



Moderating temperature

Farm diversification

Adaptation

Soil carbon increase

Erosion control

Diet diversification

Weed management

Income generation

Multiple crop yields annually

Biodiversity promotion

Nutrient cycling

Weed management

Water retention



**EXPLORING THE SOCIOECONOMIC AND ENVIRONMENTAL
FACTORS INFLUENCING SMALLHOLDER MACADAMIA
PRODUCTION AND PRODUCTIVITY IN MALAWI**

Emmanuel Junior Zuza

BSc, MSc

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**School of Environment, Earth and Ecosystem Sciences
Faculty of Science, Technology, Engineering, and Mathematics
The Open University**

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ABSTRACT

Macadamia (*Macadamia integrifolia* Maiden & Betche) is a highly valued crop in Malawi. The crop is a vital source of food security and ecosystem services, and its high-export cash value makes it a key contributor to the country's economy. Malawi ranks seventh in global macadamia production, comprising two subsectors: smallholders and commercial estates. However, significant yield gaps have been reported between smallholder and commercial estate producers. While commercial estates achieve higher average annual tree yields (30 kg), smallholder yields remain consistently low, averaging at or below 10 kg tree⁻¹ year⁻¹. Improving macadamia productivity among smallholders can help reduce poverty, improve household food security, and promote economic growth in Malawi.

Despite the significant contributions of smallholders in the Malawian macadamia subsector, research on the factors influencing the crop's productivity has primarily focused on commercial estate production. To address this knowledge gap, this Ph.D thesis focuses on smallholder macadamia production in Malawi. The thesis examines the socioeconomic characteristics of smallholder macadamia farmers, including demographics, cultivar preferences, and production constraints. Secondly, it evaluates the climatic factors influencing smallholder macadamia production and predicts the current and future suitable geographical areas for the crop. Lastly, it assesses the soil fertility status of smallholder macadamia farms in relation to macadamia production requirements.

Results of this study reveal that the majority (62%) of macadamia smallholders are over 50 years of age and consider farming their main occupation. However, this poses significant risks to the macadamia subsector, as older farmers are risk-averse and less innovative, hindering their willingness to adopt new agricultural technologies and ability to learn. Regarding cultivar preferences, the study finds that smallholder macadamia farmers prefer high-yielding cultivars

with superior nut qualities, such as large and heavy nuts, and extended flowering periods. The most preferred macadamia cultivars in descending order are Hawaiian Agricultural Experimental Station (HAES) 660, 800, 816, and 246, which are the "core" of established cultivars in Malawi. The study identifies insect pests, diseases, market availability, strong winds, and a lack of agricultural extension services as the most significant challenges affecting smallholder macadamia farmers.

The study's suitability analysis reveals that the ensemble model has an excellent fit and high performance in predicting the current agro-climatically suitable areas for macadamia production (AUC = 0.90). The findings show that precipitation related variables (60.2%) are more important in determining the suitable areas for growing macadamia than temperature related variables (39.8%). The model results show that 57% (53,925 km²) of Malawi is currently suitable for macadamia cultivation, with the central region having the highest suitability (25.8%, 24,327 km²) and the southern region the lowest (10.7%, 10,257 km²). Optimal suitability (26%, 24,565 km²) is observed in the highland areas with elevations ranging from 1000–1400 metres above sea level (m.a.s.l.). Under the intermediate emission scenario (RCP 4.5) and the pessimistic scenario (RCP 8.5), the impact models predict net losses of 18% (17,015 km²) and 21.6% (20,414 km²), respectively, in the extent of suitable areas for macadamia in the 2050s.

The results of the soil fertility analysis indicate suboptimal fertility among the sampled macadamia farms. The majority of the soils are strongly acidic and deficient in essential nutrients required for the healthy growth of macadamia trees. Moreover, the average cation exchange capacity (1.67 cmol (+) kg⁻¹) and the soil organic matter content (\leq 1%) are below the minimum optimal levels required for macadamia trees. These findings indicate that soil fertility is one of the primary limiting factors to the crop's productivity, even in areas with suitable climatic conditions. Therefore, addressing the soil fertility issues is crucial to

improving the land suitability of the smallholder farms for macadamia, which can lead to optimal yields.

This study extends the frontiers of knowledge concerning the macadamia subsector in Malawi by providing insights into the smallholder macadamia farming systems, including demographics, cultivar preferences, and production constraints. It also provides novel empirical evidence on the climate factors that influence the suitability of rainfed macadamia cultivation and identifies current and future suitable growing areas in the country. Additionally, the study addresses the research gap on the soil fertility status of Malawian smallholder macadamia farms. Therefore, the findings of this research have practical implications for various areas such as macadamia cultivar introductions and breeding, land use planning, soil fertility management, and policy formulation for agricultural extension services, inputs, and marketing of the crop.

PREFACE

The research work described in this thesis was carried out in the School of Environment, Earth and Ecosystem Sciences at the Open University in Milton Keynes between April 2019 to April 2023, under the direct supervision of Dr. Yoseph N. Araya, Dr. Kadmiel Maseyk, Prof. Shonil Bhagwat and Mr. Andrew Emmott.

I would like to declare that the research work in this thesis has never been submitted in any form to another university. It is, therefore, my original work, except where due acknowledgment is made.




