. (2013), who emphasised the importance of climate-trait associations for assisted gene flow and breeding programs, especially under projected climate scenarios.

Findings on the specific climatic conditions that promote optimal growth of desirable traits can guide decisions on where to establish plantations or restoration projects. In the context of domestication, the plasticity exhibited by *U. kirkiana* in response to different climatic conditions presents opportunities for selective breeding and cultivation. Identifying characteristics that enhance survival and productivity in different environments is useful to inform effort towards selecting elite individuals that are well-adapted to specific ecological regions. This could enhance the species' economic potential and contribute to sustainable livelihoods for local communities (Kumar 2015; Leakey and Simons 1998). The observed variation in leaf traits, reflecting an adaptation to water stress, can also inform strategies for selecting individuals with desirable characteristics for arid regions.

5.5 Population ecology and carbon storage potential of *U. kirkiana* in Malawi

5.5.1 Floristic composition and diversity of *U. kirkiana* habitat

The floristic richness of *U. kirkiana* habitats across Malawi confirms the ecological value of miombo woodlands as biodiversity hotspots in Southern Africa (White, 1983). The recorded richness of 124 species across 39 families reflects the functional complexity and structural diversity of these habitats (Appendix 5). The predominance of the Fabaceae family (42 species) reflects a

typical pattern observed in tropical dry forests and savannahs ecosystems, where nitrogen-fixing species enhance soil fertility and facilitate the regeneration of associated woody species (Chidumayo and Gumbo 2010). In addition to Fabaceae, the frequent occurrence of Phyllanthaceae, Rubiaceae, and Anacardiaceae in the sampled plots indicates structural complexity and functional diversity in these woodlands (Gondwe et al. 2021). The dominance *Brachystegia*, *Uapaca*, *Julbernardia* and *Parinari* genera confirms the typical floristic composition of miombo ecosystems. These ecosystems are globally recognised for their distinct community structure and socio-ecological importance and the genera are widely reported as ecological indicators in Tanzania, Mozambique, and Zambia (Campbell 1996). Their dominance suggests that *U. kirkiana* thrives in co-existence with key structural species and potentially benefits from facilitative interactions that enhance its regeneration and establishment. This has been observed previously in other parts of the Zambezian phytoregion (Campbell 1996; Ryan et al. 2012). This could lead to favourable ecological interactions for the natural regeneration of *U. kirkiana* (Chidumayo and Gumbo 2010).

The presence of five IUCN Red List vulnerable species in *U. kirkiana* habitats (Figure 22) highlights the importance of conserving these areas, especially in light of increasing threats such as shifting cultivation, charcoal production, and illegal timber extraction (Timberlake et al. 2010; Sosef et al. 2017). Furthermore, the identification of 25 species not yet assessed by the IUCN points to critical gaps in botanical knowledge and underscores the urgency for updated taxonomic and conservation assessments (Mazikuko and Changadeya 2024).

The result also revealed significant regional differences in alpha (α) diversity (Table 32). The central region recorded higher species richness, possibly due to lower levels of disturbance or greater environmental heterogeneity. In contrast, the southern region exhibited consistently low diversity across all indices, likely reflecting high anthropogenic pressures such as fire, overharvesting, and agricultural encroachment (Deweese et al. 2010). Interestingly, the northern region had lower species richness but higher Simpson diversity, suggesting floristic dominance by

a few species likely due to past logging or regeneration stages favoring pioneer or generalist species (Nyirenda 2022). The high Jaccard similarity between northern and southern communities may reflect shared disturbance histories, such as widespread fire regimes, or similar ecological filters (Chapagain et al. 2021; Bieng et al., 2021). This pattern is characteristic of environments that have been disturbed by human activity or are in the process of regeneration, where such influences or early successional phases favor the prevalence of certain opportunistic or pioneer species (Banda et al. 2006).

The results confirm the importance of *U. kirkiana* within Malawi's central miombo forest formations. Its high IVI value in the study area highlights its ecological importance as a dominant or co-dominant species (Table 31). As Ngulube (1998) points out, the dominance of *U. kirkiana* reflects its ability to establish itself in natural stands, making it a structuring species in miombo ecosystems. This role is all the more relevant as *U. kirkiana* is also recognised for its ecosystem services, particularly in terms of carbon storage (Shirima et al. 2011), forest regeneration, and local subsistence through its fruits. The use of IVI here makes it possible to assess not only the density and dominance of *U. kirkiana*, but also its frequency in the plots, providing a complete insight into its spatial distribution. This approach also highlights its coexistence with other key species such as *Brachystegia spiciformis* Benth. (Fabaceae), *Julbernardia paniculata* (Benth.) Troupin (Fabaceae), and *Uapaca sansibarica* Müll.Arg. (Phyllanthaceae), which, in certain forests such as Dzalanyama and Perekezi, play a significant role in population dynamics. These results showed that *U. kirkiana* should be considered an ecological and socio-economic priority species in conservation strategies. However, the variability of its indices across forests suggests the need to adapt management measures to each local context for the sustainable and effective conservation of miombo ecosystems. They also emphasise the conservation potential of these habitats and their role in maintaining ecological function under changing land use and climatic pressures (Bieng et al. 2021).

5.5.2 Structural diversity of *U. kirkiana* stand: insight for ecosystem sustainable management

The structural diversity of *U. kirkiana* stands across Malawi showed a predominance of intermediate mingling classes ($M_i = 0.50$ and 0.75) in all regions (Figure 23). This indicates moderate spatial mixing between *U. kirkiana* and associated species, a condition that is often beneficial for enhancing stand-level ecological stability, light utilisation, and resilience against biotic and abiotic stressors (Gadow et al. 2012; Pommerening, 2002). Conversely, the low representation of extreme mingling values ($M_i = 0$ or 1) suggests that pure stands or monospecific dominance is rare, reinforcing the role of *U. kirkiana* as part of mixed-species woodland systems (Kalaba et al. 2013). Similar observations were made in West Africa where *Pterocarpus erinaceus* Poir. had lower M_i values in drier zones with higher anthropogenic disturbances in Benin (Biaou et al. (2023b)).

Diameter differentiation did not vary significantly across regions, suggesting structural homogeneity, possibly due to similar management history or ecological stages (Table 33). However, the southern region displayed significantly lower inter-tree distance (D_i), indicating higher tree density and potentially stronger interspecific competition (Pretzsch 2009). This pattern is consistent with protected forest reserves in southern Malawi, where reduced human access favors natural regeneration but also increases competition. P_i showed strong regional contrasts and was highest in the central region, likely due to more intensive human utilisation (branch harvesting for fuel or fodder). Frequent pruning can modify vertical structure and influence carbon allocation, often reducing growth potential if excessive (Aerts and Honnay 2011). NPE was significantly higher in the northern region. This corresponds with higher regeneration rates in this region and aligns with earlier findings that seed source proximity, canopy cover, and moisture availability support natural recruitment in semi-deciduous forests (Chidumayo and Gumbo 2010; Swaine and Whitmore 1988). These results are contrary to those obtained by Biaou et al. (2023b), on *Pterocarpus erinaceus* Poir. in Benin, showing that the lowest density of adult trees was observed

in the Sudano-Guinean zone despite the highest regeneration. This disparity could probably be due to the highly illegal cutting and harvesting of the species because of the seasonal movements of livestock (Houéhanou et al. 2011; Sinsin et al. 2004).

Such results were also observed in the same area by Houèchégnon et al. (2015) for *Prosopis africana* (Guill. & Perr.). Taub. Reporting that the tree density was low in the most anthropised areas in Benin. This discrepancy highlights the role of protection status and anthropogenic intensity in shaping demographic structure. The Dg was significantly higher in the northern and southern regions than in the central region. This suggests that cooler, wetter, or more stable ecological conditions may favor tree longevity and growth (Mensah et al. 2014). Such patterns were also reported for *Vitellaria paradoxa* CF Gaertn. and *Afzelia africana* Sm. ex pers. In West Africa, where climatic stability and protection policies promoted basal area increment (Glèlè et al. 2011).

The analysis also revealed significant correlations among structural attributes (Figure 24). DBH showed a strong positive correlation with Qs and Di in northern and southern regions, reflecting dominance by larger trees occupying wider growing spaces, a common pattern in self-thinning or semi-climax systems (Zianis et al. 2005; Pommerening 2002). A negative correlation between DBH and DDi further indicated lower size heterogeneity in stands dominated by older, larger individuals. Notably, a negative correlation between DDi and Di in northern and southern regions suggests a more aggregated distribution in size heterogeneous stands, possibly due to regeneration pulses or gap-phase dynamics (Viljur et al. 2022; Li et al. 2024). In contrast, in West Africa, Biaou et al. (2023) reported a positive correlation between these variables, likely due to differences in rainfall seasonality and fire regimes. This trend could be explained by competition for essential resources such as light, water, and nutrients, which are important for tree growth and development (Fandohan et al. 2010; Noulèkoun et al. 2017). In the southern region, positive correlations between NPE, Pi, DDi and Dg suggest a natural self-thinning dynamic, possibly human-assisted selection. This might result from management practices such as selective pruning or assisted regeneration in fenced reserves, which were reportedly more regulated than in other zones. These findings support

the hypothesis that light anthropogenic management can facilitate structural complexity and regeneration (Chidumayo and Gumbo 2010; Seliger et al. 2024). This result is contrary to the paradigm of Yoda (1963), which stipulates that increases in stationary biomass, linked to tree development, are offset by self-thinning dynamics attributed to space filling and the subsequent scarcity of resources. These divergences could be due to differences in disturbance practices or the resource use strategy by local communities (Ssegawa and Nkuutu 2006), showing the spatial distribution and structuring of the populations.

Altitudinal gradients further shaped structural patterns (Figure 25). At higher elevations (1150-1370), DBH positively correlated with Q_s and D_i , consistent with the idea that dominant individuals emerge in less disturbed, stable conditions (Weiner 1990). Conversely, lower elevations showed negative correlations between D_g , D_i , and Q_s , likely reflecting pressure from human land use, grazing, or drought-related stress (Agea et al. 2010). Additionally, M_i exhibited variable correlations with other indices across altitudes, suggesting site-specific processes involving edaphic and climatic filters (Seydack 1995; Geldenhuys 2005). Finally, the observed positive correlation between P_i and Q_s in mid-altitude zones (950-1100 m) implies that selective human interventions may have initially supported tree growth by reducing inter-individual competition. However, the concurrent negative correlation with DD_i suggests that intensive pruning could reduce horizontal heterogeneity, especially when it becomes recurrent or spatially selective. These results, consistent with studies in tropical dry forests of East and West Africa, by highlighting the structural variation and ecological responses of *U. kirkiana* populations to regional and altitudinal gradients. They emphasise the influence of human disturbance, ecological conditions, and site-specific management on demographic structure, and call for conservation strategies tailored to regional pressures and ecological contexts.

5.5.3 Variation in diameter class structure of *U. kirkiana* populations across regions

The diameter class structure of *U. kirkiana* across the three regions of Malawi showed strong spatial variation, with patterns closely reflecting levels of disturbance, ecological conditions, and protection status. Overall, the dominance of small diameter classes (10-20 cm) in all regions indicates a population biased toward young individuals and active regeneration. However, the limited presence of larger diameter classes (>30 cm), particularly in the central and northern regions, suggests regeneration bottlenecks and potential demographic instability (Leakey et al. 2005). In the central region, the pronounced asymmetry in diameter class distribution and the higher Pi point to substantial anthropogenic disturbance. These structural imbalances likely reflect selective logging, fuelwood collection, and land use conversion, which disproportionately affect mature trees. Similar patterns were reported in West Africa, where *Pterocarpus erinaceus* populations in the Sudanian and Sudano-Guinean zones exhibited truncated structures due to heavy harvesting and insufficient recruitment into larger classes (Amahowe et al. 2019; Biao et al. 2023b). In contrast, the southern region displayed a comparatively less skewed diameter distribution, suggesting relatively better conservation of mature individuals (Figure 26). While small diameter classes still dominated, a greater proportion of individuals in mid to large diameter classes was recorded, likely due to the location of most plots within protected forest reserves with restricted access. Such patterns highlight the importance of effective forest protection in maintaining population structure and long-term viability (Nacoulma et al. 2011). The relatively stable structure in the south may also be influenced by favorable edaphic and climatic conditions, which support tree longevity and growth (Birhane et al. 2020b). The northern region, despite high regeneration rates, also lacked individuals in larger diameter classes. This trend could be attributed to historical overexploitation, compounded by climate variability (low rainfall and soil degradation), which limits the transition from sapling to adult stages (Nyirenda 2022).

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Across all regions, the scarcity of large-diameter *U. kirkiana* individuals raises concerns about population aging, reproductive potential, and long-term sustainability (Figure 27). Large trees often serve as key seed sources and contribute disproportionately to ecosystem functions, including carbon sequestration and microhabitat provisioning (Chidumayo and Gumbo 2010). Their absence may thus compromise both the ecological role and regeneration dynamics of the species. These findings highlight the need for targeted conservation actions such as enforcing cutting bans, promoting enrichment planting, and enhancing community-based protection, particularly outside protected areas. Moreover, integrating traditional ecological knowledge with scientific forest monitoring could facilitate the restoration of *U. kirkiana* population structures across Malawi (Kalaba et al. 2013; Gouwakinnou et al. 2009). Ultimately, the observed variation in diameter class structures emphasising spatial disparities in population demographics and identifying key drivers of structural degradation and resilience. It underscores the urgency of context-specific management strategies to ensure the sustainable conservation of *U. kirkiana* under mounting anthropogenic and climatic pressures.

5.5.4 Diameter structure of *U. kirkiana* populations variation across the altitudinal gradient

Diameter class distributions of *U. kirkiana* shifted notably with altitude. Across most altitudinal ranges, populations were skewed towards small trees (10-20 cm DBH), indicative of recent regeneration (Figure 28). However, at 850-959 m, the DBH distribution approached a bell-shaped curve, characteristic of structurally mature and balanced communities likely due to optimal soil moisture, moderate climate, and limited anthropogenic pressures (Mensah et al. 2016; Brien et al. 2015). At high elevations (1600-1770 m), there was a clear deficit of large trees (>30 cm DBH) and irregular class representation. This pattern is often linked to selective removal of mature trees for timber or fuel, a phenomenon documented in miombo woodlands facing pressure (Ronoh et al. 2018) and in other dry African forests (Biaou et al. 2023; Vroh et al. 2022).

The consistency of small-tree presence across altitudes suggests effective regeneration, yet the lack of larger classes highlights a developmental bottleneck likely due to combined effects of harvesting, slow growth under stress, or limited site resources (Ritsche Katzensteiner & Acácio 2021). Similar structural fragmentation has been observed in West African species like *Vitellaria paradoxa* and *Azelia africana* when mature trees were removed (Glèlè Kakaï et al. 2011; Gouwakinnou et al. 2009). Analysis of the structural quotient (Qs) showed pronounced heterogeneity at higher elevations and in the central region, indicating gaps in stand structure caused by loss of older trees. These gaps can affect canopy continuity, ecosystem function, and carbon storage (Geldenhuys 2005; Brancalion et al. 2019). These findings highlight altitude-mediated impacts on population structure. In high-altitude zones lacking mature trees, urgent conservation measures such as harvesting restrictions, enrichment planting, and community-led forest stewardship are critical to ensure sustainable ecological and socio-economic functions of *U. kirkiana* populations.

5.5.5 Natural regeneration and branching dynamics of *U. kirkiana* across different regions

U. kirkiana species in the miombo woodland has shown successful regeneration across various regions of Malawi, particularly within specific diameter classes of trees (Figure 29). Ecological,

demographic, and anthropogenic factors may probably influence the regeneration processes (Ngulube 2000). In the central region, the concentration of regeneration under trees within a diameter of 30-40 cm could indicate that this size represents an ecological or physiological optimum for *U. kirkiana* recruitment. Intermediate-sized trees are often associated with a moderately dense canopies that provide partial shade, which is favourable for germination and seedling establishment (Chidumayo and Gumbo 2010; Chidumayo 1997). To inform the conservation and management efforts of a plant in its habitat, it is important to gain better understanding of the factors that influence tree regeneration patterns (Lykke et al. 2025; Schumann et al. 2010; Sabo et al. 2023).

The absence of regeneration under very small trees (0-10 cm) suggests that these individuals are probably still juvenile and have not yet reached reproductive maturity. Meanwhile, large trees (≥ 40 cm) could create too dense a shade or accumulate litter that is unfavorable to regeneration (Ngulube 2000; Ngulube et al. 1998). Several studies have highlighted that the extracting hardwood and non-timber forest products can lead to a decline in tree populations (Djossa et al. 2008; Fandohan et al. 2010; Idrissa et al. 2018; Jurisch et al. 2013). In northern region, the more balanced distribution of *U. kirkiana* populations' structure could reflect interruptions in recruitment, potentially linked to selective anthropogenic pressure on medium-sized trees. Several studies have shown that selective logging of trees based on their diameter can alter population structures and hinder regeneration dynamics (Lykke 1998; Lykke et al. 2025; Teketay 2005). In contrast, the southern region exhibited a different configuration, with regeneration decreasing as the tree diameter increased. The high regeneration of *U. kirkiana* individuals under trees with small diameters (5-10 cm) can be explained by a recolonisation process in degraded or disturbed habitats, where young individuals develop without direct competition with mature trees (Luoga et al. 2004). This can also be interpreted as a sign of exploitation or mortality of large individuals, which allows for dense regeneration but is potentially not viable in the long term if the young plants do not reach adulthood.

5.5.6 Biomass capture and carbon sequestered by *U. kirkiana* across regions in Malawi

Carbon stock estimates for *U. kirkiana* reveal significant regional disparities that are closely linked to dendrometric traits, stand density, and disturbance regimes (Table 34). The northern region, in particular, exhibits a markedly higher carbon sequestration potential, which may be attributed to the presence of less degraded miombo ecosystems, characterised by mature trees, deeper soils, and reduced anthropogenic pressure. Similar patterns have been reported in structurally intact woodlands of Mozambique and Zambia, where carbon stocks exceeded 70 MgC/ha due to limited logging and fire influence (Bastias et al. 2020; Gu et al. 2019; Kokou et al. 2023b). Our results confirm that stand structure, specifically tree diameter and height, directly influences carbon accumulation, as shown by a study of African savannahs and dry forests (Brancalion et al. 2019). The structural composition of forest stands is crucial for determining carbon storage capacity, as it reflects competition intensity, species dominance, and spatial organisation (Gu et al. 2019; Li et al. 2021; Bastias et al. 2020).

Yang et al. (2024), demonstrated that the spatial structure of the stand positively affects the ecological system's carbon storage capacity, consequently, this capacity increases with spatial optimisation. Other authors have shown that biomass and carbon storage capacity depend on various factors, such as the diameter and height of the trees, stand density, and pedoclimatic conditions (Setyasih et al. 2025; Brown 1997; Kokou et al. 2023c). High carbon sequestration reflects denser, well-preserved forests with deeper soils and reduced disturbance, which supports greater biomass accumulation (Chave et al. 2014; Ryan et al. 2011; Kalaba 2013). In contrast, the lower carbon values observed in the southern and central regions of Malawi may reflect more intense land use, uncontrolled fire regimes and reduced basal area resulting from selective harvesting and slow natural regeneration (Kokou et al. 2023b; Shirima et al. 2011; Yang et al. 2024). These observations echo findings in the semi-arid zones of Benin where degraded stands exhibited lower biomass and higher structural instability (Biaou et al. 2023).

Beyond providing ecological insights, the economic valuation of sequestered carbon illustrates the substantial potential of *U. kirkiana* in climate-smart forestry. In the northern region, an estimated income of over one million Malawian Kwacha per hectare underscores the viability of integrating *U. kirkiana* into REDD+ and payment for ecosystem services (PES) schemes. Such strategies are becoming increasingly promoted across sub-Saharan Africa as a means of enhancing livelihoods and fostering landscape-scale restoration (Mbow et al. 2014; Pistorius et al. 2011; Vågen et al. 2016; Place et al. 2016). The dual benefits of carbon storage and socio-economic value make *U. kirkiana* a compelling candidate for community-based forestry and agroforestry interventions.

5.6 Implications of climate change on habitat suitability and altitudinal shifts of *U. kirkiana*

5.6.1 Overview of the choice of methodological approach

In this study, we used the MaxEnt algorithm to model the distribution of *U. kirkiana* in Malawi (Figure 31). MaxEnt demonstrated excellent performance in predicting the current potential distribution of the species, given the AUC value of > 0.9 . The AUC value obtained in our study (Table 35) is comparable to that reported by Jinga et al. (2020) in their study which evaluated the impact of climate change on the distribution of *U. kirkiana* in Southern Africa (Zimbabwe). We also obtained values close to one for both SEDI (0.95) and TSS (0.86), indicating the robustness and reliability of the employed model. This finding is similar to that of Atakpama et al. (2023), who reported similar values for SED (0.98) and TSS (0.93) in their study of the impact of climate change on the distribution of baobab in West Africa. MaxEnt is frequently regarded as the most reliable model for species distribution modelling due to its ability to handle presence-only data and small sample sizes (Abdelaal et al. 2019; Kaky et al. 2020). The consistent results obtained prove the model's improved performance.

Nonetheless, the modelling approach exhibited some limitations worth mentioning (Figure 32). These included the omission of demographic parameters (example fertility, mortality, growth) and population dynamics indicators (dispersal rate, population density, death rate and birth rate). For example, the dispersal ability of species and their structure are critical factors influencing the

potential impact of climate change on their habitats (Atakpama et al. 2023). Yet, integrating these parameters into the modelling framework appears to be more arduous and complex, especially on a large scale.

5.6.2 Temperature-related climatic variables determine the current potential distribution of *U. kirkiana* in Malawi

We found that temperature-related variables including average (BIO1, BIO10 and BIO11) and extreme (BIO5) values, and amplitude of variability (BIO3) were the most important variables that determined the current potential distribution of the species (Figure 34). This finding aligns with previous studies demonstrating the significance of temperature for the dynamics of plant species distribution (Lenoir et al., 2008). Annual mean temperature (BIO1) is a crucial variable because it indicates the areas in which *U. kirkiana* can survive at a temperature that meets its physiological requirements. Rising temperatures may limit a species' ability to germinate and grow, which in turn, may affect its distribution in warmer climates. Therefore, information on the annual temperature range of the potential distribution of the species is of paramount importance. Our findings indicate that *U. kirkiana* was primarily found in warm areas with mean annual temperatures around 29°C. BIO3 reflects the degree to which daily temperature variations compare to overall annual temperature range (Figure 33). Higher BIO3 values indicate more consistent daily temperature patterns throughout the year, while lower values suggest greater contrasts between daily and seasonal temperature fluctuations. A consistent temperature may reduce thermal stress on species, potentially promoting stable growth and development. For *U. kirkiana*, regions with higher isotherms may be more favorable for growth because they provide a stable thermal environment that mitigates extreme temperature variations, which can be stressful to plants (Khan and Verma 2022). BIO3 was the most important variable determining the current potential distribution of the species. *U. kirkiana* is adapted to relatively high daily temperature fluctuations (Fig. S3). Our results are reminiscent of the findings of previous studies that reported isothermality and annual temperature as the most important determinant of the distribution of *A. digitata*

(Atakpama et al., 2023, Kokou et al., 2024b, Sanchez et al., 2010), *Borassus aethiopum* Mart. (Salako et al., 2018), *Pterocarpus erinaceus* Poir. (Biaou et al. 2023a; Adjonou et al. 2020; Saliou et al. 2015) in West Africa. The importance of temperature for the distribution of the species in Malawi, which was characterised by a semi-arid climate with relatively high temperatures, may be attributed to the sensitivity of flowering species to low temperatures, particularly during the reproduction and seedling development phases (Huggett 2004). It is likely that *U. kirkiana* is vulnerable to prolonged intervals of inconsistent or fluctuating temperatures in colder climates temperature variability (O'Donnel and Ignizio 2012).

Conversely, elevated maximum temperatures, especially in the warmest month (BIO5), can cause heat exhaustion, increased evaporation, and decreased photosynthesis (Parthasarathi et al. 2022). These factors have an adverse effect on species' physiology, limiting their occurrence in overly hot regions (Jinga et al. 2020). Accordingly, we found that *U. kirkiana* had a high occurrence in areas with moderate BIO5. Lastly, BIO11 illustrates the species' resilience to low temperatures where the coldest quarter reaches temperatures that are dangerous to species survival, especially for seedlings. According to Zhang et al. (2019), areas with milder winter temperatures are better suited for the species' existence. Jinga et al. (2020) also observed that the distribution of *U. kirkiana* extends to regions with colder winters. These findings suggest that the species may exhibit greater adaptability to lower temperatures than indicated by the results of our study. Moreover, we found that precipitation and altitude were less influential for the species distribution. Disparity in the geographic coverage of the studies and the representativeness of the occurrence data may account for the discrepancies between our findings and those of previous studies (Jinga et al. 2020; Zhang et al. 2019). The sensitivity of flowering species to low temperatures, especially during reproductive and seedling development stages, underscores the importance of temperature in species distribution (Huggett 2004).

5.6.3 Climate change reduces the suitable habitats of *U. kirkiana*

The climate projections indicate that the coverage of habitats currently suitable for *U. kirkiana* will not remain stable in the future (Figure 35 and 36). Overall, the highly suitable areas for *U. kirkiana* under the current climate will strongly decline and be replaced by moderately suitable, poorly suitable, and unsuitable habitats under the future climate scenarios. Compared to the current scenario, the percentage of highly suitable and moderately suitable areas substantially decreased under the SSP3-7.0 and SSP5-8.5 scenarios (Figure 37). This reduction highlights the negative impacts of increasing greenhouse gas emissions and temperature rise on the ecological niches of the species (Jinga *et al.* 2020). Consequently, the proportion of unsuitable areas significantly expanded under the future climate, suggesting that *U. kirkiana* will face a dramatic loss of habitats conducive to its growth and survival. The increase in unsuitable areas underscores the intensification of environmental stressors, such as temperature extremes, reduced water availability, and habitat degradation, which are likely to hinder the species' regeneration and persistence. This is supported by the significant increase (BIO11, BIO10 and BIO5) a decrease (BIO 3) in the values of the determining temperature-related variables between the current climate and future scenarios. These projections align with the findings of Jinga *et al.* (2020), who reported a contraction in the potential range of *U. kirkiana* due to climate change in southern Africa. Similar patterns of habitat reduction were also reported for other species, such as *Tamarindus indica* L. in Togo (Samarou *et al.* 2023) and *Detarium microcarpum* Guill. & Perr. in Benin (Agbo *et al.* 2019). The significant decrease in suitable areas, as shown in Fig. 3, could have profound implications for local communities relying on *U. kirkiana* for food, income, and medicinal purposes.

5.6.4 Prioritisation and conservation zone of *U. kirkiana* in Malawi

This study forecasts the northern and central regions as priority zones for conserving and cultivating *U. kirkiana* in Malawi (Table 39 and Figure 39). Conversely, the central area of the Southern Region remains of very low priority. This finding indicates that, the northern and central regions of Malawi, along with certain areas in the south, harbor most of the very high priority areas

for *U. kirkiana* conservation (75-100%). Very high priority areas in the northern region included the Rumphu, Mzimba, and Chitipa districts, as well as Nyika and Vipha highlands and plateaus. The high isothermality and moderate mean annual temperatures prevailing in these regions likely create favorable conditions for the species survival, highlighting their importance as priority areas for conservation (Table S4). As a result, these regions offer a favorable environment for *U. kirkiana* to survive and ought to be given priority in conservation planning for the species. Our findings align with previous research showing that species of tropical dry forests favor regions with lower seasonal temperature fluctuations, promoting a more expansive and stable range (Bellard et al. 2012).

Priority areas in the central region are those that are adjacent to the Dowa Mountains and the Kasungu plain. These regions are distinguished by moderate maximum temperatures in the warmer months, which supports the species' continued growth. According to previous research, tropical forests benefit from moderate maximum temperatures that create favorable microclimatic conditions that promote seedling germination and establishment by reducing heat stress and supporting optimal growth (Lenoir et al. 2008). Strengthening conservation efforts in these areas while considering regional approaches to natural resource management is crucial for ensuring the sustainable preservation of *U. kirkiana* populations and their associated ecosystem services. Although there are fewer high priority areas in the southern region, the villages surrounding the Mulanje and Zomba mountains stood out due to their unique climate, which is favorable for *U. kirkiana* occurrence. Lower temperatures during the coldest quarter (BIO 11) have an impact on these areas, which were situated in the Mulanje and Zomba districts in the localities of Nkanda (Mulanje) and Mwambo (Zomba). This reduces the species' exposure to heat stress. Thompson et al. (2010) confirmed the thermal regulation of these regions by demonstrating the critical role that mountain regions, which are known for their lower temperatures, play in the survival of species that are vulnerable to climate change. In cooperation with local communities and traditional authorities, biodiversity management in these areas could be improved. Additionally, the suitable

areas of *U. kirkiana* will subtly increase in the southern region of Malawi, even though this region remains the least suitable considering both scenarios. Unsuitable habitats for the species are found in the southwestern and central-eastern parts of the country, where prevailing temperatures are less suitable.

Under the two future scenarios, the results showed that some districts that were suitable under the current climate would remain the favorable areas for the species occurrence (Mzimba District, Nkhatabay, Rumphi, Karonga, Kasungu, Dowa and Dedza) (Figure 39). Conversely, some unsuitable areas under the current climate such as the Balaka district will become poorly suitable areas in the future. In addition, a large part of the districts of Neno, Blantyre, Mwanza, Chikwawa and Nsanji that were not suitable for the occurrence of the species under the current climate conditions would become suitable for the species under the future climate scenarios, as also observed by Nouvellet et al. (2006) for the shea butter tree (*Vitellaria paradoxa* C. F. Gaertn). We also found that some current suitable habitats corresponded to places where the species is not actually present, indicating that the fundamental niche of the species extends beyond the realized niche considered in this study, as also reported in previous studies (Pearson and Dawson 2003; Atakpama et al. 2022; Gouwakinnou 2013; Van Dyke 2008).

Apart from assessing zone viability rankings, this information enables us to better assess the cost-benefit ratio of conservation/utilisation. Such data are crucial for making informed decisions regarding species conservation, utilisation, and cultivation areas. Overall, the proportion of predicted highly suitable habitats is higher than those of very high-priority habitats. This indicates that a suitable zone may not always be a priority zone for conservation or utilisation, a trend justified by habitat dynamics resulting from future climate variability. These results are in line with those of Kokou et al. (2024b) on baobab in Malawi, Atakpama et al. (2022) on *V. paradoxa*, and Samarou et al. (2023) on *T. indica* in Togo, demonstrating that the area where a species is present may not necessarily be the priority zone for its conservation.

5.6.5 Implications of the findings for the conservation of *U. kirkiana*

Climate change has raised unprecedented attention on the conservation of vulnerable species (Muluneh 2021; Mooney et al. 2009; Moritz and Agudo 2013; Robbins 2015). Our study showed that the population of *U. kirkiana* would move to higher elevations (Northern Region of Malawi) in the face of global warming. Implementing an in-situ conservation strategy for these populations will be ineffective, as most of the currently suitable areas will become unsuitable in the future. Therefore, it would be ideal to pursue both in-situ conservation in areas projected to remain suitable under future climate and ex-situ conservation strategies combined with assisted migration to ensure the survival of *U. kirkiana* under changing climatic conditions (Potter et al. 2017). *Ex-situ* conservation strategies may encompass establishment of the species in botanical gardens and germplasm collections. In addition to considering the predictions from SDMs, it is necessary to take into account the perception of local communities in management activities for the successful conservation of *U. kirkiana*, as illustrated by Agbo et al. (2019) and Biaou et al. (2023a). Ensuring appropriate management of the species and promoting the production of nursery seedlings will facilitate the relocation and integration of the species into agroforestry systems. Due to increasing human pressures on forest resources in the southern and central regions, promoting beekeeping could enhance genetic flow between species populations to maintain their viability (Salako et al. 2019).

The typical conservation approach for plant species often revolves around creating protected zones characterised by expectedly stable environmental conditions (Sanchez 2011). Conservation initiatives beyond these protected zones may encounter obstacles stemming from human activities, such as the exploitation of non-timber forest products (Ball and Brancalion 2016). With the anticipated shrinking of the natural habitat range of *U. kirkiana*, the critical importance of establishing the species in protected areas featuring favorable environmental conditions becomes evident to ensure its survival.

5.7 Chapter Summary

This chapter discussed the main findings of the study in the context of existing literature, providing an integrated interpretation of *Uapaca kirkiana*'s ecological and socio-economic dimensions in Malawi. The results revealed that local ecological knowledge and community-based practices remain central to understanding how rural populations perceive, manage and sustain this species. However, the persistence of unsustainable harvesting, limited regeneration and weak policy integration indicates that traditional knowledge alone is insufficient without ecological and institutional support.

The analysis of morpho-functional traits demonstrated significant regional differentiation, suggesting local adaptation to environmental gradients and highlighting the species' potential resilience to moderate climatic variability. This variation also underscores *U. kirkiana*'s key role in ecosystem functioning and carbon storage, particularly in mid-altitude zones. Yet, species distribution modelling revealed a progressive contraction and upward shift of suitable habitats under future climate scenarios (SSP3-7.0 and SSP5-8.5), aligning with regional studies on montane species shifts in Southern Africa but contrasting with some reports of broader ecological tolerance.

These findings advance understanding of how climate and anthropogenic pressures interact to shape the spatial ecology of a multipurpose indigenous tree. They demonstrate the necessity of coupling functional ecology, local knowledge and predictive modelling to identify conservation priorities and restoration zones. Overall, this chapter underscores that the sustainable future of *U. kirkiana* depends on integrated strategies combining scientific evidence, community stewardship and adaptive management to reconcile ecological resilience with rural livelihoods in a rapidly changing environment.

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

6.0 Introduction

This chapter presents the conclusions derived from the results of the study, highlighting how both the main and specific research objectives were addressed. It further demonstrates the contribution of the findings to the conservation and sustainable management of *Uapaca kirkiana* in Malawi. In addition, the chapter outlines the implications of the study for policy, practice and scholarship, particularly in relation to biodiversity conservation, community-based management and climate change adaptation. Finally, recommendations are provided to guide future research and to inform conservation strategies, based on the insights discussed in Chapter 5.

6.1. Conclusion

This study demonstrates that an integrated ecological and socio-ecological approach is essential for understanding and conserving multifunctional indigenous species such as *Uapaca kirkiana*. By combining local ecological knowledge, functional trait ecology, population structure analysis, and climate-based species distribution modelling, the research provides a holistic framework that captures both the biological and human dimensions of species persistence. Building on this foundation, the study addressed five interconnected research objectives to generate a comprehensive understanding of the ecology, use and conservation of *U. kirkiana* in Malawi. Together, these objectives explored the species' functional and adaptive traits, patterns of natural regeneration, ethnobotanical significance, spatial distribution under current and future climates and the implications for sustainable management.

Firstly, analysis of local ecological knowledge revealed that communities perceive a decline in *U. kirkiana* populations, with conservation awareness shaped by sociodemographic factors such as education level and profession. Despite the decline, local communities are engaging in conservation strategies, including agroforestry integration and the protection of natural regeneration. Ethnobotanical data confirmed the multipurpose role of the species, particularly for

food and therapeutic uses, while also showing that these uses contribute to its ecological vulnerability (vulnerability index = 2.25).

Secondly, ecological assessments of species composition and phylogenetic structure along altitudinal gradients demonstrated that *U. kirkiana* coexists within diverse woody communities (Fabaceae, Phyllantaceae) shaped by climatic, edaphic and topographic factors. The phylogenetic structure shifted from clustering to overdispersion across elevations, with temperature and seasonality emerging as key drivers. These findings highlight the role of both environmental filtering and neutral processes in structuring Miombo woodland biodiversity.

Thirdly, morphological and functional trait analysis revealed strong regional differentiation and high intraspecific polymorphism in leaves, fruits, seeds and growth traits. Elevation and aridity were key driver. Significant trait plasticity reflected the species' adaptive potential to contrasting climatic and edaphic conditions across Malawi. Four morphotypes were identified, underscoring the importance of distinguishing genetic versus environmental contributions to phenotypic variability. These results point to the potential for targeted domestication and breeding programs to enhance resilience.

Fourthly, population ecology analysis showed structural imbalances, with dominance of small-diameter classes and absence of large trees despite high regeneration rates, particularly in the north. This pattern, together with significant carbon storage potential, illustrates both the ecological value of *U. kirkiana* and the risks posed by anthropogenic disturbances such as fire, overgrazing and pruning. These findings highlight the urgent need for integrated, community-based management combining ecological insights with traditional practices to restore population stability while maximising ecosystem services.

Fifthly, climate change modelling indicated severe range contractions of *U. kirkiana* by 2055 (shifting from 9% to 6%), with suitable habitats shifting toward higher altitudes in northern and

central Malawi. Isothermality and temperature-related variables were the main determinants of habitat suitability. Conservation priority areas were identified in these regions, underscoring the need for proactive strategies such as assisted migration, domestication and site-specific planting programs.

Overall, this study demonstrates that the sustainability of *U. kirkiana* depends on integrating local knowledge, ecological and functional trait variability, population structure and climate projections into holistic management approaches. Future research should explore genetic diversity and adaptive traits using molecular tools, coupled with participatory conservation models that strengthen community engagement. Such efforts will not only safeguard *U. kirkiana* but also provide broader lessons for the conservation of indigenous fruit trees across Southern Africa under changing climate conditions. These findings highlight how the ecological status and sustainable use of *Uapaca kirkiana* directly support adaptive livelihoods by providing food, income and resources that enhance community resilience. Furthermore, local knowledge and community-based management practices empower rural populations to make informed decisions, demonstrating the role of conservation in strengthening community capacity and fostering transformative development.

6.2 Recommendations

This study aimed to assess the ecological, functional and socio-economic dimensions of *Uapaca kirkiana* in Malawi, with the goal of informing sustainable conservation, restoration and livelihood enhancement strategies. Based on the findings, the following recommendations are proposed:

6.2.1. Practice-Oriented / Community-Level recommendations

1. On-farm domestication and enrichment planting: Promote the cultivation of *U. kirkiana* in degraded Miombo landscapes and farming systems to improve regeneration and reduce pressure on wild populations.

2. Farmer training and capacity building: Support local communities with training in propagation techniques, nursery establishment, and silvicultural practices to enhance sustainable harvesting and tree growth.
3. Agroforestry integration: Encourage the inclusion of *U. kirkiana* in agroforestry systems to diversify household nutrition, income sources and reduce reliance on wild trees.
4. Community-based conservation initiatives: Strengthen seed banks, village nurseries and participatory forest monitoring to ensure collective stewardship and resilience of local populations.
5. Value addition and economic empowerment: Provide training in fruit processing, storage and market access to transform *U. kirkiana* from a subsistence resource into a commercially viable commodity while maintaining sustainability.

6.2.2. Research recommendations

6. Genetic vs. environmental determinants: Conduct molecular and genomic studies to disentangle the genetic and environmental contributions to morphological and functional trait variation, informing targeted domestication and selective breeding.
7. Adaptive trait plasticity under climate change: Assess how functional traits respond to projected climate scenarios to predict species resilience and guide restoration strategies.
8. Socio-ecological research: Expand studies on interactions between local ecological knowledge, cultural practices and scientific evidence to ensure conservation strategies are socially and culturally acceptable.
9. Ecological modelling at ecosystem scale: Extend modelling beyond *U. kirkiana* to include multi-species interactions and broader ecosystem dynamics in Miombo woodlands.

6.2.3. Policy recommendations

10. National recognition and integration: Elevate *U. kirkiana* as a priority indigenous fruit tree in Malawi's National Forest Policy, Agroforestry Strategy and climate change adaptation programs.

11. Conservation zones and regulations: Establish protected or semi-protected areas in northern and central regions where the species shows high resilience and carbon storage potential and develop guidelines regulating harvesting of fruits, timber and medicinal products.

12. Incentives for community-based management: Promote community forest management through financial and institutional support, including mechanisms for private sector engagement in value chain development.

6.3. Chapter Summary

This chapter presented the key conclusions drawn from this thesis on the ecology, functional traits, local uses and conservation of *U. kirkiana* in Malawi. The findings revealed significant regional and altitudinal differences in population structure, morphological and functional traits, and local knowledge, highlighting the species' ecological plasticity and adaptive capacity. Despite widespread recognition of population decline, local communities are actively implementing conservation strategies, including protection of regeneration and integration of *U. kirkiana* into agroforestry systems.

The study further demonstrated that socio-demographic factors such as education, profession, and local cultural practices strongly influence perceptions, use and commitment to conservation. Importantly, the species' ecological and economic importance, including carbon storage potential and multi-purpose uses, underscores the need for targeted conservation interventions. However, ongoing anthropogenic pressures such as overharvesting, land conversion and bushfires pose risks to population stability, particularly in regions with lower regeneration and fewer large trees.

Overall, the thesis emphasises that sustainable management of *U. kirkiana* requires an integrated approach combining scientific evidence, local ecological knowledge, community-based conservation and policy support. The conclusions call for region-specific strategies, domestication programs, and adaptive management to ensure the species' resilience under future climate and socio-economic scenarios in Malawi.