Date: 17/08/2023

Emmanuel Junior Zuza

DECLARATION 1 – STATEMENT OF ORIGINAL AUTHORSHIP

This research project was funded by the Global Challenges Research Fund doctoral training programme at the Open University. The work in this thesis has not been previously submitted to meet the requirements for an award at this or any other higher education institution. To my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

Signature :  _____

Date : 17/08/2023

DECLARATION 2 – PUBLICATIONS AND MANUSCRIPTS

PUBLISHED RESEARCH PAPERS

1. **Zuza, E. Jnr.**, Maseyk, K., Bhagwat, S., Chemura, A., Brandenburg, R.L., Emmott, A., Hancock, W., Rawes, W., Mthambala, F., Araya, Y.N. (2023). Factors affecting soil quality among smallholder macadamia farms in Malawi. *Agriculture and Food Security*, 12 (17). <https://doi.org/10.1186/s40066-023-00421-9>.
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MANUSCRIPTS IN REVIEW

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DEDICATION

This Ph.D thesis is dedicated:

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CHAPTER ONE: GENERAL INTRODUCTION

This chapter introduces this Ph.D thesis. The chapter begins with an overview of the Sustainable Development Goals (SDGs) that the thesis seeks to address. Specifically, this thesis aims to contribute to achieving several SDGs related to food security, such as Goal 1, to eliminate all forms of global poverty. Goal 2 to end hunger, achieve food security and improved nutrition, and promote sustainable agriculture. Goal 12 to ensure sustainable consumption and production patterns. Goal 13 to take urgent action to combat climate change and its impacts. Goal 15 to protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation. The chapter then delves into the significance of agriculture in the context of Malawi. It examines the potential impacts of climate change and soil degradation on the agrarian sector, specifically focusing on the smallholder subsector. To provide context for this thesis, the chapter also discusses various climate change adaptation interventions promoted by the Malawian government and various non-governmental organizations (NGOs). The chapter concludes with a justification for the study, which provides a clear rationale for the research and its significance.

1.1. Introduction

Ensuring global food security remains a formidable challenge due to population growth, shifts in food consumption, arable land degradation, and the impacts of climate change. Through the SDGs, the international community has committed to ending hunger, food insecurity, and all forms of malnutrition by 2030 (UN, 2015). However, the FAO (2022a) argues that the world is falling behind in achieving these goals, particularly in Africa, where roughly one in four people face hunger, with the most severe cases in Sub-Saharan Africa (SSA) (FAO, 2022a). In addition, SSA countries continue to rely on food aid annually, and recent crises, such as

climate extremes, land degradation, the Covid-19 pandemic, and the conflict between Russia and Ukraine, may worsen the situation (Vansant et al., 2022; FAO, 2022b).

Agriculture is crucial in ensuring food security and economic growth in Malawi, much like other SSA countries. The agricultural sector in the country comprises two subsectors: smallholders and commercial estate producers. Smallholder production is predominantly monoculture, rainfed, and technologically underdeveloped, making it vulnerable to the impacts of climate change (Hermans et al., 2020; 2023). However, sustainable food production for Malawi's growing population depends on smallholder farmer adaptation to climate change. This is because smallholder farmers are responsible for 80% of the total food produced in Malawi (Nyagumbo et al., 2022). Therefore, reducing food insecurity and poverty in the country requires a focus on improving smallholder agricultural productivity, sustainability, and feasibility (Lipper et al., 2014; Conway & Vincent, 2021). Scaling up climate-smart agriculture (CSA) practices can transform smallholder agriculture systems into a more sustainable and profitable sector in response to climate change (Eze et al., 2020; Dewa et al., 2023). Moreover, sustainable agriculture can also contribute to the achievement of SDGs.

Climate-smart agriculture (CSA) is an innovative approach to sustainable food production that aims to increase agricultural productivity and incomes while enhancing food security and reducing greenhouse gas emissions (GHG). As defined by the Food and Agriculture Organisation of the United Nations (FAO), CSA helps guide actions to transform agri-food systems towards green and climate-resilient practices (FAO, 2022a). By aligning with globally recognised targets such as the SDGs and the Paris Agreement, CSA plays a pivotal role in the FAO Strategic Framework 2022–2031 Four Betters. This is because CSA uses a range of practices tailored to a particular area's specific needs and conditions. Thus, CSA reflects and builds on the linkages of economic, social, and environmental dimensions of agrifood systems.

Common CSA practices include agroforestry, conservation agriculture (CA), crop diversification, and regenerative agriculture (Jones et al., 2023). By adopting CSA practices, farmers can increase their yields, reduce their environmental impact, and build resilience to climate change (Atta-Aidoo et al., 2022; Mutengwa et al., 2023).

Conservation agriculture is characterised by minimal soil disturbance, permanent soil cover using organic materials, and crop diversification (Kumawat et al., 2023; Tufa et al., 2023). Regional studies comparing CA performance to convention practices have consistently demonstrated numerous benefits, including improved soil structure (Ngwira et al., 2012b; Eze et al., 2020), enhanced water retention (Thierfelder et al., 2015), increased biological activity (Thierfelder et al., 2015), and higher crop yields (Hermans et al., 2020; Tufa et al., 2023). Consequently, both government and international organisations actively promote CSA systems, recognising their potential to improve soil health, increase adaptation and mitigation to climate change and increase the long-term productivity of crops. As such, showing the potential of CSA practices in improving agricultural productivity as well as protecting the soil.

Agroforestry is an agricultural system in which trees, crops, and livestock co-exist on the same land (Musokwa et al., 2019; Gassner & Dobie, 2022). Research has shown that agroforestry systems outperform traditional agricultural and forestry practices in several ways (Gassner et al., 2022; Singh et al., 2023). Primarily, they can increase crop productivity, provide economic benefits and habitat for biodiversity, regenerate soil and water resources while sequestering carbon dioxide from the atmosphere while storing carbon in the soil and promoting vegetation growth (Koech et al., 2020; Zomer et al., 2022). Consequently, agroforestry aligns with the FAO's Four Betters: better production, better nutrition, a better environment, and a better life, leaving no one behind. Hence, agroforestry practices help address global challenges systematically rather than individually. For this thesis, agroforestry refers to an agricultural

system combining macadamia trees with annual crops such as maize, soybeans, tobacco, groundnuts, and livestock in and around farmlands (Figure 1.1).