REFERENCES

- Abdelaal, M., Fois, M., Fenu, G. & Bacchetta, G. 2019, Using MaxEnt modeling to predict the potential distribution of the endemic plant *Rosa arabica* Crép. in Egypt. *Ecological Informatics*, 50, 68–75.
- Adjonou, K., Abotsi, K. E., Segla, K. N., Rabiou, H., Houetchègnon, T., Sourou, K. B., Johnson, B. N., Ouinsavi, C. A. N., Kokutse, A. D. & Mahamane, A. 2020, Vulnerability of African Rosewood (*Pterocarpus erinaceus*, Fabaceae) natural stands to climate change and implications for silviculture in West Africa. *Heliyon*, 6.
- Aerts, R. & Honnay, O. 2011, Forest restoration, biodiversity and ecosystem functioning. *BMC Ecology*, 11, 1-10.
- Agbo, R. I., Idohou, R., Vihotogbé, R., Missihoun, A. A., Dagba, R. A., Assogbadjo, A. E. & Agbangla, C. 2019, Spatio-temporal dynamics of suitable habitats for *Detarium microcarpum* Guill. & Perr. (Caesalpinaceae), a priority food tree species in Benin (West Africa). *Modeling Earth Systems and Environment*, 5, 595-604.
- Agnolucci, P., Fischer, C., Heine, D., Montes de Oca Leon, M., Pryor, J., Patroni, K. & Hallegatte, S. 2024, Measuring total carbon pricing. *The World Bank Research Observer*, 39, 227–258.
- Ahoyo, C. C., Salako, K. V., Houéhanou, T. D., Montcho, I., Glèlè Kakaï, R. L. & Houinato, M. R. B. 2023, Sociodemographic, environmental and biological factors affecting uses of plants from open ecosystems: insights for improved livelihoods and biodiversity conservation. *Frontiers in Conservation Science*, 4, 1127567.
- Akinnifesi, F., Kwesiga, F., Mhango, J., Chilanga, T., Mkonda, A., Kadu, C., Kadzere, I., Mithofer, D., Saka, J. & Sileshi, G. 2006, Towards the development of miombo fruit trees as commercial tree crops in southern Africa. *Forests, Trees and Livelihoods*, 16, 103-121.

Akinnifesi, F. K., Sileshi, G., Ajayi, O. C., Chirwa, P. W., Kwesiga, F. R. & Harawa, R. 2008, Contributions of agroforestry research and development to livelihood of smallholder farmers in Southern Africa: 2. Fruit, medicinal, fuelwood and fodder tree systems. *Agricultural Journal*, 3, 76-88.

Albert, C. H., Grassein, F., Schurr, F. M., Vieilledent, G. & Violle, C. 2011, When and how should intraspecific variability be considered in trait-based plant ecology? *Perspectives in Plant Ecology, Evolution and Systematics*, 13, 217-225.

Ali, A. & Bhattacharjee, B. 2023, Nutrition security, constraints, and agro-diversification strategies of neglected and underutilized crops to fight global hidden hunger. *Frontiers in Nutrition*, 10, 1144439.

Allouche, O., Tsoar, A. & Kadmon, R. 2006, Assessing the accuracy of species distribution models: prevalence, kappa and the true skill statistic (TSS). *Journal of Applied Ecology*, 43, 1223–1232.

Amahwe, O. I., Azihou, A. F., Armand, N. K., Biaou, S. H., Séverin, B., Dieu-Donné, A. & Salomon, B. 2019, Constraints of seedling survival and recruitment under adult tree of a multi-use species *Azizelia africana* Sm. and Pers in Sudanian region of Benin (West Africa). *Agroforestry Systems*, 93, 1147-1156.

Anderson-Teixeira, K. J., Herrmann, V., Rollinson, C. R., Gonzalez, B., Gonzalez-Akre, E. B., Pederson, N., Alexander, M. R., Allen, C. D., Alfaro-Sánchez, R. & Awada, T. 2022, Joint effects of climate, tree size, and year on annual tree growth derived from tree-ring records of ten globally distributed forests. *Global Change Biology*, 28, 245-266.

Anju, T. & Kumar, A. 2024, Traditional ecological knowledge and medicinal plant diversity usage among the Mullu Kuruman tribes of Wayanad district of Kerala, India and its implications for biodiversity conservation in the face of climate change. *Trees, Forests and People*, 100595.

APG, I. 2016, Angiosperm phylogeny group.

Asamoah, O., Danquah, J. A., Bamwesigye, D., Appiah, M. & Pappinen, A. 2024, Assessing the influence of social factors on local perceptions of climate change, product value addition, multiple uses of NTFPs, and their influence on poverty alleviation in Ghana. *Forests*, 15, 248.

Assang, M. D., Atakpama, W., Ahouadjinou, E. B. O. & Dimobe, K. 2023, Priority area for sustainable cashew (*Anacardium occidentale* L.) growing in Togo: Economic implications and conservation areas. *Revue Nature et Technologie*, 15, 29-40.

Atakpama, W., Abalo-Sama, G. J., Egbelou, H., Gouwakinnou, G. N., Dimobe, K., Samarou, M., Batawila, K. & Akpagana, K. 2022, Potentielle aire de culture du karité (*Vitellaria paradoxa* C.F. Geartn spp *paradoxa*) au Togo. *Rev. Sci. Technol., Synthèse*, 28, 31-45.

Atakpama, W., Adoko, S. A., Batawila, K. A. & Atakpama, W. 2021, Plantes et prise en charge de la santé maternelle dans la région Maritime du Togo. *Ann. Afr. Med*, 14, e4196.

Atakpama, W., Batawila, K., Dourma, M., Pereki, H., Wala, K., Dimobe, K., Akpagana, K. & Gbeassor, M. 2012. Ethnobotanical knowledge of *Sterculia setigera* Del. in the Sudanian zone of Togo (West Africa). *International Scholarly Research Notices*, 2012, 723157.

Atakpama, W., Batawila, K., Gnamkoulaba, A. & Akpagana, K. 2015, Quantitative approach of *Sterculia setigera* Del. (Sterculiaceae) ethnobotanical uses among rural communities in Togo (West Africa). *Ethnobotany Research and Applications*, 14, 063-080.

Atakpama, W., Gouwakinnou, G. N., Dimobe, K., Batawila, K., Natta, A. K. & Akpagana, K. 2023, Habitat suitability of subpopulations of *Adansonia digitata* L. in West Africa: Implications for conservation and domestication. *Trees, Forests and People*, 12, 100397.

Atkins, K. & Travis, J. 2010, Local adaptation and the evolution of species' ranges under climate change. *Journal of Theoretical Biology*, 266, 449-457.

Avocèvou-Ayisso, C., Avohou, T., Omorou, M., Dessou, G. & Sinsin, B. 2012, Ethnobotany of *Pentadesma butyracea* in Benin: A quantitative approach. *Ethnobotany Research and Applications*, 10, 151-166.

Ayantunde, A. A., Briejer, M., Hiernaux, P., Udo, H. M. & Tabo, R. 2008, Botanical knowledge and its differentiation by age, gender and ethnicity in Southwestern Niger. *Human Ecology*, 36, 881-889.

Ayéna, A., Assogbadjo, A., Adoukonou-Sagbadja, H., Mensah, G., Agbangla, C. & Ahanhanzo, C. 2016, Usages et vulnérabilité de *Pterocarpus santalinoides* L'Her. ex De (Papilionoidae), une plante utilisée dans le traitement des gastro-entérites dans le sud du Bénin. *European Scientific Journal*, 12, 14 p.

Báez, S., Fadrique, B., Feeley, K. & Homeier, J. 2022, Changes in tree functional composition across topographic gradients and through time in a tropical montane forest. *PLoS One*, 17, e0263508.

Ball, A. A. & Brancalion, P. H. 2016, Governance challenges for commercial exploitation of a non-timber forest product by marginalized rural communities. *Environmental Conservation*, 43, 208-220.

Bañares-de-Dios, G., Macía, M. J., Arellano, G., Granzow-de la Cerda, Í., Vega-Álvarez, J., Arnelas, I., Espinosa, C. I., Salinas, N. & Cayuela, L. 2024, Woody plant taxonomic, functional, and phylogenetic diversity decrease along elevational gradients in Andean tropical montane forests: Environmental filtering and arrival of temperate taxa. *Plant Diversity*, 46, 491-501.

Banda, T., Schwartz, M. W. & Caro, T. 2006, Woody vegetation structure and composition along a protection gradient in a miombo ecosystem of western Tanzania. *Forest Ecology and Management*, 230, 179-185.

- Bastias, C. C., Truchado, D. A., Valladares, F., Benavides, R., Bouriaud, O., Bruelheide, H., Coppi, A., Finér, L., Gimeno, T. E. & Jaroszewicz, B. 2020, Species richness influences the spatial distribution of trees in European forests. *Oikos*, 129, 380-390.
- Belcher, B., & Schreckenberg, K. 2007, Commercialisation of non-timber forest products: A reality check. *Development Policy Review*, 25(3), 355-377.
- Bellard, C., Bertelsmeier, C., Leadley, P., Thuiller, W. & Courchamp, F. 2012, Impacts of climate change on the future of biodiversity. *Ecology Letters*, 15, 365-377.
- Bellard, C., Leclerc, C., Leroy, B., Bakkenes, M., Veloz, S., Thuiller, W. & Courchamp, F. 2014, Vulnerability of biodiversity hotspots to global change. *Global Ecology and Biogeography*, 23, 1376-1386.
- Berkes, F., Colding, J., & Folke, C. 2000, Rediscovery of traditional ecological knowledge as adaptive management. *Ecological applications*, 10(5), 1251-1262.
- Betti, J. L. 2001, Vulnérabilité des plantes utilisées comme antipaludiques dans l'arrondissement de Mintom au sud de la réserve de biosphère du Dja (Cameroun). *Systematics and Geography of Plants*, 661-678.
- Biaou, S., Gouwakinnou, G. N., Biaou, H. S. S., Tovihessi, M. S., Awessou, B. K., Ahononga, F. C. & Houéto, F. O. 2021, Identifying the land use and land cover change drivers: methods and case studies of two forest reserves in Northern Benin. *Environment, Development and Sustainability*, 1-21.
- Biaou, S., Gouwakinnou, G. N., Noulèkoun, F., Salako, K. V., Kpoviwanou, J. M. R. H., Houéhanou, T. D. & Biaou, H. S. S. 2023a, Incorporating intraspecific variation into species distribution models improves climate change analyses of a widespread West African tree species (*Pterocarpus erinaceus* Poir, Fabaceae). *Global Ecology and Conservation*, 45, e02538.

- Biaou, S., Gouwakinnou, G. N., Noulèkoun, F., Salako, K. V., Noumagnan, N. B. A., Ahouandjinou, E. B. O. & Houehanou, T. D. 2023b, Insights from analyzing local ecological knowledge and stand structure for guiding conservation actions for the endangered tropical tree *Pterocarpus erinaceus* Poir. *Trees, Forests and People*, 14, 100447.
- Bieng, M. A. N., Oliveira, M. S., Roda, J.-M., Boissière, M., Herault, B., Guizol, P., Villalobos, R. & Sist, P. 2021, Relevance of secondary tropical forest for landscape restoration. *Forest Ecology and Management*, 493, 119265.
- Birhane, E., Asgedom, K. T., Tadesse, T., Hishe, H., Abrha, H. & Noulèkoun, F. 2020a, Vulnerability of baobab (*Adansonia digitata* L.) to human disturbances and climate change in western Tigray, Ethiopia: conservation concerns and priorities. *Global Ecology and Conservation*, 22, e00943.
- Birhane, E., Asgedom, K. T., Tadesse, T., Hishe, H., Abrha, H. & Noulèkoun, F. 2020b, Vulnerability of baobab (*Adansonia digitata* L.) to human disturbances and climate change in western Tigray, Ethiopia: conservation concerns and priorities. *Global Ecology and Conservation*, 22, e00943.
- Boffa, J.-M. 2000, *Les parcs agroforestiers en Afrique subsaharienne*. Rome, Italy: Food & Agriculture Org.
- Booth, T. H., Nix, H. A., Busby, J. R. & Hutchinson, M. F. 2014, BIOCLIM: the first species distribution modelling package, its early applications and relevance to most current MaxEnt studies. *Diversity and Distributions*, 20, 1-9.
- Bradshaw, A. D. 1965, Evolutionary significance of phenotypic plasticity in plants. *Advances in Genetics*, 13, 115-155.

- Bricca, A., Di Musciano, M., Ferrara, A., Theurillat, J.-P. & Cutini, M. 2022, Community assembly along climatic gradient: contrasting pattern between- and within-species. *Perspectives in Plant Ecology, Evolution and Systematics*, 56, 125675.
- Brose, U., Jonsson, T., Berlow, E. L., Warren, P., Banasek-Richter, C., Bersier, L.-F., Blanchard, J. L., Brey, T., Carpenter, S. R. & Blandenier, M.-F. C. 2006, Consumer–resource body-size relationships in natural food webs. *Ecology*, 87, 2411–2417.
- Brown, S. 1997, Estimating biomass and biomass change of tropical forests: a primer. Rome, Italy: FAO, Food & Agriculture Org.
- Burkhart, H. E. & Tomé, M. 2012, *Modeling forest trees and stands*. Springer Science & Business Media.
- Cadotte, M. W., Cardinale, B. J. & Oakley, T. H. 2008, Evolutionary history and the effect of biodiversity on plant productivity. *Proceedings of the National Academy of Sciences*, 105, 17012–17017.
- Campbell, B., Angelsen, A., Cunningham, A., Katerere, Y., Siteo, A. & Wunder, S. 2007, *Miombo woodlands opportunities and barriers to sustainable forest management*. Bogor, Indonesia: Center for International Forestry Research.
- Campbell, B. M. 1996, *The Miombo in transition: woodlands and welfare in Africa*. Bogor: CIFOR.
- Cavender-Bares, J., Gamon, J. A., Hobbie, S. E., Madritch, M. D., Meireles, J. E., Schweiger, A. K. & Townsend, P. A. 2017, Harnessing plant spectra to integrate the biodiversity sciences across biological and spatial scales. *American Journal of Botany*, 104, 966–969.
- Cavender-Bares, J., Kozak, K. H., Fine, P. V. & Kembel, S. W. 2009, The merging of community ecology and phylogenetic biology. *Ecology Letters*, 12, 693–715.

- Chapin III, F. S., Autumn, K. & Pugnaire, F. 1993, Evolution of suites of traits in response to environmental stress. *The American Naturalist*, 142, S78-S92.
- Chapman, H., Cordeiro, N. J., Dutton, P., Wenny, D., Kitamura, S., Kaplin, B., Melo, F. P. & Lawes, M. J. 2016, Seed-dispersal ecology of tropical montane forests. *Journal of Tropical Ecology*, 32, 437-454.
- Chave, J., Réjou-Méchain, M., Búrquez, A., Chidumayo, E., Colgan, M. S., Delitti, W. B., Duque, A., Eid, T., Fearnside, P. M. & Goodman, R. C. 2014, Improved allometric models to estimate the aboveground biomass of tropical trees. *Global Change Biology*, 20, 3177–3190.
- Chaves, M. M., Maroco, J. P. & Pereira, J. S. 2003, Understanding plant responses to drought from genes to the whole plant. *Functional Plant Biology*, 30, 239-264.
- Chawafambira, A., Sedibe, M. M., Mpofu, A. & Achilonu, M. 2020, *Uapaca kirkiana*, an indigenous fruit tree in sub-Saharan Africa: A comprehensive review. *Cogent Food & Agriculture*, 6, 1766735.
- Chidumayo, E. N. 1997, *Miombo ecology and management: an introduction*.
- Chidumayo, E. N. & Gumbo, D. J. 2010, *The dry forests and woodlands of Africa*. London: Earthscan.
- Chirwa, P., Syampungani, S. & Geldenhuys, C. 2008, The ecology and management of the Miombo woodlands for sustainable livelihoods in southern Africa: the case for non-timber forest products. *Southern Forests: A Journal of Forest Science*, 70, 237-245.
- Chivenge, P., Mabhaudhi, T., Modi, A. T. & Mafongoya, P. 2015, The potential role of neglected and underutilised crop species as future crops under water scarce conditions in Sub-Saharan Africa. *International Journal of Environmental Research and Public Health*, 12, 5685-5711.

- Cisneros, C. M. G., Heringer, G., Domen, Y. S. M., Sanchez, L. R. & Meira-Neto, J. A. A. 2021, The environmental filtering and the conservation of tropical dry forests in mountains in a global change scenario. *Biodiversity and Conservation*, 30, 2689-2705.
- Comita, L. S. & Engelbrecht, B. M. 2009, Seasonal and spatial variation in water availability drive habitat associations in a tropical forest. *Ecology*, 90, 2755-2765.
- Dagnelie, P. 1998, *Statistique théorique et appliquée* vol. 2. De Boeck et Larcier: Paris.
- Dehling, D. M., Fritz, S. A., Töpfer, T., Päckert, M., Estler, P., Böhning-Gaese, K. & Schleuning, M. 2014, Functional and phylogenetic diversity and assemblage structure of frugivorous birds along an elevational gradient in the tropical Andes. *Ecography*, 37, 1047-1055.
- Delavenne, J., Metcalfe, K., Smith, R. J., Vaz, S., Martin, C. S., Dupuis, L., Coppin, F. & Carpentier, A. 2012, Systematic conservation planning in the eastern English Channel: comparing the Marxan and Zonation decision-support tools. *ICES Journal of Marine Science*, 69, 75-83.
- Delgado, T. S., Mccall, M. K. & López-Binnqüist, C. 2023, Non-timber forest products: small matters, big significance, and the complexity of reaching a workable definition for sustainability. *Small-scale Forestry*, 22, 37-68.
- Delignette-Muller, M. L. & Dutang, C. 2015, fitdistrplus: An R package for fitting distributions. *Journal of Statistical Software*, 64, 1-34.
- Demie, D. T., Seidel, S. J., Wallach, D., Döring, T. F., Ewert, F., Gaiser, T., Paul, M. & Hernández-Ochoa, I. M. 2025, Resource acquisition and interactions in spring wheat/faba bean intercropping under diverse environments. *Field Crops Research*, 325, 109817.
- Demissie, T. & Gebrechorkos, S. H. 2024, Spatio-temporal trends in precipitation, temperature, and extremes: A study of Malawi and Zambia (1981–2021). *Sustainability*, 16, 3885.

- Deressa, T. T., Hassan, R. M., & Ringler, C. 2011, Perception of and adaptation to climate change by farmers in the Nile basin of Ethiopia. *The Journal of Agricultural Science*, 149(1), 23-31.
- Devereux, S. 2009, Seasonality and social protection in Africa. *Future Agricultures & Centre for Social Protection*, 28, 22.
- Deweese, P. A., Campbell, B. M., Katerere, Y., Siteo, A., Cunningham, A. B., Angelsen, A. & Wunder, S. 2010, Managing the miombo woodlands of southern Africa: policies, incentives and options for the rural poor. *Journal of Natural Resources Policy Research*, 2, 57-73.
- Di Minin, E., Brooks, T. M., Toivonen, T., Butchart, S. H., Heikinheimo, V., Watson, J. E., Burgess, N. D., Challender, D. W., Goettsch, B. & Jenkins, R. 2019, Identifying global centers of unsustainable commercial harvesting of species. *Science Advances*, 5, eaau2879.
- Díaz, S., Kattge, J., Cornelissen, J. H., Wright, I. J., Lavorel, S., Dray, S., Reu, B., Kleyer, M., Wirth, C. & Colin Prentice, I. 2016, The global spectrum of plant form and function. *Nature*, 529, 167-171.
- Ding, Y., Zang, R., Lu, X., Huang, J. & Xu, Y. 2019, The effect of environmental filtering on variation in functional diversity along a tropical elevational gradient. *Journal of Vegetation Science*, 30, 973-983.
- Dinh, D.-T., Fujinami, T. & Huynh, V.-N. 2019, Estimating the optimal number of clusters in categorical data clustering by silhouette coefficient. In: *Knowledge and Systems Sciences: 20th International Symposium, KSS 2019, Da Nang, Vietnam, November 29-December 1, 2019, Proceedings 20*. Springer, 1-17.
- Dixon, P. 2003, VEGAN, a package of R functions for community ecology. *Journal of Vegetation Science*, 14, 927-930.