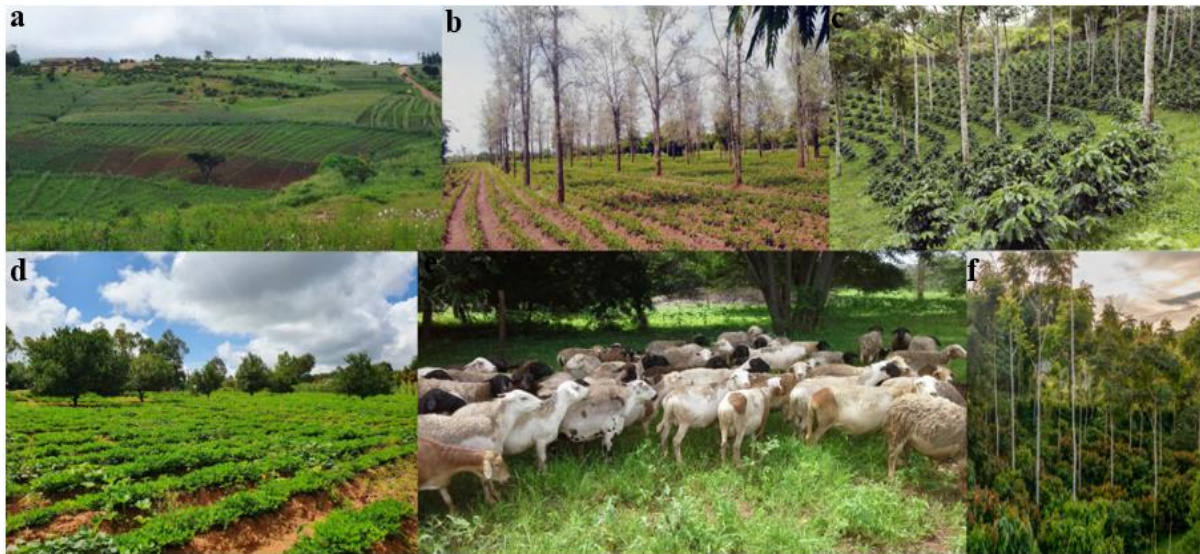


Figure 1.1: a) Nitrogen-fixing biennial crop agroforestry (maize with *Sesbania sesban*); b) *Fardhebia abida* agroforestry; c) coffee agroforestry; d) macadamia agroforestry; e) silvopastoral agroforestry; and f) cacao agroforestry systems in Malawi.

Malawi's agricultural production is mainly oriented toward maize for food and tobacco for exports. Maize accounts for more than 54% of the national caloric intake (Murayama et al., 2017), while tobacco makes up 66% of the nation's agricultural exports (Government of Malawi, 2020; 2022). However, climate change and soil degradation are projected to cause significant reductions in crop yields (Murayama et al., 2017; Jennings et al., 2022). For example, climate change coupled with ineffective agricultural policies is expected to cause annual average reductions in maize, potato, and tobacco of 30%, 29%, and 10%, respectively (CIAT, 2018; Wineman et al., 2022; Jennings et al., 2022). Therefore, Malawi's smallholder farmers must identify alternative and supplemental crops for their resilience and survival.

Recognising the need for farm diversification, the Malawian government and NGOs are advocating for macadamia production as a suitable supplement to the smallholder maize-based diets and as an alternative cash crop to tobacco and tea. The rationale for this recommendation

is that macadamia nuts are highly nutritious, require minimal maintenance, and fetch high market prices (NAIP 2016; NPC, 2022). In addition, macadamia nuts are well-suited to Malawi's climate and can assist smallholder farmers to build resilience to climate change while contributing to sustainable land management (Toit et al., 2017). Hence, promoting macadamia production in Malawi has the potential to diversify the agricultural sector, improve food security, and support smallholder farmer livelihoods.

In light of this, the government of Malawi, in collaboration with other stakeholders, has been implementing several projects to promote the expansion of macadamia production among smallholder farmers in the country. One notable initiative is the Macadamia Smallholder Development Project (MSDP), which commenced in 1996 with funding from the African Development Bank. The MSDP had a clear focus on improving macadamia extension services provided to smallholder farmers, enhancing the construction of essential infrastructure such as warehouses and road access in key areas, and facilitating the development of nurseries to meet the growing demand from smallholders (Toit et al., 2017; Evans, 2021). These concerted efforts proved fruitful, resulting in the successful establishment of approximately 1320 hectares of macadamia under smallholder management (AfDB, 2009; Parshotam, 2018). Furthermore, other initiatives like the Farm Income Diversification Program I (2005) and II (2010) have been implemented to increase smallholder farmer production of macadamia and to diversify their agricultural activities (Irish Aid, 2017; Evans, 2020). These programs aim to create an enabling environment and support smallholders transitioning into macadamia production.

Additionally, to increase production, expand market access, and improve socio-economic outcomes for smallholder macadamia farmers, the government has implemented a range of policy interventions. An illustrative example is the implementation of the National Export Strategy (2016), which designates 60% of smallholder macadamia nuts as grade A. This

classification ensures that smallholder farmers receive higher profits for their nuts, incentivising increased production and quality control. Moreover, the government encourages collaboration by incentivising commercial estate producers to assist smallholder farmers in establishing tree seedling nurseries, sharing knowledge, and providing market opportunities for macadamia nuts. Recently, the government of Malawi has enacted the Agricultural Policies and National Development Plan (Vision 2063), which aims to commercialise smallholder agriculture and promote the production of high-value perennial crops, including macadamia.