- Djossa, B. A., Fahr, J., Wiegand, T., Ayihouénou, B., Kalko, E. & Sinsin, B. A. 2008, Land use impact on *Vitellaria paradoxa* C. F. Gaerten. stand structure and distribution patterns: a comparison of Biosphere Reserve of Pendjari in Atacora district in Benin. *Agroforestry Systems*, 72, 205-220.
- Doležal, J., Dančák, M., Kučera, J., Majeský, L., Altman, J., Řeháková, K., Čapková, K., Vondrák, J., Fibich, P. & Liancourt, P. 2022, Fire, climate and biotic interactions shape diversity patterns along an Afrotropical elevation gradient. *Journal of Biogeography*, 49, 1248-1259.
- Domínguez-Amaya, N., Brambach, F., Corral-Rivas, J. J. & Ehbrecht, M. 2025, Tree diversity patterns along an elevational gradient in Durango, Mexico. *Frontiers in Ecology and Evolution*, 13, 1562841.
- Dossou, J., Houetchegnon, T., Ouinsavi, C. A. & Suinyuy, T. N. 2025, Effects of leaf harvesting intensity on fruiting processes in three fodder tree species in the West African savannah. *Forest Ecology and Management*, 583, 122589.
- Elith, J. & Graham, C. H. 2009, Do they? How do they? Why do they differ? On finding reasons for differing performances of species distribution models. *Ecography*, 32, 66-77.
- Elith, J., Phillips, S. J., Hastie, T., Dudík, M., Chee, Y. E. & Yates, C. J. 2011, A statistical explanation of MaxEnt for ecologists. *Diversity and Distributions*, 17, 43-57.
- Faith, D. P. 1992, Conservation evaluation and phylogenetic diversity. *Biological Conservation*, 61, 1-10.
- Fandohan, A. B., Assogbadjo, A. E., Kakaï, R. L. G., Sinsin, B. & Van Damme, P. 2010, Impact of habitat type on the conservation status of tamarind (*Tamarindus indica* L.) populations in the W National Park of Benin. *Fruits*, 65, 11-19.
- FAO & ISRIC. 2012, JRC: Harmonized world soil database (version 1.2). FAO, Rome, Italy and IIASA, Laxenburg, Austria.

- Ferro, C. A. & Stephenson, D. B. 2011, Extremal dependence indices: Improved verification measures for deterministic forecasts of rare binary events. *Weather and Forecasting*, 26, 699-713.
- Fick, S. E. & Hijmans, R. J. 2017, WorldClim 2: New 1-km spatial resolution climate surfaces for global land areas. *International Journal of Climatology*, 37, 4302-4315.
- Fischer, J., Hartel, T. & Kuemmerle, T. 2012, Conservation policy in traditional farming landscapes. *Conservation Letters*, 5, 167-175.
- Folega, A. A., Folega, F., Woegan, Y., Wala, K. & Akpagana, K. 2021, Dynamique des émissions de gaz à effet de serre liées au secteur foresterie et autres affectations des terres (FAT) dans le paysage du socle éburnéen au Togo. *Rev Écosystèmes et Paysages*, 1, 58-72.
- Fred, F., Mwabumba, L., Mhango, J., Missanjo, E., Kadzuwa, H. & Likoswe, M. 2023, Genetic and phenotypic parameters for growth traits of *Widdringtonia whytei*-Rendle translocation provenance trials in Malawi. *J. Glob. Ecol. Environ.*, 17, 32-48.
- Friendly, M., Fox, J. & Friendly, M. M. 2017, Package ‘candisc’. R package.
- Fyllas, N. M., Patiño, S., Baker, T. R., Bielefeld Nardoto, G., Martinelli, L. A., Quesada, C. A., Paiva, R., Schwarz, M., Horna, V. & Mercado, L. 2009, Basin-wide variations in foliar properties of Amazonian forest: phylogeny, soils and climate. *Biogeosciences*, 6, 2677-2708.
- Gadow, K. V., Zhang, C. Y., Wehenkel, C., Pommerening, A., Corral-Rivas, J., Korol, M., Myklush, S., Hui, G. Y., Kiviste, A. & Zhao, X. H. 2012, Forest structure and diversity. *Continuous Cover Forestry*, 29-83.
- Galluzzi, G., Eyzaguirre, P. & Negri, V. 2010, Home gardens: neglected hotspots of agrobiodiversity and cultural diversity. *Biodiversity and Conservation*, 19, 3635-3654.

- Garba, A., Amani, A., Abdou, L. & Mahamane, A. 2019, Perceptions et usages socioéconomiques du tamarinier (*Tamarindus indica* L.) dans le Sud-Ouest du Niger: implications pour une domestication et une conservation durable. *Journal of Animal & Plant Sciences*, 40, 6584-6602.
- Garnier, E., Shipley, B., Roumet, C. & Laurent, G. 2001, A standardized protocol for the determination of specific leaf area and leaf dry matter content. *Functional Ecology*, 688-695.
- Geldenhuys, C. 2005, Basic guidelines for silviculture and forest management practices in Mozambique. Report Number FW-04/05, Forestwood cc, Pretoria.
- Gentry, A. H. 1988. Changes in plant community diversity and floristic composition on environmental and geographical gradients. *Annals of the Missouri Botanical Garden*, 1-34.
- Ghalambor, C. K., McKay, J. K., Carroll, S. P. & Reznick, D. N. 2007, Adaptive versus non-adaptive phenotypic plasticity and the potential for contemporary adaptation in new environments. *Functional Ecology*, 21, 394-407.
- Gilbert, J. 2018. *Natural resources and human rights: an appraisal*. Oxford University Press.
- Glèlè, K. R. A., Assogbadjo, A. E., Gaoué, O. G., Chakeredza, S. G., Mbaï, C. P., Agbangla, G. & Sinsin, B. 2011, Ecological adaptation of the shea butter tree (*Vitellaria paradoxa* C.F. Gaertn.) along climatic gradient in Bénin, West Africa. *African Journal of Ecology*, 49, 440-449.
- Gomez-Beloz, A. 2002, Plant use knowledge of the Winikina Warao: the case for questionnaires in ethnobotany. *Economic Botany*, 56, 231-241.
- Gondwe, M. F. K., Geldenhuys, C. J., Chirwa, P. W. C., Assédé, E. S. P., Syampungani, S. & Cho, M. A. 2021, Tree species composition and diversity in miombo woodlands between co-managed and government-managed regimes, Malawi. *African Journal of Ecology*, 59, 225-240.

- González-Caro, S., Umaña, M. N., Álvarez, E., Stevenson, P. R. & Swenson, N. G. 2014, Phylogenetic alpha and beta diversity in tropical tree assemblages along regional-scale environmental gradients in northwest South America. *Journal of Plant Ecology*, 7, 145-153.
- Gonzalez, C., Macip-Rios, R. & Suazo-Ortuno, I. 2022, Phylogenetic structure and diversity among herpetofaunal communities along a successional gradient of a tropical dry forest in Mexico. *Perspectives in Ecology and Conservation*, 20, 249-255.
- Gouwakinnou, G. N., Biaou, S., Vodouhe, F. G., Tovihessi, M. S., Awessou, B. K. & Biaou, H. S. 2019, Local perceptions and factors determining ecosystem services identification around two forest reserves in northern Benin. *Journal of Ethnobiology and Ethnomedicine*, 15, 1-12.
- Gouwakinnou, N. G. 2013, Using niche modeling to plan conservation of an indigenous tree species under changing climate: example of *Sclerocarya birrea* in Benin, West Africa. *Research and Development in Sub-Saharan Africa*, 5, 1-8.
- Gu, L., O'Hara, K. L., Li, W. Z. & Gong, Z. W. 2019, Spatial patterns and interspecific associations among trees at different stand development stages in the natural secondary forests on the Loess Plateau, China. *Ecology and Evolution*, 9, 6410-6421.
- Guisan, A., Thuiller, W. & Zimmermann, N. E. 2017. *Habitat suitability and distribution models: with applications in R*. Cambridge University Press.
- Haghtalab, N., Moore, N. & Ngongondo, C. 2019, Spatio-temporal analysis of rainfall variability and seasonality in Malawi. *Regional Environmental Change*, 19, 2041-2054.
- Hardcastle, P. 1977, A preliminary silvicultural classification of Malawi. Inst. Malawi, Zomba, Malawi.

- Harris, J. B. C., Dwi Putra, D., Gregory, S. D., Brook, B. W., Prawiradilaga, D. M., Sodhi, N. S., Wei, D. & Fordham, D. A. 2014, Rapid deforestation threatens mid-elevational endemic birds but climate change is most important at higher elevations. *Diversity and Distributions*, 20, 773-785.
- Hartel, T., Fischer, J., Câmpeanu, C., Milcu, A. I., Hanspach, J. & Fazey, I. 2014, The importance of ecosystem services for rural inhabitants in a changing cultural landscape in Romania. *Ecology and Society*, 19.
- Honeck, E., Sanguet, A., Schlaepfer, M. A., Wyler, N. & Lehmann, A. 2020, Methods for identifying green infrastructure. *SN Applied Sciences*, 2, 1-25.
- Hothorn, T., Bretz, F. & Westfall, F. 2008, Simultaneous inference in general parametric models. *Biometrical Journal: Journal of Mathematical Methods in Biosciences*, 50, 346-363.
- Houehanou, T. D., Assogbadjo, A. E., Kakai, R. G., Houinato, M. & Sinsin, B. 2011, Valuation of local preferred uses and traditional ecological knowledge in relation to three multipurpose tree species in Benin (West Africa). *Forest Policy and Economics*, 13, 554-562.
- Houehanou, T. D., Prinz, K., Hellwig, F., Assogbadjo, A. E., Gebauer, J., Glèlè Kakai, R. L. & Sinsin, B. 2019, Morphological trait variation and relationships of *Afzelia africana* Sm. caused by climatic conditions and anthropogenic disturbance in Benin (West Africa). *Genetic Resources and Crop Evolution*, 66, 1091-1105.
- Houèchégnon, T., Gbèmavo, D. S. J. C., Ouinsavi, C. A. I. N. & Sokpon, N. 2015, Structural characterization of *Prosopis africana* populations (Guill., Perrott., and Rich.) Taub in Benin. *International Journal of Forestry Research*, 2015, 101373.
- Hu, Y., Ding, Z., Hu, H., Gibson, L., Liang, D., Zhou, Z., Liang, J. & Scheffers, B.R. 2024, Functional and phylogenetic structure of mammals along elevational gradients in the Central and East Himalayas. *Ecological Processes*, 13, 65.

Huggett, R.J. 2004. *Fundamentals of biogeography*. London: Routledge.

Husen, A., Bachheti, R.K. & Bachheti, A. 2021, *Non-timber forest products: Food, healthcare and industrial applications*. Springer Nature.

Idrissa, B., Idrissa, S., Issiaka, Y., Karimou, A.J., Mahamane, A., Mahamane, S. & Weber, J.C. 2018, Trend and structure of populations of *Balanites aegyptiaca* in parkland agroforests in western Niger.

Idrissa, I., Morou, B., Abdourhamane, H., Karim, S., Abdourhamane, T., Djibo, I. & Mahamane, A. 2020, Diversité floristique et structure démographique des peuplements ligneux des parcours naturels sahéliens du Sud-Est du Niger: Cas de l'enclave pastorale «Dadaria» (Mainé-Soroa, Diffa). *International Journal of Biological and Chemical Sciences*, 14, 06.

Issifou, I., Kpérkouma, W., Dourma, M., Atakpama, W., Kanda, M. & Akpagana, K. 2018, Valeur ethnobotanique de l'espèce *Khaya senegalensis* (Desr.) A. Juss (Meliaceae) auprès des populations riveraines de la chaîne de l'Atacora au Togo. *Revue Marocaine des Sciences Agronomiques et Vétérinaires*, 6, 64-72.

Jin, L.S., Cadotte, M.W. & Fortin, M.J. 2015, Phylogenetic turnover patterns consistent with niche conservatism in montane plant species. *Journal of Ecology*, 103, 742-749.

Jin, Y. & Qian, H. 2022, V. PhyloMaker2: An updated and enlarged R package that can generate very large phylogenies for vascular plants. *Plant Diversity*, 44, 335-339.

Jinga, P., Palagi, J., Chong, J.P. & Bobo, E.D. 2020, Climate change reduces the natural range of African wild loquat (*Uapaca kirkiana* Müll. Arg., Phyllanthaceae) in south-central Africa. *Regional Environmental Change*, 20, 108.

Jump, A.S. & Peñuelas, J. 2005, Running to stand still: adaptation and the response of plants to rapid climate change. *Ecology Letters*, 8, 1010-1020.

- Jurisch, K., Hahn, K., Wittig, R. & Bernhardt-Römermann, M. 2013, Land-use impact on the growth and survival of seedlings and saplings in West African savannas. *Journal of Vegetation Science*, 24, 101-112.
- Kachamba, D. J., Eid, T., & Gobakken, T. 2016, Above- and Belowground Biomass Models for Trees in the Miombo Woodlands of Malawi. *Forests*, 7(2), 38. <https://doi.org/10.3390/f7020038>
- Kaky, E., Nolan, V., Alatawi, A. & Gilbert, F. 2020, A comparison between Ensemble and MaxEnt species distribution modelling approaches for conservation: A case study with Egyptian medicinal plants. *Ecological Informatics*, 60, 101150.
- Kalaba, F.K. 2013, *Forest ecosystem services, rural livelihoods and carbon storage in Miombo woodland in the Copperbelt region of Zambia*. University of Leeds.
- Kalinganire, A., Weber, J., Uwamariya, A. & Koné, B. 2008, Improving rural livelihoods through domestication of indigenous fruit trees in the parklands of the Sahel. In: *Indigenous fruit trees in the tropics: domestication, utilization and commercialization*. CABI, Wallingford, UK.
- Kamoto, J., Clarkson, G., Dorward, P., & Shepherd, D. 2013, Doing more harm than good? Community based natural resource management and the neglect of local institutions in policy development. *Land use policy*, 35, 293-301.
- Kaonga, C.C., Kosamu, I.B.M. & Tenthani, C. 2015, Climate variation based on temperature and solar radiation data over a 29 year period in Lilongwe City, Malawi. *African Journal of Environmental Science and Technology*, 9, 346-353.
- Kebebew, Z. & Ozanne, C. 2022, Woody plant conservation value of three contrasting forest management regimes in southwest Ethiopia. *Forests*, 13, 1438.

Kébenzikato, A.B., Wala, K., Atakpama, W., Dimobé, K., Dourma, M., Woégan, A.Y., Batawila, K. & Akpagana, K. 2015, Connaissances ethnobotaniques du baobab (*Adansonia digitata* L.) au Togo. *Base*.

Kembel, S.W., Cowan, P.D., Helmus, M.R., Cornwell, W.K., Morlon, H., Ackerly, D.D., Blomberg, S.P. & Webb, C.O. 2010, Picante: R tools for integrating phylogenies and ecology. *Bioinformatics*, 26, 1463-1464.

Khan, S. & Verma, S. 2022, Ensemble modeling to predict the impact of future climate change on the global distribution of *Olea europaea* subsp. *cuspidata*. *Frontiers in Forests and Global Change*, 5, 977691.

Kindt, R. 2018, BiodiversityR: Package for Community Ecology and Suitability Analysis. Version 2.9-2.

Kitikidou, K., Milios, E., Stampoulidis, A., Pipinis, E. & Radoglou, K. 2024. Using biodiversity indices effectively: considerations for forest management. *Ecologies*, 5, 42-51.

Kokou, B.K., Atakpama, W., Msiska, U., Ahouandjinou, S.D.I.T.K., Biaou, S., Nababi, J., Alunga, G.L., Agnandji, P., Kimwanga, P.S. & Tételi, C.S. 2025a, Sustainable management insights from the population ecology and carbon storage of *Uapaca kirkiana* Müll. Arg. across geographic regions in Malawi (Southern Africa). *Trees, Forests and People*, 100959.

Kokou, B.K., Ulemu, M., Atakpama, W., Biaou, S., Teteli, S.C., Raoul, S.K., Mnthambala, F., Mavuto, T., MunyenyeMbe, P. & Noulèkoun, F. 2025b, Climate change reduces and shifts suitable habitats of *Uapaca kirkiana* Müll. Arg. to higher altitudes in Malawi. *Trees, Forests and People*, 100884.

Kokou, K., Atakpama, W., Kombate, B., Egbelou, H. & Koffi, N. 2023a, Dynamique et modélisation du stock de carbone de la Forêt Classée d'Amou-Mono au Togo. *Revue Écosystèmes et Paysages*, 3, 1-16.

Kokou, K., Atakpama, W., Kombate, B., Egbelou, H., Koffi, N., Elangilangi, M. & Batawila, K. 2023b, Dynamique et modélisation du stock de carbone de la Forêt Classée d'Amou-Mono au Togo. *Revue Écosystèmes et Paysages*, 3, 1-16.

Kokou, K.B., Atakpama, W., Kombate, B., Egbelou, H., Koffi N'déré, A., Elangilangi, M.J., Ganyo, K.K., Sambieni, K.R., Bogaert, J. & Batawila, K. 2023c, Dynamique et modélisation du stock de carbone de la Forêt Classée d'Amou-Mono au Togo. *Revue Écosystèmes et Paysages*, 3, 15.

Kokou, K.B., Msiska, U., Atakpama, W., Salumu, K., Prosper, Balde, I., Nababi, J., Tembo, M. & MunyenyeMbe, P. 2024a, State of knowledge and perspectives on wild loquat: *Uapaca kirkiana* Müll. Arg. (Euphorbiaceae) in Malawi (Southern Africa). *Revue Écosystèmes et Paysages (Ecosystems and Landscapes Review)*, 4, 18.

Kokou, K.B., Salumu, P., Kimwanga, Balde, I., Nababi, J., Lufungula, G., Alunga, Teteli, C., Wanjala, F., Paul, Ulemu, M., Mavuto, T., MunyenyeMbe, P. & Rudant, J. 2024b, Modelling the current and future spatial distribution area of *Adansonia digitata* L. in the context of climate change in Malawi (Southern Africa). *Journal of Agricultural Science*, 16, 17.

Komsta, L. & Novomestky, F. 2015, Moments, cumulants, skewness, kurtosis and related tests. R package version, 14.

Körner, C. 2007, The use of 'altitude' in ecological research. *Trends in Ecology & Evolution*, 22, 569-574.

- Koura, K., Ganglo, J.C., Assogbadjo, A.E. & Agbangla, C. 2011, Ethnic differences in use values and use patterns of *Parkia biglobosa* in Northern Benin.
- Kraft, N.J., Godoy, O. & Levine, J.M. 2015, Plant functional traits and the multidimensional nature of species coexistence. *Proceedings of the National Academy of Sciences*, 112, 797-802.
- Kuhnlein, H.V. 2015, Food system sustainability for health and well-being of Indigenous Peoples. *Public Health Nutrition*, 18, 2415-2424.
- Kujala, H., Moilanen, A., Araujo, M.B. & Cabeza, M. 2013, Conservation planning with uncertain climate change projections. *PloS One*, 8, e53315.
- Kujala, H., Moilanen, A. & Gordon, A. 2018, Spatial characteristics of species distributions as drivers in conservation prioritization. *Methods in Ecology and Evolution*, 9, 1121-1132.
- Laurance, W. F., Clements, G. R., Sloan, S., O'Connell, C. S., Mueller, N. D., Goosem, M., Venter, O., Edwards, D. P., Phalan, B. & Balmford, A. 2014, A global strategy for road building. *Nature*, 513, 229-232.
- Lawin, I. F., Fandohan, A. B., Salako, K. V., Assogbadjo, A. E. & Ouinsavi, C. A. I. N. 2021, Morphological variability of fruits of *Cola millenii* K. Schum. from seven phytogeographical districts in Benin: opportunity for domestication. *Genetic Resources and Crop Evolution*, 68, 1225-1242.
- Lawley, V., Parrott, L., Lewis, M., Sinclair, R. & Ostendorf, B. 2013, Self-organization and complex dynamics of regenerating vegetation in an arid ecosystem: 82 years of recovery after grazing. *Journal of Arid Environments*, 88, 156-164.
- Leakey, R. R., Tchoundjeu, Z., Schreckenberg, K., Shackleton, S. E. & Shackleton, C. M. 2005, Agroforestry tree products (AFTPs): targeting poverty reduction and enhanced livelihoods. *International Journal of Agricultural Sustainability*, 3, 1-23.

- Lehtomäki, J. & Moilanen, A. 2013. Methods and workflow for spatial conservation prioritization using Zonation. *Environmental Modelling & Software*, 47, 128-137.
- Lenoir, J., Gégout, J.-C., Marquet, P. A., de Ruffray, P. & Brisse, H. 2008, A significant upward shift in plant species optimum elevation during the 20th century. *Science*, 320, 1768-1771.
- Li, T., Xu, L., Wang, F., Zhang, W., Duan, J., Shen-Tu, X., Song, Y., Zang, R. & Dong, M. 2022, Novel evidence from *Taxus fuana* forests for niche-neutral process assembling community. *Forest Ecosystems*, 9, 100035.
- Li, X. H., Zhu, X. X., Niu, Y. & Sun, H. 2014, Phylogenetic clustering and overdispersion for alpine plants along elevational gradient in the Hengduan Mountains region, southwest China. *Journal of Systematics and Evolution*, 52, 280-288.
- Li, Y., Li, M., Ming, A., Wang, H., Yu, S. & Ye, S. 2021, Spatial pattern dynamics among co-dominant populations in early secondary forests in Southwest China. *Journal of Forestry Research*, 32, 1373-1384.
- Linhart, Y. B. & Grant, M. C. 1996, Evolutionary significance of local genetic differentiation in plants. *Annual Review of Ecology and Systematics*, 27, 237-277.
- Liu, C., Wolter, C., Xian, W. & Jeschke, J. M. 2020, Species distribution models have limited spatial transferability for invasive species. *Ecology Letters*, 23, 1682-1692.
- Liu, H., Liu, H., Chen, Y., Xu, Z., Dai, Y., Chen, Q. & Ma, Y. 2021, Identifying the patterns of changes in α - and β -diversity across *Dacrydium pectinatum* communities in Hainan Island, China. *Ecology and Evolution*, 11, 4616-4630.
- Liu, Y. & El-Kassaby, Y. A. 2019, Phenotypic plasticity of natural *Populus trichocarpa* populations in response to temporal environmental change in a common garden. *BMC Evolutionary Biology*, 19, 1-15.