Despite significant efforts by the Malawian government and NGOs to promote macadamia production, smallholder adoption of the crop has been relatively slow (Evans, 2020). Parshotam (2018) identifies three primary causes for this low uptake. Firstly, the government's provision of tree seedlings unsuited to growing areas resulted in low yields and poor quality nuts. Secondly, the lack of a structured market outlet for the crop has made it difficult for farmers to sell their produce at fair prices. Finally, a lack of agricultural extension services has meant that farmers lack access to the necessary knowledge and resources to grow the crop effectively. As a result of these challenges, many smallholders have been demotivated from growing macadamia in favour of other, more commercially viable crops like common beans, groundnuts, soybeans, sunflower, and tobacco.

Several NGOs have taken action to address some of the issues demotivating smallholder macadamia farmers. For instance, AgDevCo, Development Aid from People to People (DAPP), and the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) have been distributing macadamia tree seedlings based on recommendations from the Malawian commercial macadamia subsector and have assisted in identifying suitable markets for the nuts from the smallholders. Others, such as Irish Aid and the Business Innovation Facility, have invested in the Malawian macadamia sector to help identify business models that can improve smallholder productivity and access to high-quality export markets (Toit et al., 2017).

The Highlands Macadamia Cooperative Union Limited (HIMACUL) and the Neno Macadamia Trust (NMT) have also been expanding macadamia agroforestry activities in some parts of central and southern Malawi. Despite these opportunities, smallholder macadamia yields and nut quality are still lower than commercial estate producers (Evans, 2008; Zuza et al., 2021a). Evans (2021) argues that commercial producers' higher macadamia nut yields are attributed to careful cultivar selection for the growing areas, extensive use of agricultural inputs, including inorganic fertilisers and pesticides, and substantial investments in irrigation systems.

The interaction of macadamia cultivars with the agroecological zone (AEZ) and climate is crucial in determining the crop's yields and ability to thrive in a given area (Britz, 2015). AEZs are geographical areas with similar climatic conditions that can support rainfed agriculture (Sebastian, 2010). Despite its relatively small size, Malawi has significant agroecological diversity, reflecting the diverse landforms associated with the Great Rift Valley (Benson et al., 2016). Subsequently, the country is classified into three distinct AEZs (Figure 1.2): the Lower Shire Valley, and the Lakeshore plains, the Upper Shire Valley, and the mid-altitude plateau, with the highlands, sometimes considered a fourth agroecological zone (Mutegi et al., 2015). The classification system is based on the differences between the zones in the amount, duration, and variability of precipitation, temperature regimes, elevation, and soil characteristics (Mutegi et al., 2015). This diversity has significant implications for crop production, with different crops and varieties performing better in specific agroecological zones.

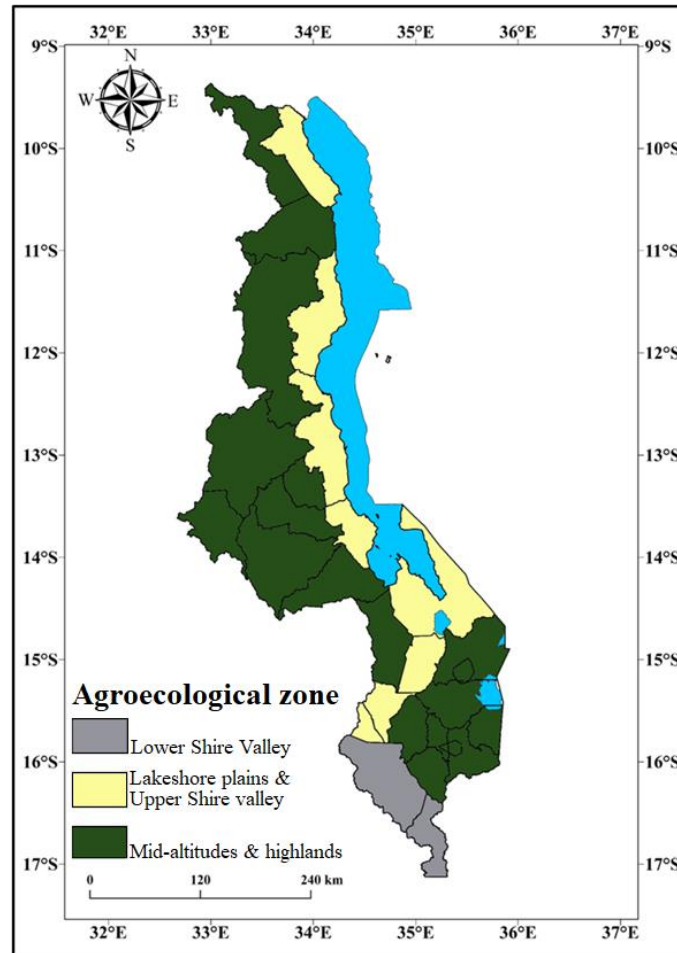


Figure 1.2: Agroecological zones in Malawi.

Certain districts in Malawi have multiple AEZs attributed to significant altitudinal differences in the country. This leads to variations in crop growth, yields, and phenology within the same district. For example, macadamia nut harvesting typically occurs from December to May (Toit et al., 2017). However, in Ntchisi district, differences in altitudinal ranges cause harvesting times to vary among the cooperatives. Malomo cooperative, located at ≤ 1000 m.a.s.l, begins harvesting approximately two months later than Tithandizane cooperative, located at an altitude of ≥ 1500 m.a.s.l, highlighting the influence of altitude on crop phenology.

Furthermore, the yields and quality of macadamia nuts are influenced by cultivar type, tree age, and soil fertility (Chandler, 2018). However, in Malawi, research on the impacts of these factors on crop productivity has primarily focused on smallholder grown staples and cash crops, with little attention to macadamia (Benson et al., 2016; Gashu et al., 2021). Thus, there

is a lack of detailed knowledge on the factors influencing smallholder macadamia productivity. Furthermore, a comprehensive assessment of socioecological factors contributing to macadamia's suitability and long-term management implications are lacking, leading to the low productivity of smallholder-managed macadamia. To address this knowledge gap, this Ph.D research aims to provide a detailed analysis of the factors influencing smallholder macadamia production and productivity in Malawi.