- Lokonon, B. E., Sodoté, F. E., Simbo, D. & Kakaï, R. G. 2021, Use of local knowledge for contributing to the conservation of *Caesalpinia bonduc* (L.) Roxb in southern Benin (West Africa). *Global Ecology and Conservation*, 27, e01551.
- Losos, J. B. 2011, Convergence, adaptation, and constraint. *Evolution*, 65, 1827-1840.
- Loughran, T. F., Boysen, L., Bastos, A., Hartung, K., Havermann, F., Li, H., Nabel, J. E. M. S., Obermeier, W. A. & Pongratz, J. 2021, Past and future climate variability uncertainties in the global carbon budget using the MPI Grand Ensemble. *Global Biogeochemical Cycles*, 35, e2021GB007019.
- Luo, Y., Zhou, M., Jin, S., Wang, Q. & Yan, D. 2023, Changes in phylogenetic structure and species composition of woody plant communities across an elevational gradient in the southern Taihang Mountains, China. *Global Ecology and Conservation*, 42, e02412.
- Luoga, E. J., Witkowski, E. & Balkwill, K. 2004, Regeneration by coppicing (resprouting) of miombo (African savanna) trees in relation to land use. *Forest Ecology and Management*, 189, 23–35.
- Lyaruu, H. V., Eliapenda, S. & Backéus, I. 2000, Floristic, structural and seed bank diversity of a dry Afromontane forest at Mafai, central Tanzania. *Biodiversity & Conservation*, 9, 241-263.
- Lykke, A. M. 1998, Assessment of species composition change in savanna vegetation by means of woody plants' size class distributions and local information. *Biodiversity & Conservation*, 7, 1261-1275.
- Lykke, A. M., Rømer, N., Gonzalez, P., Kakaï, R. G., Rabiou, H., Amegnaglo, K. B., Ganaba, S., Sambou, B., Niang, F. & Herault, B. 2025, Tree populations show low regeneration of valued species in West Africa. *Biological Conservation*, 301, 110891.

- Machac, A., Janda, M., Dunn, R. R. & Sanders, N. J. 2011, Elevational gradients in phylogenetic structure of ant communities reveal the interplay of biotic and abiotic constraints on diversity. *Ecography*, 34, 364-371.
- Magurran, A. E. 2021, Measuring biological diversity. *Current Biology*, 31, R1174-R1177.
- Margules, C. R. & Pressey, R. L. 2000, Systematic conservation planning. *Nature*, 405, 243-253.
- Martín-López, B., Iniesta-Arandia, I., García-Llorente, M., Palomo, I., Casado-Arzuaga, I., Amo, D. G. D., Gómez-Baggethun, E., Oteros-Rozas, E., Palacios-Agundez, I. & Willaarts, B. 2012, Uncovering ecosystem service bundles through social preferences. *PLoS One*, 7, e38970.
- Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L. & Gomis, M. 2021, Climate change 2021: the physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change, 2, 2391.
- Mauritsen, T., Bader, J., Becker, T., Behrens, J., Bittner, M., Brokopf, R., Brovkin, V., Claussen, M., Crueger, T. & Esch, M. 2019, Developments in the MPI-M Earth System Model version 1.2 (MPI-ESM1.2) and its response to increasing CO₂. *Journal of Advances in Modeling Earth Systems*, 11, 998-1038.
- Mbow, C., van Noordwijk, M., Luedeling, E., Neufeldt, H., Minang, P. A. & Kowero, G. 2014, Agroforestry solutions to address food security and climate change challenges in Africa. *Current Opinion in Environmental Sustainability*, 6, 61-67.
- McGill, B. J., Enquist, B. J., Weiher, E. & Westoby, M. 2006, Rebuilding community ecology from functional traits. *Trends in Ecology & Evolution*, 21, 178-185.
- Mcsweeney, C., New, M., Lizcano, G., & Lu, X. 2010, The UNDP Climate Change Country Profiles: Improving the accessibility of observed and projected climate information for studies of

climate change in developing countries. *Bulletin of the American Meteorological society*, 91(2), 157-166.

MEA 2005, Ecosystems and human well-being: current state and trends. Findings of the Condition and Trends Working Group, Washington DC.

Mekonnen, A. B., Mohammed, A. S. & Demissew, A. 2023, Species diversity, structure, and regeneration status of woody plants in Saleda Yohans Church Forest, South Wollo, Ethiopia. *Scientifica*, 2023, 3853463.

Meng, W., Zhang, H., Sun, L., Xu, J., Qiao, Y. & Li, H. 2025, Phylogenetic structure shifts across life-history stages in response to microtopography and competition in subtropical forests. *Plants*, 14, 2098.

Mensah, S., Houehanou, T. D., Sogbohossou, E. A., Assogbadjo, A. E. & Kakai, R. G. 2014, Effect of human disturbance and climatic variability on the population structure of *Afzelia africana* Sm. ex Pers. (Fabaceae–Caesalpinioideae) at country broad-scale (Bénin, West Africa). *South African Journal of Botany*, 95, 165-173.

Mensah, S., Veldtman, R., Assogbadjo, A. E., Ham, C., Kakai, R. G. & Seifert, T. 2017, Ecosystem service importance and use vary with socio-environmental factors: a study from household-surveys in local communities of South Africa. *Ecosystem Services*, 23, 1-8.

Metz, M. R., Wright, S. J., Zimmerman, J. K., Hernández, A., Smith, S. M., Swenson, N. G., Umaña, M. N., Valencia, L. R., Waring-Enriquez, I. & Wordell, M. 2023, Functional traits of young seedlings predict trade-offs in seedling performance in three neotropical forests. *Journal of Ecology*, 111, 2568-2582.

- Moilanen, A., Lehtinen, P., Kohonen, I., Jalkanen, J., Virtanen, E. A. & Kujala, H. 2022, Novel methods for spatial prioritization with applications in conservation, land use planning and ecological impact avoidance. *Methods in Ecology and Evolution*, 13, 1062-1072.
- Moles, A. T. & Westoby, M. 2006. Seed size and plant strategy across the whole life cycle. *Oikos*, 113, 91-105.
- Moombe, K. B., Ham, C., Clarke, J., Franzel, S. & Ackerman, P. 2014, Consumer preferences for *Uapaca kirkiana* fruits in Zambia. *Forests, Trees and Livelihoods*, 23, 248-260.
- Mooney, H., Larigauderie, A., Cesario, M., Elmquist, T., Hoegh-Guldberg, O., Lavorel, S., Mace, G. M., Palmer, M., Scholes, R. & Yahara, T. 2009, Biodiversity, climate change, and ecosystem services. *Current Opinion in Environmental Sustainability*, 1, 46-54.
- Moritz, C. & Agudo, R. 2013, The future of species under climate change: resilience or decline? *Science*, 341, 504-508.
- Moukrim, S., Lahssini, S., Rifai, N., Menzou, K., Mharzi-Alaoui, H., Labbaci, A., Rhazi, M., Wahby, I. W., El Madihi, M. & Rhazi, L. 2020, Modélisation de la distribution potentielle de *Cedrus atlantica* Manetti au Maroc et impacts du changement climatique. *Bois & Forêts des Tropiques*, 344, 3-16.
- Moura, I., Maquia, I., Rija, A. A., Ribeiro, N. & Ribeiro-Barros, A. I. 2017. Biodiversity studies in key species from the African mopane and miombo woodlands. *Genetic Diversity*. IntechOpen.
- Mulenga, B. P., Richardson, R. B., Mapemba, L. D. & Tembo, G. 2011, The contribution of non-timber forest products to rural household income in Zambia.
- Müller, W. A., Jungclaus, J. H., Mauritsen, T., Baehr, J., Bittner, M., Budich, R., Bunzel, F., Esch, M., Ghosh, R. & Haak, H. 2018, A higher-resolution version of the Max Planck Institute Earth

System Model (MPI-ESM1.2-HR). *Journal of Advances in Modeling Earth Systems*, 10, 1383-1413.

Muluneh, M. G. 2021, Impact of climate change on biodiversity and food security: a global perspective a review article. *Agriculture & Food Security*, 10, 1-25.

Mustapha, Y., Adamu, S. & Inuwa, A. 2022, Importance Value Index (IVI) of tree species and diversity of Baturiya Hadejia Wetland National Park, Jigawa State, Nigeria. *Int. J. Trend Sci. Res. Dev.*, 6, 876-883.

Muyanja, C., Narvhus, J. A., Treimo, J. & Langsrud, T. 2003. Isolation, characterisation and identification of lactic acid bacteria from Bushera: a Ugandan traditional fermented beverage. *International Journal of Food Microbiology*, 80, 201-210.

Mwase, W. F., Akinnifesi, F., Stedjec, B., Kwapata, M. & Bjørnstadd, Å. 2010, Genetic diversity within and among southern African provenances of *Uapaca kirkiana* Müell. Arg using morphological and AFLP markers. *Tanzania Journal of Forestry and Nature Conservation*, 80, 19-35.

Nduche, M., Brehm, J. M., Abberton, M., Omosun, G., & Maxted, N. 2021, West African crop wild relative checklist, prioritization and inventory. In Genetic resources (Vol. 2, No. 4, pp. 55-65).

Ngulube, M. R. 1996. Ecology and management of *Uapaca kirkiana* in southern Africa. University of Wales, Bangor.

Ngulube, M. R. 2000, Population structures of *Uapaca kirkiana* (Euphorbiaceae) in the miombo woodlands of Malawi: status and management prospects for fruit production. *Journal of Tropical Forest Science*, 459-471.

Ngulube, M. R., Hall, J. B. & Maghembe, J. 1998, Reproductive ecology of *Uapaca kirkiana* (Euphorbiaceae) in Malawi, southern Africa. *Journal of Tropical Ecology*, 14, 743-760.

Ngulube, P. 2002, Managing and preserving indigenous knowledge in the knowledge management era: challenges and opportunities for information professionals. *Information Development*, 18, 95-102.

Nicotra, A. B., Atkin, O. K., Bonser, S. P., Davidson, A. M., Finnegan, E. J., Mathesius, U., Poot, P., Purugganan, M. D., Richards, C. L. & Valladares, F. 2010, Plant phenotypic plasticity in a changing climate. *Trends in Plant Science*, 15, 684-692.

Nkomwa, E. C., Joshua, M. K., Ngongondo, C., Monjerezi, M., & Chipungu, F. 2014, Assessing indigenous knowledge systems and climate change adaptation strategies in agriculture: A case study of Chagaka Village, Chikhwawa, Southern Malawi. *Physics and Chemistry of the Earth, Parts a/b/c*, 67, 164-172.

Noulèkoun, F., Chude, S., Zenebe, A. & Birhane, E. 2017, Climate change impacts on *Faidherbia albida* (Delile) A. Chev. distribution in dry lands of Ethiopia. *African Journal of Ecology*, 55, 233–243.

Nouvellet, Y., Kassambara, A. & Besse, F. 2006, The shea park in Mali: inventory, volume, crown size, and fruit production. *Bois et Forêts des Tropiques*, 287, 5–20.

Ntupanyama, Y. M., Mwase, W. F., Stedje, B., Kwapata, M. B., Bokosi, J. & Hvoslef-Eide, A. K. 2008, Indigenous knowledge of rural communities in Malawi on socio-economic use, propagation, biology, biodiversity and ecology of *Uapaca kirkiana* Muell. Arg. *African Journal of Biotechnology*, 7.

O'Donnel, M. S. & Ignizio, D. A. 2012, Bioclimatic predictors for supporting ecological applications in the conterminous United States. US Geological Survey.

- Ocholla, J. A., Inoti, S. K. & Obwoyere, G. O. 2023, Comparative assessment of regeneration, structure and species diversity of woody vegetation in disturbed and undisturbed sites of a secondary montane forest, Kenya. *Asian J. Res. Agric. Forestry*, 9, 38-48.
- Okiror, P., Chono, J., Nyamukuru, A., Lwanga, J. S., Sasira, P. & Diogo, P. 2012, Variation in woody species abundance and distribution in and around Kibale National Park, Uganda. *International Scholarly Research Notices*, 2012, 490461.
- Oksanen, J., Simpson, G. L., Blanchet, F. G., Kindt, R., Legendre, P., Minchin, P. R., O'Hara, R., Solymos, P., Stevens, M. H. H. & Szöecs, E. 2001, *Vegan: community ecology package*. (No Title).
- Onditi, K. O., Song, W.-Y., Li, X.-Y., Chen, Z.-Z., Li, Q., He, S.-W., Musila, S., Kioko, E. & Jiang, X.-L. 2022, Patterns and predictors of small mammal phylogenetic and functional diversity in contrasting elevational gradients in Kenya. *Frontiers in Ecology and Evolution*, 9, 742524.
- Padakale, E., Dourma, M., Atakpama, W., Wala, K., Guelly, K. & Akpagana, K. 2018, *Parkia biglobosa* Jacq. Dong: Une espèce agroforestière à usages multiples dans la zone soudanienne au Togo. *RAMReS-Sciences Humaines*, 10, 403-421.
- Padonou, E. A., Kassa, B., Assogbadjo, A., Chakeredza, S., Babatoundé, B. & Glèlè Kakaï, R. 2013, Differences in germination capacity and seedling growth between different seed morphotypes of *Afzelia africana* Sm. in Benin (West Africa). *The Journal of Horticultural Science and Biotechnology*, 88, 679-684.
- Padullés Cubino, J., Chytrý, M., Divíšek, J. & Jiménez-Alfaro, B. 2022, Climatic filtering and temporal instability shape the phylogenetic diversity of European alpine floras. *Ecography*, 2022, e06316.
- Paradis, E., Claude, J. & Strimmer, K. 2004, APE: analyses of phylogenetics and evolution in R language. *Bioinformatics*, 20, 289-290.

- Parr, C. L., Lehmann, C. E., Bond, W. J., Hoffmann, W. A. & Andersen, A. N. 2014, Tropical grassy biomes: misunderstood, neglected, and under threat. *Trends in Ecology & Evolution*, 29, 205-213.
- Parthasarathi, T., Firdous, S., David, E. M., Lesharadevi, K. & Djanaguiraman, M. 2022, Effects of high temperature on crops. *Advances in Plant Defense Mechanisms*. IntechOpen.
- Pashirzad, M., Ejtehadi, H., Vaezi, J. & Shefferson, R. P. 2018, Spatial scale-dependent phylogenetic signal in species distributions along geographic and elevation gradients in a mountainous rangeland. *Ecology and Evolution*, 8, 10364-10373.
- Pearson, R. G. & Dawson, T. P. 2003, Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful? *Global Ecology and Biogeography*, 12, 361-371.
- Perez-Harguindeguy, N., Diaz, S., Garnier, E., Lavorel, S., Poorter, H., Jaureguiberry, P., Bret-Harte, M. S., Cornwell, W. K., Craine, J. M. & Gurvich, D. E. 2016, Corrigendum to: New handbook for standardised measurement of plant functional traits worldwide. *Australian Journal of Botany*, 64, 715-716.
- Phillips, S. J., Anderson, R. P., Dudík, M., Schapire, R. E. & Blair, M. E. 2017, Opening the black box: An open-source release of Maxent. *Ecography*, 40, 887-893.
- Phillips, S. J., Anderson, R. P. & Schapire, R. E. 2006, Maximum entropy modeling of species geographic distributions. *Ecological Modelling*, 190, 231-259.
- Pigliucci, M., Murren, C. J. & Schlichting, C. D. 2006, Phenotypic plasticity and evolution by genetic assimilation. *Journal of Experimental Biology*, 209, 2362-2367.
- Pinheiro, J. 2011. nlme: Linear and nonlinear mixed effects models. R package version, 3, 1.

- Pistorius, T., Schmitt, C., Benick, D., Entenmann, S. & Reinecke, S. 2011, Greening REDD+ challenges and opportunities for integrating biodiversity safeguards at and across policy levels. *German Journal of Forest Science*, 182, 82-98.
- Place, F., Garrity, D., Mohan, S. & Agostini, P. 2016, Tree-based production systems for Africa's drylands. World Bank Publications.
- Platts, J. A., Ermondi, G., Caron, G., Ravera, M., Gabano, E., Gaviglio, L., Pelosi, G. & Osella, D. 2011, Molecular and statistical modeling of reduction peak potential and lipophilicity of platinum (IV) complexes. *JBIC Journal of Biological Inorganic Chemistry*, 16, 361-372.
- Pommerening, A. 2002, Approaches to quantifying forest structures. *Forestry*, 75, 305-324.
- Pommerening, A. 2006, Evaluating structural indices by reversing forest structural analysis. *Forest Ecology and Management*, 224, 266-277.
- Poorter, H., Böhler, J., van Dusschoten, D., Climent, J. & Postma, J. A. 2012, Pot size matters: a meta-analysis of the effects of rooting volume on plant growth. *Functional Plant Biology*, 39, 839-850.
- Potter, K. M., Jetton, R. M., Bower, A., Jacobs, D. F., Man, G., Hipkins, V. D. & Westwood, M. 2017, Banking on the future: progress, challenges and opportunities for the genetic conservation of forest trees. *New Forests*, 48, 153-180.
- Pressey, R. L. & Bottrill, M. C. 2008, Opportunism, threats, and the evolution of systematic conservation planning. *Conservation Biology*, 22, 1340-1345.
- Pretzsch, H. 2009, Forest dynamics, growth, and yield: From measurement to model. Springer Berlin Heidelberg.

- Qian, H., Hao, Z. & Zhang, J. 2014, Phylogenetic structure and phylogenetic diversity of angiosperm assemblages in forests along an elevational gradient in Changbaishan, China. *Journal of Plant Ecology*, 7, 154-165.
- Qian, H., Kessler, M., Deng, T. & Jin, Y. 2021, Patterns and drivers of phylogenetic structure of pteridophytes in China. *Global Ecology and Biogeography*, 30, 1835-1846.
- Qian, H. & Ricklefs, R. E. 2016, Out of the tropical lowlands: latitude versus elevation. *Trends in Ecology & Evolution*, 31, 738-741.
- Qian, H. & Sandel, B. 2017, Phylogenetic structure of regional angiosperm assemblages across latitudinal and climatic gradients in North America. *Global Ecology and Biogeography*, 26, 1258-1269.
- Qin, T. J., Zhou, J., Sun, Y., Müller-Schärer, H., Luo, F. L., Dong, B. C., Li, H. L. & Yu, F. H. 2020, Phylogenetic diversity is a better predictor of wetland community resistance to *Alternanthera philoxeroides* invasion than species richness. *Plant Biology*, 22, 591-599.
- Rabiou, H., Bationo, B. A., Adjonou, K., Kokutse, A. D., Mahamane, A. & Kokou, K. 2017, Perception paysanne et importance socioculturelle et ethnobotanique de *Pterocarpus erinaceus* au Burkina Faso et au Niger. *Afrique Science*, 13, 43-60.
- Radha, Kumar, M., Puri, S., Pundir, A., Bangar, S. P., Changan, S., Choudhary, P., Parameswari, E., Alhariri, A. & Samota, M. K. 2021, Evaluation of nutritional, phytochemical, and mineral composition of selected medicinal plants for therapeutic uses from cold desert of Western Himalaya. *Plants*, 10, 1429.
- Rahbek, C., Borregaard, M. K., Antonelli, A., Colwell, R. K., Holt, B. G., Nogues-Bravo, D., Rasmussen, C. M., Richardson, K., Rosing, M. T. & Whittaker, R. J. 2019, Building mountain biodiversity: Geological and evolutionary processes. *Science*, 365, 1114-1119.