1.2. Justification

Given the numerous benefits of macadamia nuts, the production of the crop among smallholder producers is expected to increase in the country. However, despite receiving government and NGO support, smallholder macadamia productivity is still far from reaching its full potential yields (Makoka, 1991; Toit et al., 2017). A major reason for this is the lack of empirical knowledge regarding the climatic and soil factors that affect the suitability of macadamia production under smallholder rainfed conditions. Additionally, since the 1990s, few studies have attempted to provide land suitability assessment for smallholder macadamia production, citing infrequent data and a lack of funding for the activity (AfDB, 2009).

However, the first step in land use planning is land suitability assessment. A land suitability assessment determines which land use type suits a particular location and includes qualitative and quantitative evaluations (Li et al., 2017). In the qualitative evaluations, information about climate, soil properties, topography, vegetation, and hydrology are considered, and the quantitative assessment includes yield estimates for the various crops, constraints analysis, land capability analysis, land use requirements, and mapping (Taghizadeh-Mehrjardi et al., 2020). Another important factor affecting smallholder macadamia productivity is the scarcity of scientific information on socioeconomic factors influencing smallholder motivations and cultivar preferences. Therefore, this Ph.D research aims to address this research gap.

1.2.1. The overarching research question and specific research questions

Informed by the knowledge gaps summarised in Section 1.1. this thesis asks:

- What are the social, biophysical, and ecological factors influencing smallholder macadamia production in Malawi, and what are the current and projected impacts of climate change on macadamia suitability in the country?

The thesis answers three interconnected specific research questions (RQ):

RQ. 1a. What are the socioeconomic characteristics of smallholder macadamia farmers in Malawi, their farming systems, and preferred macadamia cultivars?

RQ.1b. What challenges hinder smallholder macadamia production in Malawi?

RQ.2a. What are the key climatic factors influencing the area suitability of smallholder macadamia cultivation in Malawi?

RQ.2b. How will climate change impact the current geographical distribution of smallholder macadamia cultivation areas in Malawi?

RQ. 3a. What is the current soil fertility status of smallholder macadamia farms in Malawi?

RQ.3b. How does smallholder macadamia farms' current soil fertility status compare to macadamia nutritional requirements?

1.2.2. Main research objectives and specific objectives

In seeking answers to these research questions, this study aims to achieve the following objectives:

1. To characterise smallholder macadamia farming systems and preferred macadamia cultivars and to identify constraints to nut production in Malawi.

- a. To conduct a baseline survey of smallholder macadamia farmer demographics, farming systems, and motivations for cultivating macadamia.
 - b. To determine factors influencing smallholder farmer preference for various macadamia cultivars.
 - c. To examine challenges encountered by smallholder macadamia producers.
2. To examine climatic factors influencing smallholder macadamia production in Malawi and the potential impacts of climate change on the suitability of the crop.
 - a. To identify climatic factors that influence suitability for smallholder macadamia cultivation in Malawi.
 - b. To assess the present geographical distribution of climatically suitable growing areas for macadamia in Malawi.
 - c. To evaluate the potential impacts of climate change on the future geographical distribution of growing areas for macadamia in Malawi.
 3. To determine the soil fertility status of smallholder macadamia farms in Malawi.
 - a. To assess the chemical and physical properties of soil among smallholder macadamia farms in Malawi.

Based on the above information, Figure 1.3 diagrammatically summarises the study chapters and the specific research questions they address.