- Reich, P. B. 2014, The world-wide ‘fast–slow’ plant economics spectrum: a traits manifesto. *Journal of Ecology*, 102, 275-301.
- Reed, M. S., Stringer, L. C., Dougill, A. J., Perkins, J. S., Atlhopheng, J. R., Mulale, K., & Favretto, N. 2015, Reorienting land degradation towards sustainable land management: Linking sustainable livelihoods with ecosystem services in rangeland systems. *Journal of environmental management*, 151, 472-485.
- Reid, N. M., Wigley, K., Nusrath, A., Smaill, S. J. & Garrett, L. G. 2024, Use of nitrogen-fixing plants to improve planted forest soil fertility and productivity in New Zealand: A review. *New Zealand Journal of Forestry Science*, 54.
- Reza, S., Nayak, D., Mukhopadhyay, S., Chattopadhyay, T. & Singh, S. 2017, Characterizing spatial variability of soil properties in alluvial soils of India using geostatistics and geographical information system. *Archives of Agronomy and Soil Science*, 63, 1489-1498.
- Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O’Neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R. & Fricko, O. 2017, The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, 42, 153-168.
- Ringelberg, J. J., Koenen, E. J., Sauter, B., Aebli, A., Rando, J. G., Iganci, J. R., de Queiroz, L. P., Murphy, D. J., Gaudeul, M. & Bruneau, A. 2023, Precipitation is the main axis of tropical plant phylogenetic turnover across space and time. *Science Advances*, 9, eade4954.
- Robbins, K. 2015, The biodiversity paradigm shift: adapting the Endangered Species Act to climate change. *Fordham Envtl. L. Rev.*, 27, 57.
- Roeber, C., Raabe, N., Luebke, K., Ligges, U., Szepannek, G., Zentgraf, M., Ligges, M. U. & Svmlight, S. 2020, Package ‘klaR’. Package ‘klaR’.

- Romdal, T. S. & Rahbek, C. 2009, Elevational zonation of afrotropical forest bird communities along a homogeneous forest gradient. *Journal of Biogeography*, 36, 327–336.
- Rondeux, J. 2021, La mesure des arbres et des peuplements forestiers. Presses agronomiques de Gembloux.
- Ryan, C. M., Williams, M. & Grace, J. 2011, Above- and belowground carbon stocks in a miombo woodland landscape of Mozambique. *Biotropica*, 43, 423-432.
- Sabo, P., Ouédraogo, A., Lankoandé, B., Salako, K. V., Ouédraogo, H. & Kakaï, R. G. 2023, Influence of topography on the natural stand structure of *Boswellia dalzielii* Hutch. in a semi-arid environment: Insight into hill ecosystems conservation in Burkina Faso. *Global Ecology and Conservation*, 43, e02430.
- Saha, S., Rajwar, G.-S. & Kumar, M. 2016, Forest structure, diversity and regeneration potential along altitudinal gradient in Dhanaulti of Garhwal Himalaya. *Forest Systems*, 25, e058-e058.
- Saka, J., Rapp, I., Akinnifesi, F., Ndolo, V. & Mhango, J. 2007, Physicochemical and organoleptic characteristics of *Uapaca kirkiana*, *Strychnos cocculoides*, *Adansonia digitata* and *Mangifera indica* fruit products. *International Journal of Food Science & Technology*, 42, 836-841.
- Salako, K. V., Moreira, F., Gbedomon, R. C., Tovissodé, F., Assogbadjo, A. E. & Glèlè Kakaï, R. L. 2018, Traditional knowledge and cultural importance of *Borassus aethiopum* Mart. in Benin: interacting effects of socio-demographic attributes and multi-scale abundance. *Journal of Ethnobiology and Ethnomedicine*, 14, 1-16.
- Salako, V. K., Assogbadjo, A. E., Adomou, A. C., Agbangla, C. & Glèlè Kakaï, R. L. 2015, Latitudinal distribution, co-occurring tree species and structural diversity of the threatened palm *Borassus aethiopum* (Arecaceae) in Benin, West Africa. *Plant Ecology and Evolution*, 148, 335-349.

Salako, V. K., Vihotogbé, R., Houéhanou, T., Sodé, I. A. & Glèlè Kakaï, R. 2019, Predicting the potential impact of climate change on the declining agroforestry species *Borassus aethiopum* Mart. in Benin: a mixture of geostatistical and SDM approach. *Agroforestry Systems*, 93, 1513-1530.

Saliou, A., Oumorou, M. & Sinsin, B. A. 2015, Modélisation des niches écologiques des ligneux fourragers en condition de variabilité bioclimatique dans le moyen-Bénin (Afrique de l'Ouest). *Revue d'Ecologie, Terre et Vie*, 70, 342-353.

Samarou, M., Atakpama, W., Kanda, M., Tchacondo, T., Batawila, K. & Akpagana, K. 2021, *Tamarindus indica* L. (Fabaceae) in ecological zone I of Togo: use value and vulnerability. *International Journal of Complementary and Alternative Medicine*, 14, 307-315.

Samarou, M., Atakpama, W., Kombate, B., Egbelou, H., Folega, F., Batawila, K. & Akpagana, K. 2023, Vulnerability of tamarind (*Tamarindus indica* L., Fabaceae) facing the climate change: a case of Togo. *AgroBiologia*, 13, 3300-3313.

Sanchez, A. C. 2011, The baobab tree in Malawi. *Fruits*, 66, 405-416.

Sanchez, A. C., Osborne, P. E. & Haq, N. 2010, Identifying the global potential for baobab tree cultivation using ecological niche modelling. *Agroforestry Systems*, 80, 191-201.

Saradoum, G., Félicité Temgoua, L., Mbaikembeye, M. O., Tedou, F. B. S. & Behimnan, A. 2022, Estimation du potentiel de séquestration de carbone des aires protégées: cas de la Forêt Classée de Djoli-Kera, Tchad. *VertigO-la revue électronique en sciences de l'environnement*.

Sawchuk, J. H., Beaudreau, A. H., Tonnes, D. & Fluharty, D. 2015, Using stakeholder engagement to inform endangered species management and improve conservation. *Marine Policy*, 54, 98–107.

Schlichting, C. D. 1986, The evolution of phenotypic plasticity in plants. *Annual Review of Ecology and Systematics*, 17, 667-693.

Schumann, K., Wittig, R., Thiombiano, A., Becker, U. & Hahn, K. 2010, Impact of land-use type and bark-and leaf-harvesting on population structure and fruit production of the baobab tree (*Adansonia digitata* L.) in a semi-arid savanna, West Africa. *Forest Ecology and Management*, 260, 20352044.

Setyasih, D. M. D., Putri, R. A. S., Raharjo, Y. A. A., Izdiyar, R. S., Kusumaningrum, L. & Setyawan, A. D. 2025, Potential aboveground carbon storage in the community forest area of Tawangmangu, Karanganyar District, Indonesia. *Asian Journal of Forestry*, 9.

Seydack, A. H. 1995, An unconventional approach to timber yield regulation for multi-aged, multispecies forests. I. Fundamental considerations. *Forest Ecology and Management*, 77, 139–153.

Shackleton, C. M. 2015, Non-timber forest products in livelihoods. In *Ecological sustainability for non-timber forest products* (pp. 12-30). Routledge.

Shackleton, C., & Shackleton, S. 2004, The importance of non-timber forest products in rural livelihood security and as safety nets: a review of evidence from South Africa. *South African Journal of Science*, 100 (11), 658-664.

Shackleton, C. M., & Pandey, A. K. 2014, Positioning non-timber forest products on the development agenda. *Forest Policy and Economics*, 38, 1-7.

Shackleton, C. M., & Pullanikkatil, D. 2018, Considering the links between non-timber forest products and poverty alleviation. In *Poverty Reduction Through Non-Timber Forest Products: Personal Stories* (pp. 15-28). Cham: Springer International Publishing.

Sharma, R., Garg, P., Kumar, P., Bhatia, S. K. & Kulshrestha, S. 2020, Microbial fermentation and its role in quality improvement of fermented foods. *Fermentation*, 6, 106.

Shelef, O., Weisberg, P. J. & Provenza, F. D. 2017, The value of native plants and local production in an era of global agriculture. *Frontiers in Plant Science*, 8, 2069.

Shell, A. B., Ojha, S. K. & Sharma, A. 2021, Region-wide characterization of structural diversity of the US Outer Coastal Plain Mixed Forests Province. *Forest Ecology and Management*, 488, 118979.

Shirima, D. D., Munishi, P. K., Lewis, S. L., Burgess, N. D., Marshall, A. R., Balmford, A., Swetnam, R. D. & Zahabu, E. M. 2011, Carbon storage, structure and composition of miombo woodlands in Tanzania's Eastern Arc Mountains. *African Journal of Ecology*, 49, 332-342.

Shorrocks, B. & Bates, W. 2015, *The biology of African savannahs*. Oxford University Press.

Siddique, A. B. 2017, Leaf-inhabiting mycobiomes under different environmental conditions: local habitat conditions, leaf biochemistry and seasonal variations drive fungal community dynamics. Dissertation, Greifswald, Ernst-Moritz-Arndt-Universität.

Sinsin, B., Eyog Matig, O., Assogbadjo, A., Gaoué, O. & Sinadouwirou, T. 2004, Dendrometric characteristics as indicators of pressure of *Afzelia africana* Sm. dynamic changes in trees found in different climatic zones of Benin. *Biodiversity & Conservation*, 13, 1555-1570.

Smith, S. A. & Brown, J. W. 2018, Constructing a broadly inclusive seed plant phylogeny. *American Journal of Botany*, 105, 302-314.

Sosef, M. S., Dauby, G., Blach-Overgaard, A., van der Burgt, X., Catarino, L., Damen, T., Deblauwe, V., Dessein, S., Dransfield, J. & Droissart, V. 2017, Exploring the floristic diversity of tropical Africa. *BMC Biology*, 15, 1-23.

Ssegawa, P. & Nkuutu, D. N. 2006, Diversity of vascular plants on Ssesse islands in Lake Victoria, central Uganda. *African Journal of Ecology*, 44, 22-29.

Sultan, S. E. 2000, Phenotypic plasticity for plant development, function and life history. *Trends in Plant Science*, 5, 537–542.

Sunday, J., Bennett, J. M., Calosi, P., Clusella-Trullas, S., Gravel, S., Hargreaves, A. L., Leiva, F. P., Verberk, W. C., Olalla-Tárraga, M. Á. & Morales-Castilla, I. 2019, Thermal tolerance patterns across latitude and elevation. *Philosophical Transactions of the Royal Society B*, 374, 20190036.

Swaine, M. D. & Whitmore, T. C. 1988, On the definition of ecological species groups in tropical rain forests. *Vegetatio*, 75, 81-86.

Swap, J., Ribeiro, N. S., Buramuge, V., Domingos, J. C., Fernando, J., Govene, J. & Mandlate, H. J. 2023, Investigating the effects of fires on plant diversity of the miombo woodlands in Gilé National Park, Central Mozambique. *AGU Fall Meeting Abstracts*, B13K-205.

Swenson, N. G. 2011, Phylogenetic beta diversity metrics, trait evolution and inferring the functional beta diversity of communities. *PLoS One*, 6, e21264.

Syampungani, S., Geldenhuys, C. J. & Chirwa, P. W. 2016, Regeneration dynamics of miombo woodland in response to different anthropogenic disturbances: forest characterisation for sustainable management. *Agroforestry Systems*, 90, 563-576.

Team, R. C. 2022, *R: a language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing.

Teketay, D. 2005, Seed and regeneration ecology in dry Afromontane forests of Ethiopia: I. Seed production-population structures. *Tropical Ecology*, 46, 29-44.

Teklehaimanot, Z. 2004, Exploiting the potential of indigenous agroforestry trees: *Parkia biglobosa* and *Vitellaria paradoxa* in sub-Saharan Africa. In: *New Vistas in Agroforestry: A Compendium for 1st World Congress of Agroforestry*, Springer, 207-220.

Thattantavide, A. & Kumar, A. 2024, Local food systems as a resilient strategy to ensure sustainable food security in crisis: Lessons from COVID-19 pandemic and perspectives for the post-pandemic world. *CABI Reviews*.

Thomas, C. D. 2010, Climate, climate change and range boundaries. *Diversity and Distributions*, 16, 488-495.

Thuiller, W., Lafourcade, B., Engler, R. & Araújo, M. B. 2009, BIOMOD a platform for ensemble forecasting of species distributions. *Ecography*, 32, 369-373.

Tiétiambou, F. R. S., Salako, K. V., Tohoun, J. R. & Ouédraogo, A. 2020, Local preferences for three indigenous oil-seed plants and attitudes towards their conservation in the Kénédougou province of Burkina Faso, West-Africa. *Journal of Ethnobiology and Ethnomedicine*, 16, 1-16.

Timberlake, J., Chidumayo, E. & Sawadogo, L. 2010, Distribution and characteristics of African dry forests and woodlands. In *The dry forests and woodlands of Africa*. Routledge, 2, 11-41.

Traore, L., Ouedraogo, I., Ouedraogo, A. & Thiombiano, A. 2011, Perceptions, usages et vulnérabilité des ressources végétales ligneuses dans le Sud-Ouest du Burkina Faso. *International Journal of Biological and Chemical Sciences*, 5.

Trotter, F. D., Lehmann, C. E., Donaldson, J. E., Mangena, H. E., Parr, C. L. & Archibald, S. 2022, Drought and fire determine juvenile and adult woody diversity and dominance in a semi-arid African savanna. *Biotropica*, 54, 1015-1029.

Tucker, C. M., Cadotte, M. W., Carvalho, S. B., Davies, T. J., Ferrier, S., Fritz, S. A., Grenyer, R., Helmus, M. R., Jin, L. S. & Mooers, A. O. 2017, A guide to phylogenetic metrics for conservation, community ecology and macroecology. *Biological Reviews*, 92, 698-715.

- Vågen, T.-G., Winowiecki, L. A., Tondoh, J. E., Desta, L. T. & Gumbrecht, T. 2016, Mapping of soil properties and land degradation risk in Africa using MODIS reflectance. *Geoderma*, 263, 216-225.
- Valladares, F., Gianoli, E. & Gómez, J. M. 2007, Ecological limits to plant phenotypic plasticity. *New Phytologist*, 176.
- Valladares, F. & Niinemets, Ü. 2008, Shade tolerance, a key plant feature of complex nature and consequences. *Annual Review of Ecology, Evolution, and Systematics*, 39, 237-257.
- Valladares, F., Sanchez-Gomez, D. & Zavala, M. A. 2006, Quantitative estimation of phenotypic plasticity: bridging the gap between the evolutionary concept and its ecological applications. *Journal of Ecology*, 94, 1103-1116.
- Valladares, F., Matesanz, S., Guilhaumon, F., Araújo, M. B., Balaguer, L., Benito-Garzón, M. & Zavala, M. A. 2014, The effects of phenotypic plasticity and local adaptation on forecasts of species range shifts under climate change. *Ecology letters*, 17(11), 1351-1364.
- Van Dyke, F. 2008, Conservation biology: Foundations, concepts, applications (2nd ed.). Dordrecht, the Netherlands: Springer. ISBN 978-1-4020-6588-3.
- Vaz, A. S., Kueffer, C., Kull, C. A., Richardson, D. M., Vicente, J. R., Kühn, I., Schröter, M., Hauck, J., Bonn, A. & Honrado, J. P. 2017, Integrating ecosystem services and disservices: insights from plant invasions. *Ecosystem Services*, 23, 94-107.
- Venables, W. N., & Ripley, B. D. 2013, Modern applied statistics with S (4th ed.). New York, NY: Springer. ISBN 978-0-387-78845-3.
- Viljür, M. L., Abella, S. R., Adámek, M., Alencar, J. B. R., Barber, N. A., Beudert, B., Burkle, L. A., Cagnolo, L., Campos, B. R. & Chao, A. 2022, The effect of natural disturbances on forest biodiversity: an ecological synthesis. *Biological Reviews*, 97, 1930-1947.

- Violle, C., Navas, M. L., Vile, D., Kazakou, E., Fortunel, C., Hummel, I. & Garnier, E. 2007, Let the concept of trait be functional! *Oikos*, 116, 882-892.
- Wang, M., Zhang, J., Guo, Z., Guan, Y., Qu, G., Liu, J., Guo, Y. & Yan, X. 2020, Morphological variation in *Cynodon dactylon* (L.) Pers., and its relationship with the environment along a longitudinal gradient. *Hereditas*, 157, 1-11.
- Wang, X., Zeng, J., Chen, F., Wang, Z., Liu, H., Zhang, Q., Liu, W., Wang, W., Guo, Y. & Niu, Y. 2024, Aridity shapes distinct biogeographic and assembly patterns of forest soil bacterial and fungal communities at the regional scale. *Science of the Total Environment*, 948, 174812.
- Webb, C. O., Ackerly, D. D., McPeck, M. A. & Donoghue, M. J. 2002, Phylogenies and community ecology. *Annual Review of Ecology and Systematics*, 33, 475-505.
- Weiner, J. 1990, Asymmetric competition in plant populations. *Trends in Ecology & Evolution*, 5, 360-364.
- West, P. W. 2015. *Stand measurement*. In: *Tree and Forest Measurement*, Springer.
- Westoby, M. 1998, A leaf-height-seed (LHS) plant ecology strategy scheme. *Plant and Soil*, 199, 213-227.
- White, F. 1983. *The vegetation of Africa*. Natural Resources Research, UNESCO.
- Workeneh, D. S. & Kafumbata, D. D. 2020, Assessment of woody species diversity, biomass and carbon stock potential of Dzalanyama Forest Reserve, Malawi. Haramaya University.
- Wright, I. J., Reich, P. B., Westoby, M., Ackerly, D. D., Baruch, Z., Bongers, F., Cavender-Bares, J., Chapin, T., Cornelissen, J. H. & Diemer, M. 2004, The worldwide leaf economics spectrum. *Nature*, 428, 821-827.

Wunderlich, R. F., Lin, Y.-P., Anthony, J. & Petway, J. R. 2019, Two alternative evaluation metrics to replace the true skill statistic in the assessment of species distribution models. *Nature Conservation*, 35, 97-116.

Xiao, S., Li, S., Huang, J., Wang, X., Wu, M., Karim, R., Deng, W. & Su, T. 2024, Influence of climate factors on the global dynamic distribution of *Tsuga* (Pinaceae). *Ecological Indicators*, 158, 111533.

Yaipharrembi, N., Huidrom, E., Nongalleima, K. & Singh, H. B. 2023, An ethnobotanical study on the dietary use of wild trees as traditional vegetables by three ethnic communities in Manipur, North East India. *Economic Botany*, 77, 324-339.

Yang, B., Ma, R., Zhai, J., Du, J., Bai, J. & Zhang, W. 2024, Stand spatial structure is more important than species diversity in enhancing the carbon sink of fragile natural secondary forest. *Ecological Indicators*, 158, 111449.

Yanou, M. P., Ros-Tonen, M. A., Reed, J., Moombe, K., & Sunderland, T. 2023, Integrating local and scientific knowledge: The need for decolonising knowledge for conservation and natural resource management. *Heliyon*, 9(11).

Yoda, K. 1963, Intraspecific competition among higher plants. XI: Self-thinning in overcrowded pure stands under cultivated and natural conditions. *Journal of Biology, Osaka City University*, 14, 107-129.

Zeileis, A. & Kleiber, C. 2014, *ineq: Measuring Inequality, Concentration, and Poverty*. R package version 0.2-13. Vienna, Austria: The R Foundation.

Zhang-Zheng, H., Malhi, Y., Gvozdevaite, A., Peprah, T., Boakye, M., Ziemińska, K., Adu-Bredu, S., Gutiérrez, J. A., Sandoval, D. & Tang, M. 2024, Variation in plant traits along a tropical wet-dry gradient: a test of ecophysiological theories.

Zhang, H., Li, Y., Xu, K., Yu, L., He, P., Zeng, S., Song, Y., Liu, R. & Sun, Y. 2024, Effects of anthropogenic disturbance on the structure, competition, and succession of *Abies ziyuanensis* communities. *Forests*, 15, 1001.

Zhang, W., Huang, D., Wang, R., Liu, J. & Du, N. 2016, Altitudinal patterns of species diversity and phylogenetic diversity across temperate mountain forests of northern China. *PLoS One*, 11, e0159995.

Zhang, Z., Xu, S., Capinha, C., Weterings, R. & Gao, T. 2019, Using species distribution model to predict the impact of climate change on the potential distribution of Japanese whiting *Sillago japonica*. *Ecological Indicators*, 104, 333-340.

Zhao, Q., Mi, Z. Y., Lu, C., Zhang, X. F., Chen, L. J., Wang, S. Q., Niu, J. F. & Wang, Z. Z. 2022, Predicting potential distribution of *Ziziphus spinosa* (Bunge) HH Hu ex FH Chen in China under climate change scenarios. *Ecology and Evolution*, 12, e8629.

Zianis, D., Muukkonen, P., Mäkipää, R. & Mencuccini, M. 2005, Biomass and stem volume equations for tree species in Europe. FI.