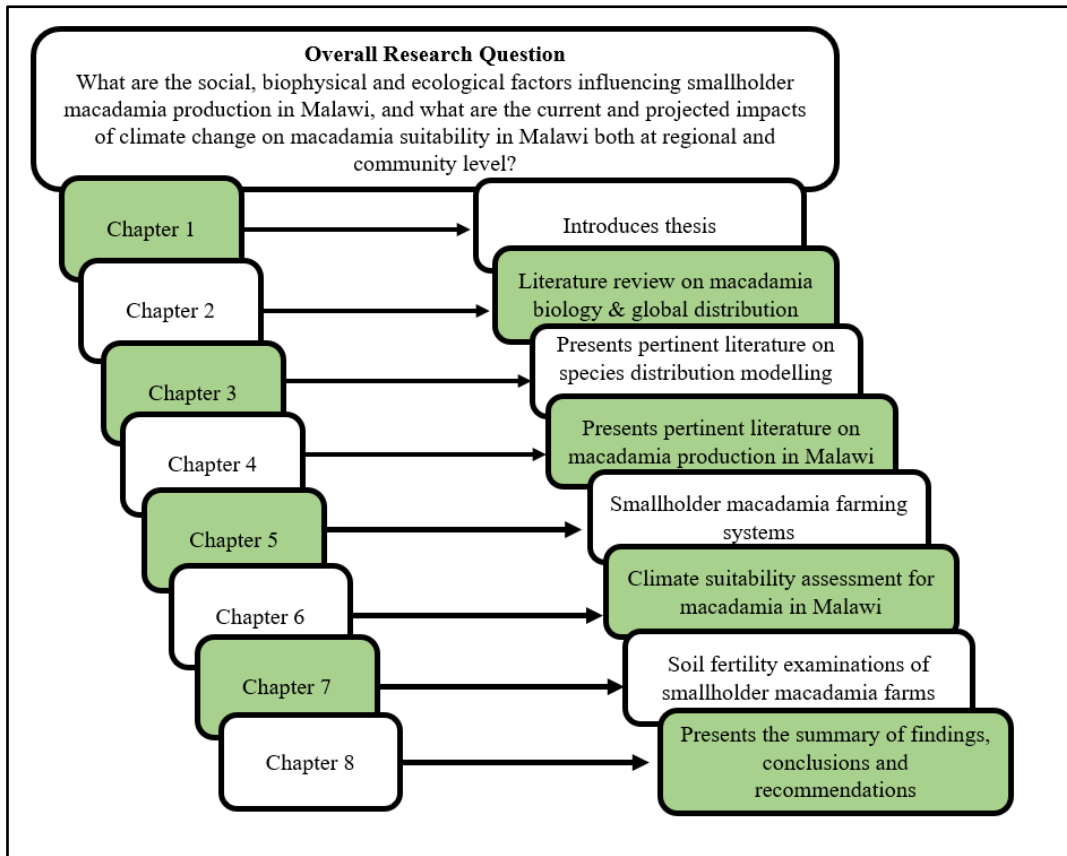


Figure 1.3: Summary of chapters in relation to research questions.

1.3. Research approach

Detailed discussions for each research question and objectives are presented in each standalone chapter.

The research uses mixed methods to provide answers to the research questions. With mixed methods, both 'hard generalisable data' associated with quantitative methods and 'deep, rich observational data' associated with qualitative methods are obtained (Sieber, 1973). Combining qualitative and quantitative methods in this research provides support and a deeper understanding of data triangulation. For instance, qualitative data acquired from structured interviews, focus group discussions, key informants, and field observations are used to corroborate climate model results on climatic factors perceived to be affecting macadamia suitability. Moreover, using mixed research methods reduced the bias and weaknesses associated with a single research method. As a result, the interpretations and conclusions drawn from the results reflect reality.

This research purposively selected seven primary Highlands Macadamia Cooperative Union Limited (HIMACUL) cooperatives as the main focus of the study (Figure 1.4). This is because HIMACUL represents the majority of smallholder macadamia producers in Malawi. Prior to undertaking the fieldwork, ethical approval was received from the Open University Human Research Ethics Committee (HREC/3306/Zuza, Appendix 1). In accordance with ethical requirements, the research questionnaire had an information sheet containing all the basic information about the study. The information sheet was provided to all research participants and explained to those who could not read, so they could decide whether to participate in the study.

Prior to participating in the study, all research participants were provided with a consent form, which they signed to confirm their understanding of the study's objectives, methodology, and willingness to participate (Appendix 2). Participants were informed that their information would be kept confidential and published anonymously in the thesis. The target population was enthusiastic about participating in the study, likely due to the strong relationship between HIMACUL and the Open University fostered by NMT.

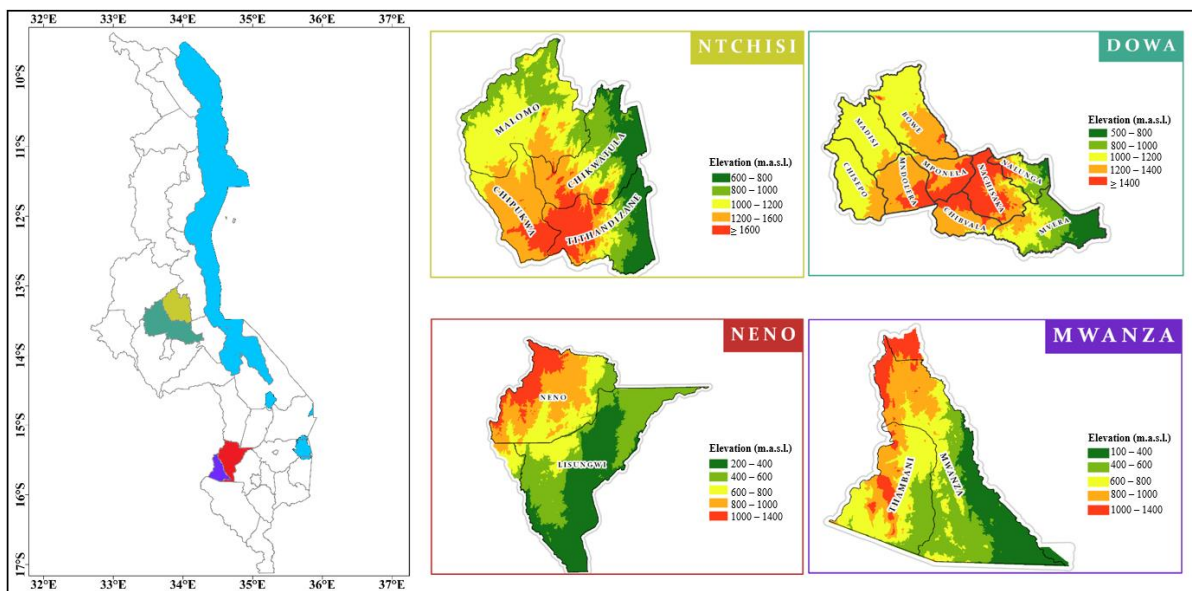


Figure 1.4: Map of Malawi showing the study areas (HIMACUL cooperatives) and elevation.

The first part of the study involved conducting a survey with open and closed questions, which was designed to ensure a representative sample of male and female farmers and young farmers (Appendix 3). By virtue of the sampling method and sample size, the findings from this research can be generalised to other districts in the country with similar economic and cultural practices (Kemper et al., 2003). The second part of the study included focus group discussions (FDGs) with the aim of collecting rich qualitative data that supplemented the survey results, providing a more comprehensive understanding of the research topic. The last part of the socioeconomic study included field observations and informal interviews with the farmers in the seven HIMACUL primary cooperatives.

Data was collected from representative smallholder macadamia farms nationwide to create the climate-suitability model. A total of 120 farms, each containing at least 100 ten-year-old macadamia trees per hectare (ha), were sampled. For the soil nutritional study, 189 soil samples were collected underneath macadamia trees from 63 randomly selected locations among the seven HIMACUL cooperatives.