Zon, A. O., Tiétiambou, F. R. S., Kabré, B., Kouassi, K. E. & Ouédraogo, A. 2022, Assessment of the conservation status of *Borassus akeassii* Bayt., Ouédr. & Guinko in Western Burkina Faso through local communities perceptions and the species stands structure. *Global Ecology and Conservation*, 39, e02284.

APPENDIX

Appendix 1: Interviewer Administered Data Collection of *Uapaca kirkiana* in MALAWI

(research objective 1)

Generality on study Area

Characteristic	Answers
District	
TA	
Locality/Village	

Characteristics of the respondent (household)

headings	Codes	Answers
Professional Group(s)	1-Farmer; 2-Hunter; 3-Housewife; 4-Merchant; 6- Retailer; 7- Civil servant; 8- Traditional practitioner; 9-Phytopharmacist; 10- Others (specify)	
Main Activity		
Secondary Activity(ies)		
Gender	1- Male / 2- Female	
Ethnic group	• Chewa • Lomwe • Yao • Ngoni • Tumbuka • Sena • Mang'anja	

	• Tonga • Nyanja • Nyakyusa • Other	
Religion	-Animist; 2-Christian; 3-Muslim; 4-Others	
Age	Youth (19-29 years), adult (30-59 years) and old (≥ 60 years)	
Academic level	None ☐ Primary ☐ High school ☐ University ☐	
Marital status	Single ☐ Married ☐ Widow ☐	

KNOWLEDGE OF USE AND VULNERABILITY OF *Uapaca kirkiana*

1. Do you know the species (*U. kirkiana*)? Yes / No

2. Do you know any plants that accompany or are associated with *Uapaca kirkiana*?

- ☐ No

- ☐ Yes

If yes, which ones?

1. Species 1:

2. Species 2:

3. Species 3:

Species 4:

Species 5:

3. Does it exist in this locality? Yes / No

4. Field Habitat: 1 = Courtyard garden; 2 = Field; 3 = Fallow land; 4 = Forest; 5 =

Wetland. 6. Others (please specify):

6. How often: 1. scarce, 2. moderately abundant, 3. abundant, 4. very abundant

7. If the species is present in your field, will you spare it? Yes / No

8. If yes, why...

9. Do you plan to conserve this plant?

- ☐ Yes

- ☐ No

If yes, what are the reasons?

10. What do you think of the availability of *U. kirkiana* plant? - ☐ Available

- ☐ More or less available, - ☐ Less available - ☐ Rare - ☐ Very rare

The reasons:

11. Does this plant influence the productivity of your crops?

- ☐ Positively

- ☐ Negatively

- ☐ Neutral

12. What are other uses of *Uapaca kirkiana*?

- ☐ Erosion control

- ☐ Habitat for certain wildlife species

- ☐ Flood control

- ☐ Local climate regulation

- ☐ Cultural value

- ☐ Biological restoration

- ☐ Others (please specify):

13. How many times does the species produce in a year?

14. What are the months of fruit production for the species?

15. How does *Uapaca* regenerate: 1. natural regeneration; 2. Plantations

If it is by plantation, is it by: 1. Seedling; 2. Sapling; 3. cutting planting

Plant part, use and vulnerability of *Uapaca kirkiana*

1. What are the parts of the *Uapaca kirkiana* and others plant that you use or exploit?

Characterization of trees plant organs or plant parts.

Plants names	Organ	User: Code: 1-Woman; 2- Forest operator; 3-Traditional practitioner; 4- Others (specify)	Types of Uses (1. Food; 2. Medicinal; 3. Harvesting Socio-cultural; 4. Artisanal; 5. Cosmetic; 6. Forage; Energy Wood; 8. Service Wood)	Method or Tool: 1. Hand; 2. Machete; 3. Hoe	Harvesting Stage of the Organ (1. Young, 2. Adult, 3. Old)
<i>U. kirkiana</i>	Kernel				
	Fruit				
	Stem Bark				
	Flowers				
	Leaf				
	Seed				
	Trunk				
	Branch				
	Roots				
	Seed coat				
	Young shoots				
	Sap				

--	--	--	--	--	--

2. What are the preparation methods, the dose to take and the frequency of use of the different products from *U. kirkiana*?

Products	Method of preparation/dose/frequency of use

Local perceptions of population's dynamics of *Uapaca kirkiana*

- 1) How *Uapaca* is available in your locality?

Absent in the locality ☐ Rare ☐ Less abundant ☐ Abundant ☐

- 2) What is the evolution trend of the species in your locality the last 10 years?

Stable ☐ Progressing ☐ Regressing ☐

- 3) What are the reasons that underpin the regressive trend?

Harvesting ☐ Agriculture ☐ drought ☐ Pests ☐ Other ☐

Additional note:

- 4) What are the causes of its population decline?

Logging ☐ Agriculture ☐ Charcoal ☐ Population growth ☐
☐ Deforestation ☐ Lack of enforcement of legislations ☐ Climate change ☐
☐ Other ☐

Here is the translation:

5. What are the ecosystem services provided by *Uapaca kirkiana* using a five-point Likert scale: (5 = strongly agree, 4 = agree, 3 = undecided/neutral, 2 = disagree, and 1 = strongly disagree)?

6. To what extent do you agree that *Uapaca kirkiana* contributes to food provision for local communities?
7. In your opinion, does *Uapaca kirkiana* play an aesthetic role?
8. To what extent do you think *Uapaca kirkiana* provides shade in your area?
9. Do you agree that *Uapaca kirkiana* contributes to environmental cooling?
10. To what extent do you consider *Uapaca kirkiana* as a source of medicine?
11. Do you think *Uapaca kirkiana* is a source of firewood for local households?
12. Does *Uapaca kirkiana* contribute, in your opinion, to oxygen production or air quality?
13. To what extent do you agree that *Uapaca kirkiana* serves as a habitat for birds and wildlife?
14. Do you think *Uapaca kirkiana* improves air quality in your community?
15. Does *Uapaca kirkiana* act as a windbreak?

Local conservation practice of *Uapaca kirkiana*

- 1) Did you actively practice any conservative actions to maintain the species? Yes ☐
No ☐
- 2) What are the conservation strategies you practice?
 - ☐ Seed collection and storage
 - ☐ Replanting and reforestation
 - ☐ Protection of natural habitats
 - ☐ Agroforestry practices
 - ☐ Controlled harvesting
 - ☐ Establishment of protected areas
 - ☐ Community awareness and education
 - ☐ Others (please specify):

REGENERATION AND ECOLOGY OF *Uapaca kirkiana*

1. In your opinion, what influence can fruit harvesting have on the regeneration of the species?

- ☐ No significant influence (Harvesting does not affect the regeneration of the species).
- ☐ Reduction in regeneration (Harvesting reduces the number of seeds available for regeneration).
- ☐ Disruption of seed dispersal (Harvesting limits, the natural spread of seeds.
- ☐ Slowing down of regeneration)

Harvesting slows down the regeneration process.

- ☐ Improvement in regeneration (Harvesting sometimes helps regeneration by aiding in seed dispersal).
- ☐ Depends on the amount harvested (The impact depends on how many fruits are harvested).
- ☐ Influence on young plants (Harvesting can affect the development of young plants).

2. Have you ever planted *Uapaca*? Yes / No Why? :.....

3. If yes, by what method? Sowing / Cuttings / Grafting

4. How many *Uapaca kirkiana* plants have you planted on average over the course of five last years?

Years	Number of the plants of <i>U. kirkiana</i> planting
2019	
2020	
2021	
2022	
2023	

5. How important is the fruit of *Uapaca kirkiana* to your household?

Main source of income ☐

Secondary source of income ☐

Only consumed for family food ☐

Not important ☐

6. What quantities can you sell during the availability period of the species' fruits?

7. Is the commercialization of fruits profitable? Yes / No

8. How would you describe the demand for *U. kirkiana* fruits in the market? Very high / Moderately high / High / Low / Not high

9. What quantity of fruit have you sold in the past and your income?

Years	Quantities of fruit sold	Income
2019		
2020		
2021		
2022		
2023		

10. What are the challenges encountered in the commercialization process of *Uapaca kirkiana* fruits?

- ☐ Difficulty accessing markets
- ☐ Lack of transportation
- ☐ Low demand in the market
- ☐ Lack of knowledge on preservation techniques
- ☐ Competition with other fruits
- ☐ Issues with fruit quality
- ☐ Other (please specify): _____

11. Which distribution channels are used to sell the fruits?

- ☐ Local markets
- ☐ Regional markets
- ☐ National markets
- ☐ Supermarkets
- ☐ Exportation
- ☐ Online sales

☐ Other (please specify): _____

12. What is the current demand for these fruits in the local market?

☐ Very high

☐ High

☐ Moderate

☐ Low

☐ Very low

13. What methods do you use to increase the value of the fruit?

Processing into derived products (jams, juices, etc.) ☐

Better packaging ☐

Selling in bulk ☐

No specific method ☐

Other (please specify) ☐

Appendix 2: Stand structure to guide conservation actions of *Uapaca kirkiana* in Malawi:

objective 2 and 4

Inventory Data Collection

ECOLOGICAL INVENTORY SHEET

OBSERVER.....N°.....Date.....

Long..... Lat..... Elevation.....

Plot size REGION.....TA..... Locality.....

Ecology characteristic	Information
Types of Parks	1.1. Forest
	1.2. Others (Specify)
Topographical Situation	2.1. Plain
	2.2. Slope base
	2.3. Mid-slope
	2.4. Slope top
	2.5. Others
Situation in relation to watercourses/ponds	3.1. Riverbanks
	3.2. Pond edges
	3.3. Marshy area
	3.4. Flood zone
	3.5. Others
Situation in relation to human settlements	4.1. Close to settlements (less than 100 m)
	4.2. More or less close to settlements
	4.3. Far from settlements (more than 2 km)
	4.4. Within settlements
	4.5. Others
Canopy closure degree	< 25%; 25 – 50%, 50 – 80%, > 80%

Woody population density	Low dense, Moderately dense, Very dense
Relief type	Plain, Plateau, Undulating, Interfluve, Slope, Valley, Ravine
Weathering	None, Small plates, Large Plates, Continuous
Soil texture	Sandy, Loamy, Clayey, Sandy-loamy, Sandy-clayey, Clayey-loamy
Signs of erosion	None, Weak, Medium, Pronounced
Anthropogenic actions	Absent, Low, Medium, Frequent
Vegetation fires	Absent, Low, Medium, Frequent
Wood cutting	Absent, Low, Medium, Frequent
Charcoal burning	Absent, Low, Medium, Frequent
Clearance	Absent, Low, Medium, Frequent
Fishing	Absent, Low, Medium, Frequent
Hunting	Absent, Low, Medium, Frequent
Honey collection	Absent, Low, Medium, Frequent
Dominant species	

➤ **Forest inventory**

OBSERVER.....N°.....Date.....
 Long..... Lat..... Altitude..... Plot size.....
 REGION.....
 TA.....Locality.....

N°	scientific name	DBH	Dist_ref Neighbor1	Dist_vi Neighbor2	Dis_bas Neighbor3	Dis_ Neighbor4	Trunk height	Height total

Key: For regeneration, count the individuals considered during inventories that have not been measured. Health Quality: 1 = healthy; 2 = rot; 3 = broken crown; 4 = bark stripped; 5 = pruned; 6 = more than one defect.

Trunk Quality: 1 = straight; 2 = twisted; 3 = candelabra; 4 = more than one defect.

➤ Regeneration inventory

Observation.....N°.....Date.....

Long..... Lat..... Altitude..... Plot size.....

REGION..... District.....

TA.....Locality.....

Species name	local name	Sucker	Basal shoots (stems) – Count / Number	Rejection of strain (Count Number)	Barrel quality	Health	Use food, fruit, fire, habit, medicine,

Key: Health quality: 1= healthy; 2= rot; 3= broken crown; 4= Barked; 5=Pruned, 6=more than one defect.Barrel quality: 1= straight; 2= twisted; 3=candlestick; 4= more than one defect

Appendix 3: Data collection sheet on morphological and functional traits for research objective 3

I. General Information

Date

☐ yyyy-mm-dd

☐ hh:mm

Region

☐ North

☐ Central

☐ South

GPS Coordinates (for each sampled tree)

Latitude (x.y °) : _____

Longitude (x.y °) : _____

Altitude (m) : _____

Précision (m) : _____

II. Morphological Data (Tree Level, Canopy Volume)

2.1. Number of Sample (total trees observed): _____

2.2. Code of Sample (tree code): _____

2.3. Tree Diameter at Base Level (0.8 m), in cm: _____

2.4. Tree Diameter at Breast Height (1.30 m), in cm: _____

2.5. Total Height of *U. kirkiana*, in m: _____

2.6. Crown Base Height (Hauteur fût), in m: _____

2.7. Perpendicular Measured Radius of Crown (m):

Radius 1: _____

Radius 2: _____

2.8. Number of Primary Branches per Tree: _____

III. Fruit Measurement (Weight)

3.1. Number of Fruits per Tree Measured: 10 (fixed)

3.2. Fruit Weight (g):

Fruit 1: _____

Fruit 2: _____

Fruit 3: _____

Fruit 4: _____

Fruit 5: _____

Fruit 6: _____

Fruit 7: _____

Fruit 8: _____

Fruit 9: _____

Fruit 10: _____

IV. Fruit Measurement (Length)

Fruit 1: _____

Fruit 2: _____

Fruit 3: _____

Fruit 4: _____

Fruit 5: _____

Fruit 6: _____

Fruit 7: _____

Fruit 8: _____

Fruit 9: _____

Fruit 10: _____

V. Fruit Measurement (Diameter)

Fruit 1: _____

Fruit 2: _____

Fruit 3: _____

Fruit 4: _____

Fruit 5: _____

Fruit 6: _____

Fruit 7: _____

Fruit 8: _____

Fruit 9: _____

Fruit 10: _____

VI. Seed Level (Number of Seeds per Fruit)

Fruit 1: _____

Fruit 2: _____

Fruit 3: _____

Fruit 4: _____

Fruit 5: _____

Fruit 6: _____

Fruit 7: _____

Fruit 8: _____

Fruit 9: _____

Fruit 10: _____

VII. Seed Level (Weight)

Fruit 1: _____

Fruit 2: _____

Fruit 3: _____

Fruit 4: _____

Fruit 5: _____

Fruit 6: _____

Fruit 7: _____

Fruit 8: _____

Fruit 9: _____

Fruit 10: _____

VIII. Leaf Level (Collected at Levels 1, 3, 5, 7, 9)

Leaf Length (Muyanja et al.):

Leaf 1: _____

Leaf 3: _____

Leaf 5: _____

Leaf 7: _____

Leaf 9: _____

Leaf Width (Muyanja et al.):

Leaf 1: _____

Leaf 3: _____

Leaf 5: _____

Leaf 7: _____

Leaf 9: _____

IX. Disturbance Variables (Human Disturbance Indices for *U. kirkiana*)

Oxen Passage (Frequency of oxen passing or grazing around *U. kirkiana* populations):

☐ Insignificant

☐ Minor; ☐ Moderate; ☐ Major; ☐ Catastrophic

Pruning Rate (Frequency/intensity of pruning for fruit harvesting or branch management):

☐ Never; ☐ Unlikely; ☐ Possible; ☐ Likely; ☐ Always

Appendix 4: Occurrence data collection for research objective five

Fiche N°/_____/ Collection date: /_____/_____/_____/

Name of the collector(s):

Region: /_____/ District: /_____/ TA: /_____/ Locality:

/_____/ Ethnic: /_____/

Scientific name: *Uapaca kirkiana* ; Local name:

Habitat: Forest; fields; Fallows; Home garden; Savannah; Other (s) to be specified) :.....

N°	Longitude (X)	Latitude (Y)	Altitude (m)	Observation

Thank you for sharing your knowledge with us!

Appendix 5: Species inventoried across study area (89 genera and 39 botanical families)

Species	Families	Genre
<i>Acacia goetzei</i> Harms.	Fabaceae	Acacia
<i>Acacia karroo</i> Hayne	Fabaceae	Acacia
<i>Acacia polyacantha</i> Willd.	Fabaceae	Acacia
<i>Acacia spirocarpa</i> Hochst. ex A.Rich.	Fabaceae	Acacia
<i>Adina microcephala</i> (Delile) Hiern	Rubiaceae	Adina
<i>Afzelia quanzensis</i> Welw.	Fabaceae	Afzelia
<i>Agauria salicifolia</i> (Comm. ex Lam.) Hook. f. ex Oliv.	Ericaceae	Agauria
<i>Albizia antunesiana</i> Harms	Fabaceae	Albizia
<i>Albizia gueperei</i> (Benth.)	Fabaceae	Albizia
<i>Albizia tanganyicensis</i> Baker f.	Fabaceae	Albizia
<i>Albizia versicolor</i> Welw. ex Oliv.	Fabaceae	Albizia
<i>Anisophyllea boehmii</i> Engl.	Anisophylleaceae	Anisophyllea
<i>Annona senegalensis</i> Pers.	Annonaceae	Annona
<i>Antidesma venosum</i> (Forssk.) M.A. Larsen.	Phyllanthaceae	Antidesma
<i>Azanza garckeana</i> (Fresen.) F. Müll.	Malvaceae	Azanza
<i>Barkea africana</i> (F. Muell.) M. Vahl.	Fabaceae	Barkea
<i>Bauhinia petersiana</i> Benth.	Fabaceae	Bauhinia
<i>Bauhinia thonningii</i> Schumach.	Fabaceae	Bauhinia
<i>Bobgunnia madagascariensis</i> (Desv.) J.H.Kirkbr. & Wiersema.	Fabaceae	Bobgunnia
<i>Brachystegia boehmii</i> (Taub.)	Fabaceae	Brachystegia
<i>Brachystegia bussei</i> Harms	Fabaceae	Brachystegia
<i>Brachystegia floribunda</i> Benth.	Fabaceae	Brachystegia
<i>Brachystegia longifolia</i> (Benth.)	Fabaceae	Brachystegia
<i>Brachystegia spiciformis</i> (Benth.)	Fabaceae	Brachystegia
<i>Brachystegia stipulata</i> De Wild.	Fabaceae	Brachystegia
<i>Brachystegia taxifolia</i> (Benth.)	Fabaceae	Brachystegia
<i>Brachystegia utilis</i> (S. Moore) Taub.	Fabaceae	Brachystegia
<i>Bridelia cathartica</i> Bertol. f.	Phyllanthaceae	Bridelia
<i>Bridelia micrantha</i> (Hochst.) Baill.	Phyllanthaceae	Bridelia
<i>Burkea africana</i> (J.F. Gmel.) Hochst.	Fabaceae	Burkea
<i>Cassia angolensis</i> Hiern	Fabaceae	Cassia
<i>Cassia petersiana</i> Bolle	Fabaceae	Cassia
<i>Catunaregam spinosa</i> (Thunb.) Tirveng.	Rubiaceae	Catunaregam
<i>Cedrela toona</i> (Roxb. ex Rottler) M.J. Roem.	Meliaceae	Cedrela
<i>Ceratonia siliqua</i> L.	Combretaceae	Combretum
<i>Combretum zeyheri</i> Sond.	Combretaceae	Combretum
<i>Combretum molle</i> R. Br. ex G. Don	Burseraceae	Commiphora
<i>Commiphora africana</i> (Rich.) Engl.	Boraginaceae	Cordia
<i>Cordia myxa</i> L.	Fabaceae	Cordyla
<i>Cordyla africana</i> Lour.	Euphorbiaceae	Croton
<i>Croton macrostachyus</i> Hochst. ex Delile	Araliaceae	Cusonia

Species	Families	Genre
<i>Cusonia arborea</i> (L.) R.Br. ex A.Rich.	Fabaceae	Dalbergia
<i>Dalbergia arbutifolia</i> Baker	Fabaceae	Dalbergia
<i>Dalbergia nitidula</i> Welw. ex Baker.	Fabaceae	Dalbergia
<i>Dichrostachys cinerea</i> (L.) Wight & Arn.	Fabaceae	Dichrostachys
<i>Diospyros kirkii</i> Hiern	Ebenaceae	Diospyros
<i>Diplorhynchus condylocarpon</i> (Müll. Arg.) Pichon	Apocynaceae	Diplorhynchus
<i>Dombeya rotundifolia</i> (Hochst.) Planch.	Malvaceae	Dombeya
<i>Dombeya torrida</i> (D. goetzenii)	Malvaceae	Dombeya
<i>Ekebergia benguelensis</i> Welw. ex C.DC	Meliaceae	Ekebergia
<i>Erica arborea</i> L.	Ericaceae	Erica
<i>Erythrina abyssinica</i> Lam. ex DC.	Fabaceae	Erythrina
<i>Eucalyptus camaldulensis</i> Dehnh.	Myrtaceae	Eucalyptus
<i>Euclea crispa</i> (Thunb.) Sond. ex Gürke	Ebenaceae	Euclea
<i>Faurea rochetiana</i> (A. Rich.) Pic.Serm.	Proteaceae	Faurea
<i>Faurea saligna</i> Harv.	Proteaceae	Faurea
<i>Ficus capensis</i> Thunb.	Moraceae	Ficus
<i>Flacourtia indica</i> (Burm. f.) Merr.	Salicaceae	Flacourtia
<i>Gardenia imperialis</i> K. Schum.	Rubiaceae	Gardenia
<i>Gmelina arborea</i> Roxb.	Lamiaceae	Gmelina
<i>Grewia bicolor</i> Juss.	Malvaceae	Grewia
<i>Harungana madagascariensis</i> Lam. ex Poir.	Hypericaceae	Harungana
<i>Hippocratea parviflora</i> N.E.Br.	Celastraceae	Hippocratea
<i>Hymenocardia acida</i> Tul.	Phyllanthaceae	Hymenocardia
<i>Hyparrhenia cymbaria</i> (L.)	Poaceae	Hyparrhenia
<i>Jasminum fluminense</i> Vell.	Oleaceae	Jasminum
<i>Julbernardia globiflora</i> (Benth.)	Fabaceae	Julbernardia
<i>Julbernardia paniculata</i> (Benth.)	Fabaceae	Julbernardia
<i>Keetia gueinzei</i> (Sond.) Bridson	Rubiaceae	Keetia
<i>Khaya anthotheca</i> (Welw.) C. DC.	Meliaceae	Khaya
<i>Kirkia acuminata</i> Oliv.	Kirkiaceae	Kirkia
<i>Lannea discolor</i> (Sond.) Engl.	Anacardiaceae	Lannea
<i>Lantana camara</i> L.	Verbenaceae	Lantana
<i>Mangifera indica</i> L.	Anacardiaceae	Mangifera
<i>Maprounea africana</i> Müll. Arg.	Euphorbiaceae	Maprounea
<i>Margaritaria discoidea</i> (Baill.) G.L. Webster	Phyllanthaceae	Margaritaria
<i>Memecylon flavovirens</i> Baker	Melastomataceae	Memecylon
<i>Monotes africanus</i> A. DC.	Dipterocarpaceae	Monotes
<i>Multidentia crassa</i> (Hiern.) Bridson & Verdc.	Fabaceae	Multidentia
<i>Mundulea sericea</i> (Willd.) A. Chev.	Fabaceae	Mundulea
<i>Ochna schweinfurthiana</i> F. Hoffm.	Ochnaceae	Ochna
<i>Oncoba spinosa</i> Forsk	Salicaceae	Oncoba
<i>Ozoroa insignis</i> Delile	Anacardiaceae	Ozoroa
<i>Ozoroa reticulata</i> (Baker f.) R. Fern. & A. Fern.	Anacardiaceae	Ozoroa
<i>Parinari curatellifolia</i> Planch. ex Benth.	Chrysobalanaceae	Parinari
<i>Parinari excelsa</i> Sabine	Chrysobalanaceae	Parinari

Species	Families	Genre
<i>Pericopsis angolensis</i> (Fyllas et al.)	Fabaceae	Pericopsis
<i>Pinus patula</i> Schltdl. & Cham.	Pinaceae	Pinus
<i>Protea madiensis</i> Oliv.	Proteaceae	Protea
<i>Protea nitida</i> Mill.	Proteaceae	Protea
<i>Pseudolachnostylis maprouneifolia</i> Pax	Phyllanthaceae	Pseudolachnostylis
<i>Psorospermum febrifugum</i> Spach	Hypericaceae	Psorospermum
<i>Pterocarpus angolensis</i> DC.	Fabaceae	Pterocarpus
<i>Pterocarpus rotundifolius</i> (Sond.)	Fabaceae	Pterocarpus
<i>Randia</i> Sp	Rubiaceae	Randia
<i>Rawsonia usambarensis</i> Engl. & Gilg	Achariaceae	Rawsonia
<i>Rhus longipes</i> Engl.	Anacardiaceae	Rhus
<i>Rothmannia engleriana</i> (K. Schum.)	Rubiaceae	Rothmannia
<i>Rourea orientalis</i> Baill.	Connaraceae	Rourea
<i>Senna petersiana</i> (Bolle) Lock	Fabaceae	Senna
<i>Senna singueana</i> (Delile) Lock	Fabaceae	Senna
<i>Steganotaenia araliacea</i> Hochst.	Apiaceae	Steganotaenia
<i>Stereospermum kunthianum</i> Cham.	Bignoniaceae	Stereospermum
<i>Strychnos spinosa</i> Lam.	Loganiaceae	Strychnos
<i>Swartzia madagascariensis</i> Desv.	Loganiaceae	Swartzia
<i>Syzygium cordatum</i> Hochst. ex Krauss	Fabaceae	Syzygium
<i>Syzygium guineense</i> (Willd.) DC.	Myrtaceae	Syzygium
<i>Syzygium owariense</i> (P. Beauv.) Benth.	Myrtaceae	Syzygium
<i>Terminalia sericea</i> Burch. ex DC.	Myrtaceae	Terminalia
<i>Terminalia stenostachya</i> Engl. & Diels	Combretaceae	Terminalia
<i>Themeda triandra</i> Forssk.	Combretaceae	Themeda
<i>Toona ciliata</i> M.Roem.	Poaceae	Toona
<i>Trichocladus crinitus</i> (Thunb.) Pers.	Meliaceae	Trichilia
<i>Turraea nilotica</i> Kotschy & Peyr.	Hamamelidaceae	Turraea
<i>Uapaca kirkiana</i> Müll. Arg.	Phyllanthaceae	Uapaca
<i>Uapaca nitida</i> Müll. Arg.	Phyllanthaceae	Uapaca
<i>Uapaca sansibarica</i> Pax	Phyllanthaceae	Uapaca
<i>Vachellia hockii</i> (De Wild.) Seigler & Ebinger	Phyllanthaceae	Uapaca
<i>Vachellia karroo</i> (Hayne) Banfi & Galasso	Fabaceae	Vachellia
<i>Vangueria infausta</i> Burch.	Fabaceae	Vangueria
<i>Vitex doniana</i> Sweet.	Rubiaceae	Vitex
<i>Vitex mombassae</i> Vatke	Lamiaceae	Vitex
<i>Vitex payos</i> (P. Beauv.)	Lamiaceae	Vitex
<i>Ximenia americana</i> L.	Lamiaceae	Ximenia

Appendix 6: Specific frequencies of *U. kirkiana* habitats across studies areas

Species	number of species	Frequency (%)
<i>Uapaca sansibarica</i>	453	12.49
<i>Brachystegia spiciformis</i>	253	6.98
<i>Brachystegia taxifolia</i>	248	6.84
<i>Parinari curatellifolia</i>	204	5.63
<i>Julbernardia paniculata</i>	150	4.14
<i>Combretum molle</i>	129	3.56
<i>Brachystegia longifolia</i>	116	3.20
<i>Brachystegia floribunda</i>	115	3.17
<i>Syzygium guineense</i>	109	3.01
<i>Uapaca nitida</i>	104	2.87
<i>Parinari excelsa</i>	97	2.68
<i>Annona senegalensis</i>	83	2.29
<i>Brachystegia utilis</i>	68	1.88
<i>Pericopsis angolensis</i>	68	1.88
<i>Pseudolachnostylis maprouneifolia</i>	61	1.68
<i>Agauria salicifolia</i>	60	1.65
<i>Ochna schweinfurthiana</i>	60	1.65
<i>Faurea saligna</i>	59	1.63
<i>Combretum zeyheri</i>	54	1.49
<i>Burkea africana</i>	52	1.43
<i>Lannea discolor</i>	49	1.35
<i>Eucalyptus camaldulensis</i>	47	1.30
<i>Bridelia micrantha</i>	44	1.21
<i>Monotes africanus</i>	38	1.05
<i>Brachystegia bussei</i>	37	1.02
<i>Cussonia arborea</i>	37	1.02
<i>Diplorhynchus condylocarpon</i>	35	0.97
<i>Brachystegia boehmii</i>	33	0.91
<i>Vitex doniana</i>	30	0.83
<i>Syzygium owariense</i>	29	0.80
<i>Syzygium cordatum</i>	28	0.77
<i>Vitex payos</i>	28	0.77
<i>Bobgunnia madagascariensis</i>	25	0.69
<i>Vangueria infausta</i>	24	0.66
<i>Julbernardia globiflora</i>	23	0.63
<i>Pterocarpus angolensis</i>	23	0.63
<i>Bauhinia petersiana</i>	19	0.52
<i>Flacourtia indica</i>	19	0.52
<i>Hymenocardia acida</i>	18	0.50
<i>Pinus patula</i>	18	0.50
<i>Keetia gueinzei</i>	17	0.47
<i>Faurea rochetiana</i>	15	0.41
<i>Strychnos spinosa</i>	15	0.41

Species	number of species	Frequency (%)
<i>Bauhinia thonningii</i>	13	0.36
<i>Erica arborea</i>	13	0.36
<i>Senna singueana</i>	13	0.36
<i>Margaritaria discoidea</i>	12	0.33
<i>Multidentia crassa</i>	12	0.33
<i>Steganotaenia araliacea</i>	12	0.33
<i>Afzelia quanzensis</i>	11	0.30
<i>Ozoroa insignis</i>	11	0.30
<i>Terminalia stenostachya</i>	11	0.30
<i>Antidesma venosum</i>	10	0.28
<i>Brachystegia stipulata</i>	10	0.28
<i>Bridelia cathartica</i>	10	0.28
<i>Acacia goetzei</i>	9	0.25
<i>Jasminum fluminense</i>	9	0.25
<i>Memecylon flavovirens</i>	9	0.25
<i>Protea nitida</i>	9	0.25
<i>Ceratonia siliqua</i>	8	0.22
<i>Dombeya torrida</i>	8	0.22
<i>Gardenia imperialis</i>	8	0.22
<i>Gmelina arborea</i>	8	0.22
<i>Trichocladus crinitus</i>	8	0.22
<i>Azanza garckeana</i>	7	0.19
<i>Dalbergia nitidula</i>	7	0.19
<i>Ekebergia benguelensis</i>	7	0.19
<i>Rourea orientalis</i>	7	0.19
<i>Anisophyllea boehmii</i>	6	0.17
<i>Diospyros kirkii</i>	6	0.17
<i>Hippocratea parviflora</i>	6	0.17
<i>Mundulea sericea</i>	6	0.17
<i>Rhus longipes</i>	6	0.17
<i>Terminalia sericea</i>	6	0.17
<i>Vachellia karroo</i>	6	0.17
<i>Vitex mombassae</i>	6	0.17
<i>Albizia antunesiana</i>	5	0.14
<i>Dichrostachys cinerea</i>	5	0.14
<i>Erythrina abyssinica</i>	5	0.14
<i>Grewia bicolor</i>	5	0.14
<i>Keetia venosa</i>	5	0.14
<i>Khaya anthotheca</i>	5	0.14
<i>Oncoba spinosa</i>	5	0.14
<i>Themeda triandra</i>	5	0.14
<i>Toona ciliata</i>	5	0.14
<i>Turraea nilotica</i>	5	0.14
<i>Albizia gueperei</i>	4	0.11
<i>Albizia tanganyicensis</i>	4	0.11

Species	number of species	Frequency (%)
<i>Cordia myxa</i>	4	0.11
<i>Lantana camara</i>	4	0.11
<i>Maprounea africana</i>	4	0.11
<i>Acacia karroo</i>	3	0.08
<i>Albizia versicolor</i>	3	0.08
<i>Cassia angolensis</i>	3	0.08
<i>Catunaregam spinosa</i>	3	0.08
<i>Cordyla africana</i>	3	0.08
<i>Euclea crispa</i>	3	0.08
<i>Ficus capensis</i>	3	0.08
<i>Hyparrhenia cymbaria</i>	3	0.08
<i>Kirkia acuminata</i>	3	0.08
<i>Mangifera indica</i>	3	0.08
<i>Protea madiensis</i>	3	0.08
<i>Psorospermum febrifugum</i>	3	0.08
<i>Rothmannia engleriana</i>	3	0.08
<i>Senna petersiana</i>	3	0.08
<i>Acacia polyacantha</i>	2	0.06
<i>Adina microcephala</i>	2	0.06
<i>Barkea africana</i>	2	0.06
<i>Cassia petersiana</i>	2	0.06
<i>Commiphora africana</i>	2	0.06
<i>Dalbergia arbutifolia</i>	2	0.06
<i>Ozoroa reticulata</i>	2	0.06
<i>Pterocarpus rotundifolius</i>	2	0.06
<i>Randia Sp</i>	2	0.06
<i>Swartzia madagascariensis</i>	2	0.06
<i>Vachellia hockii</i>	2	0.06
<i>Acacia spirocarpa</i>	1	0.03
<i>Cedrela toona</i>	1	0.03
<i>Croton macrostachyus</i>	1	0.03
<i>Dalbergia melanoxydon</i>	1	0.03
<i>Dombeya rotundifolia</i>	1	0.03
<i>Harungana madagascariensis</i>	1	0.03
<i>Rawsonia usambarensis</i>	1	0.03
<i>Stereospermum kunthianum</i>	1	0.03

Appendix 7: Species with IUCN status across studies areas

Species	IUCN Status
<i>Afzelia quanzensis</i>	VU
<i>Albizia tanganyicensis</i>	VU
<i>Khaya anthotheca</i>	VU
<i>Ozoroa reticulata</i>	VU
<i>Pterocarpus angolensis</i>	VU
<i>Dalbergia melanoxylon</i>	NT
<i>Eucalyptus camaldulensis</i>	NT
<i>Acacia spirocarpa</i>	NE
<i>Adina microcephala</i>	NE
<i>Agauria salicifolia</i>	NE
<i>Albizia gueperei</i>	NE
<i>Anisophyllea boehmii</i>	NE
<i>Azanza garckeana</i>	NE
<i>Barkea africana</i>	NE
<i>Cassia angolensis</i>	NE
<i>Cedrela toona</i>	NE
<i>Cussonia arborea</i>	NE
<i>Dombeya torrida</i>	NE
<i>Ficus capensis</i>	NE
<i>Grewia bicolor</i>	NE
<i>Hippocratea parviflora</i>	NE
<i>Hyparrhenia cymbaria</i>	NE
<i>Jasminum fluminense</i>	NE
<i>Keetia gueinzei</i>	NE
<i>Lantana camara</i>	NE
<i>Memecylon flavovirens</i>	NE
<i>Randia Sp</i>	NE
<i>Rawsonia usambarensis</i>	NE
<i>Rhus longipes</i>	NE
<i>Swartzia madagascariensis</i>	NE
<i>Terminalia stenostachya</i>	NE
<i>Themeda triandra</i>	NE
<i>Acacia goetzei</i>	LC
<i>Acacia karroo</i>	LC
<i>Acacia polyacantha</i>	LC
<i>Albizia antunesiana</i>	LC
<i>Albizia versicolor</i>	LC
<i>Annona senegalensis</i>	LC
<i>Antidesma venosum</i>	LC
<i>Bauhinia petersiana</i>	LC
<i>Bauhinia thonningii</i>	LC
<i>Bobgunnia madagascariensis</i>	LC
<i>Brachystegia boehmii</i>	LC

Species	IUCN Status
<i>Brachystegia bussei</i>	LC
<i>Brachystegia floribunda</i>	LC
<i>Brachystegia longifolia</i>	LC
<i>Brachystegia spiciformis</i>	LC
<i>Brachystegia stipulata</i>	LC
<i>Brachystegia taxifolia</i>	LC
<i>Brachystegia utilis</i>	LC
<i>Bridelia cathartica</i>	LC
<i>Bridelia micrantha</i>	LC
<i>Burkea africana</i>	LC
<i>Cassia petersiana</i>	LC
<i>Catunaregam spinosa</i>	LC
<i>Combretum zeyheri</i>	LC
<i>Combretum molle</i>	LC
<i>Commiphora africana</i>	LC
<i>Cordia myxa</i>	LC
<i>Cordyla africana</i>	LC
<i>Croton macrostachyus</i>	LC
<i>Dalbergia arbutifolia</i>	LC
<i>Dalbergia nitidula</i>	LC
<i>Dichrostachys cinerea</i>	LC
<i>Diospyros kirkii</i>	LC
<i>Diplorhynchus condylocarpon</i>	LC
<i>Dombeya rotundifolia</i>	LC
<i>Ekebergia benguelensis</i>	LC
<i>Erica arborea</i>	LC
<i>Erythrina abyssinica</i>	LC
<i>Euclea crispa</i>	LC
<i>Faurea rochetiana</i>	LC
<i>Faurea saligna</i>	LC
<i>Flacourtia indica</i>	LC
<i>Gardenia imperialis</i>	LC
<i>Gmelina arborea</i>	LC
<i>Harungana madagascariensis</i>	LC
<i>Hymenocardia acida</i>	LC
<i>Julbernardia globiflora</i>	LC
<i>Julbernardia paniculata</i>	LC
<i>Kirkia acuminata</i>	LC
<i>Lannea discolor</i>	LC
<i>Maprounea africana</i>	LC
<i>Margaritaria discoidea</i>	LC
<i>Monotes africanus</i>	LC
<i>Multidentia crassa</i>	LC
<i>Mundulea sericea</i>	LC
<i>Ochna schweinfurthiana</i>	LC

Species	IUCN Status
<i>Oncoba spinosa</i>	LC
<i>Ozoroa insignis</i>	LC
<i>Parinari curatellifolia</i>	LC
<i>Parinari excelsa</i>	LC
<i>Pericopsis angolensis</i>	LC
<i>Pinus patula</i>	LC
<i>Protea madiensis</i>	LC
<i>Protea nitida</i>	LC
<i>Pseudolachnostylis maprouneifolia</i>	LC
<i>Psorospermum febrifugum</i>	LC
<i>Pterocarpus rotundifolius</i>	LC
<i>Rothmannia engleriana</i>	LC
<i>Rourea orientalis</i>	LC
<i>Senna petersiana</i>	LC
<i>Senna singueana</i>	LC
<i>Steganotaenia araliacea</i>	LC
<i>Stereospermum kunthianum</i>	LC
<i>Strychnos spinosa</i>	LC
<i>Syzygium cordatum</i>	LC
<i>Syzygium guineense</i>	LC
<i>Syzygium owariense</i>	LC
<i>Terminalia sericea</i>	LC
<i>Toona ciliata</i>	LC
<i>Trichocladus crinitus</i>	LC
<i>Turraea nilotica</i>	LC
<i>Uapaca nitida</i>	LC
<i>Uapaca sansibarica</i>	LC
<i>Vachellia hockii</i>	LC
<i>Vachellia karroo</i>	LC
<i>Vangueria infausta</i>	LC
<i>Vitex doniana</i>	LC
<i>Vitex mombassae</i>	LC
<i>Vitex payos</i>	LC
<i>Ximenia americana</i>	LC
<i>Ximenia caffra</i>	LC
<i>Mangifera indica</i>	DD

Appendix 8: MZUNIREC Ethics and Regulatory Approval



MZUZU UNIVERSITY

DIRECTORATE OF RESEARCH

Mzuzu University
Private Bag 201
Luwinga
Mzuzu 2
MALAWI
TEL: 01 320 722
FAX: 01 320 648

MZUZU UNIVERSITY RESEARCH ETHICS COMMITTEE (MZUNIREC)

Ref No: MZUNIREC/DOR/24/104

14/10/2024.

Kokou Kokouvi Bruno,
Mzuzu University,
P/Bag 201, Luwinga,
Mzuzu 2.

Email: kokoubruno7@gmail.com

Dear Kokou,

**RESEARCH ETHICS AND REGULATORY APPROVAL AND PERMIT FOR
PROTOCOL REF NO. MZUNIREC/DOR/24/104: UAPACAKIRKIANA MUELL.
ARG: UTILIZATION UNDER ANTHROPOGENIC THREATS AND CLIMATE
CHANGE IN MALAWI.**

Having satisfied all the relevant ethical and regulatory requirements, I am pleased to inform you that the above referred research protocol has officially been approved. You are now permitted to proceed with its implementation. Should there be any amendments to the approved protocol in the course of implementing it, you shall be required to seek approval of such amendments before implementation of the same.

This approval is valid for one year from the date of issuance of this approval. If the study goes beyond one year, an annual approval for continuation shall be required to be sought from the Mzuzu University Research Ethics Committee (MZUNIREC) in a format that is available at the Secretariat. Once the study is

finalised, you are required to furnish the Committee with a final report of the study.

The Committee reserves the right to carry out compliance inspection of this approved protocol at any time as may be deemed by it. As such, you are expected to properly maintain all study documents including consent forms.

Wishing you a successful implementation of your study.

Yours Sincerely,



Wanangwa K. Msowoya
MZUNIREC Secretariat
FOR: MZUNIREC CHAIRPERSON



Mzuzu University Research Ethics Committee
Directorate of Research
Mzuzu University
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Luwinga
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