1.4. Theses outline

The thesis has eight chapters that present the research in a clear and logical manner, covering its purpose, methods, findings, and recommendations. The primary objective of this chapter is to lay the foundation of the thesis.

Chapter 2: The history, biology, and production of macadamia: A literature review.

Chapter Two presents a literature review of the history of macadamia production on a global scale. Then dives into the factors that influence macadamia productivity.

Chapter 3: Species distribution modelling and its applications: A literature review.

This chapter highlights the increasing role and importance of species distribution modelling. It presents general information on the progress toward suitability modelling and the potential

of using it for agricultural applications. Specifically, the chapter demonstrates how species distribution modelling can be applied to land use planning and the identification of important climate factors that influence a species' suitability in a given area. This is crucial because crop suitability in current growing areas is anticipated to change due to the predicted effects of climate change in the near future.

Chapter 4: Macadamia nut production trends and marketing in Malawi: A historical and current perspective on smallholders.

This chapter examines the significance of smallholder macadamia production to the producers and the entire nation of Malawi. The chapter concludes by analysing some of the reported causes for the low macadamia yields among smallholder farmers.

Chapter 5: Socioecological characteristics of smallholder macadamia farmers.

This is the first of the three chapters in the thesis that presents empirical findings from undertaken fieldwork. This chapter answers the first specific objective of characterising Malawi's smallholder macadamia farming systems. The chapter also explores how smallholders utilise macadamia, identifies the causes of tree death, examines the macadamia marketing systems, evaluates access to agricultural extension services, and assesses preference for specific macadamia cultivars.

Chapter 6: Climate suitability predictions for the cultivation of macadamia in Malawi.

This chapter uses species distribution modelling techniques to report findings on the current and future climatically suitable areas for growing macadamia in Malawi under smallholder rainfed conditions. Specifically, the chapter provides information on the environmental variables influencing smallholder macadamia production in Malawi and the impacts of projected climate change on the area suitability of the crop.

Chapter 7: Soil fertility status of smallholder macadamia farms in Malawi.

This chapter assesses soil fertility status in smallholder macadamia farms and analyses the relationship with production. The chapter provides recommendations for soil fertility management practices that can facilitate in restoring the soil healthy.

Chapter 8: Synthesis

The chapter reflects on the results and provides conclusions for the thesis. It also highlights the policy implications of this work and areas for future research. Although this research is grounded in the Malawian context, which could differ from other countries, the findings may still be relevant for other African producing countries. Specifically for the Malawi government, these findings point to areas that must be addressed to ensure that smallholder macadamia production is profitable and sustainable. Figure 1.5 shows how the relationship between the chapters in the thesis.

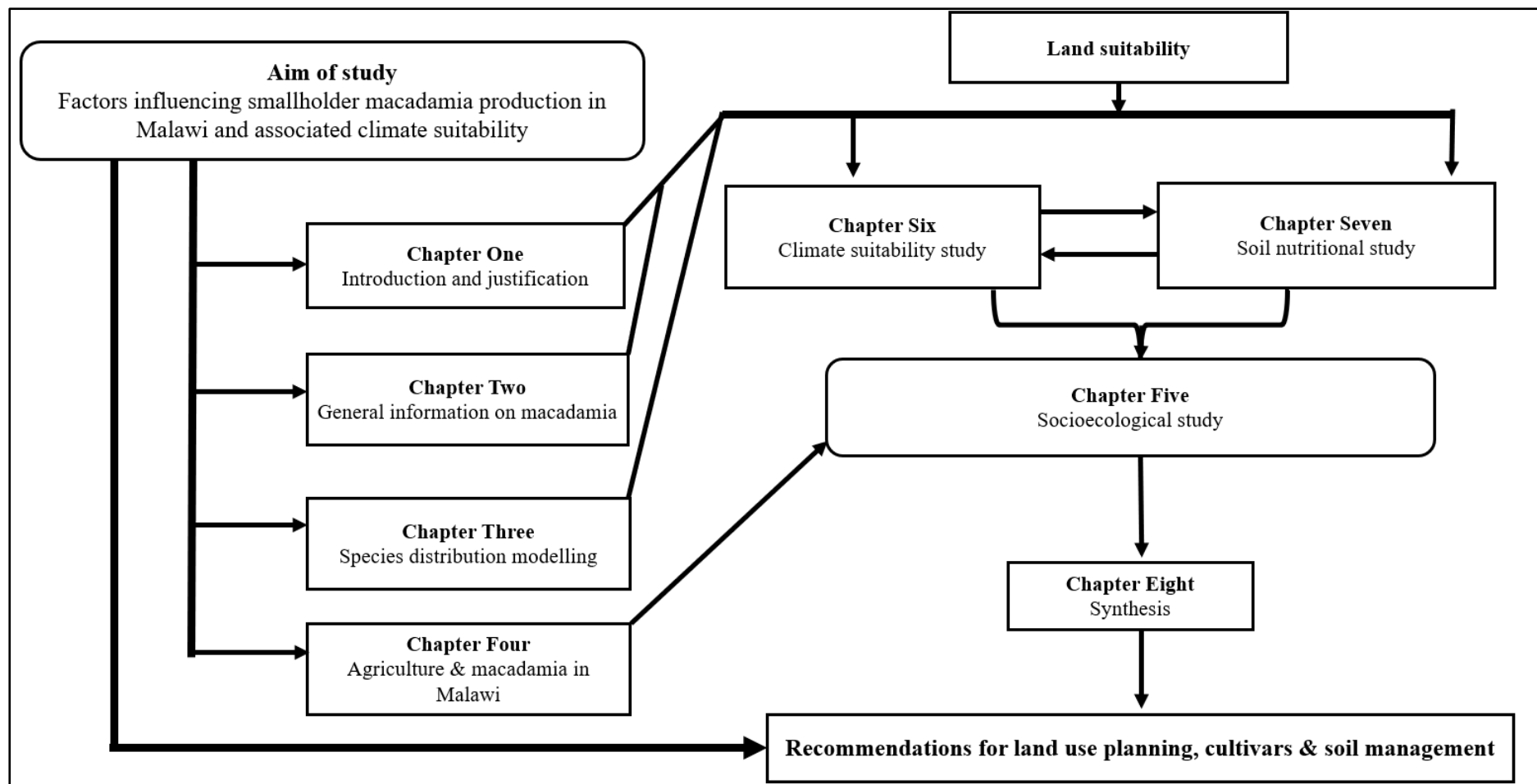


Figure 1.5: Thesis schematic outline.

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CHAPTER TWO: THE HISTORY, BIOLOGY, AND PRODUCTION OF MACADAMIA.

This chapter serves as a synthesis of the background ideas that form the basis for the topic and research questions of this thesis. Firstly, it provides an overview of the current understanding of the biology and ecology of macadamia, including species-specific details where available. Secondly, it explores the influence of both biotic and abiotic factors on macadamia productivity. The chapter concludes by presenting global trends in macadamia production, consumption, and exports. Although the content can be read as a standalone background, its primary objective is to provide context and background information that will aid in interpreting the results presented in the subsequent chapters.

2.1. Origin of macadamia

For centuries before the arrival of Europeans in Australia, the indigenous people of the subtropical eastern coastal rainforest of southern Queensland and northern New South Wales (NSW) were consuming native nuts that grew in the rainforests on the western slopes of the Great Diving Range (Hardner, 2016; Alam et al., 2019). One of these indigenous nuts was called "*gyndi*" or "*jindilli*" in the local languages, later changed to "*kindal*" by early Europeans. Because of their high oil content and taste, *kindal* nuts were much sought after as an essential component of the traditional diet (Moncur et al., 1985). The nut oil was also used as a base for face and body paint and a carrier medium for medicinal plant extracts. Today, this nut is known as the macadamia nut, named by Ferdinand von Mueller in 1857 as a dedication to Dr. John Macadam, who was the Secretary of the Philosophical Institute of Victoria at the time (Hardner et al. 2009).

Despite the plant's Australian origins, the initial large-scale commercialisation happened in Hawai'i (Shigeura & Ooka, 1984), where W.H. Purvis, a sugar plantation manager, made the

first documented introduction of the crop outside its native environment in about 1882 (Hamilton et al., 1983). Since then, commercial macadamia cultivation has spread globally, with major producers including Australia, Brazil, China, Colombia, Costa Rica, Guatemala, Hawai'i, Kenya, Malawi, and South Africa (INC, 2022). There are also expanding industries in Argentina, Fiji, Jamaica, Mexico, Mozambique, Nepal, New Zealand, Swaziland, Tanzania, Venezuela, Vietnam, and Zimbabwe (Figure 2.1).

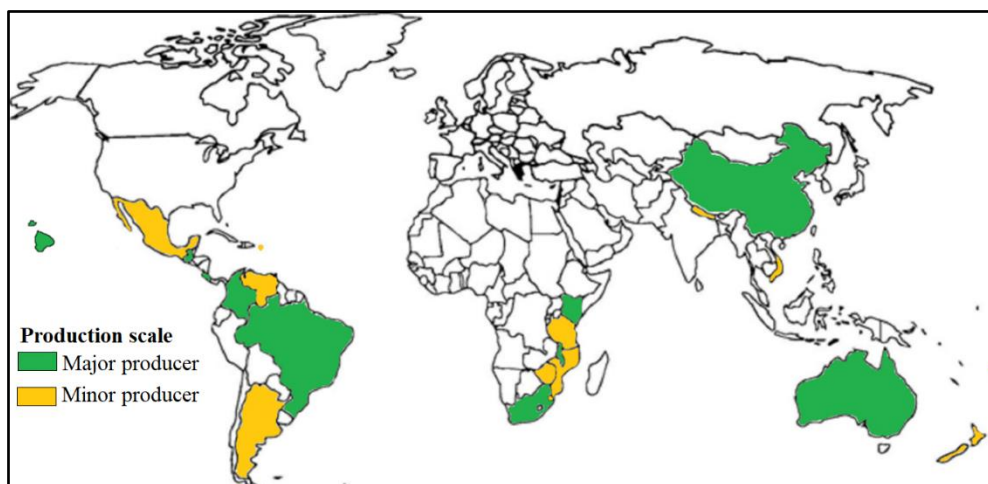


Figure 2.1: Global macadamia growing areas (Based on INC, 2022)

2.2. Botanical classification

Macadamia belongs to the *Proteaceae* family, subfamily *Grevilleoideae*, and tribe *Macadamieae* (Nagao et al., 1994). Eight macadamia species have been described, six of which are native to Australia and two to the Indonesian island of Sulawesi (Nagao et al., 2019). *Macadamia tetraphylla* and *Macadamia integrifolia*, indigenous to Australia's east coastal rainforests, produce edible kernels (Mai et al., 2020). Hybridisation between the two species occurs freely, which is an essential source of variability for macadamia cultivar selection (Wasilwa et al., 2019). The other macadamia species are inedible due to high concentrations of cyanogenic glucosides, which are toxic to humans and livestock (Castada et al., 2020; Nyirenda, 2020). The subsequent sections provide a concise overview of each macadamia species, emphasizing their attributes. However, the primary focus of this study is *Macadamia integrifolia*, which is widely cultivated for consumption and commercial purposes.

2.2.1. *Macadamia integrifolia*

M. integrifolia, the primary commercial species of macadamia, is native to southeast Queensland (Nerang River, Beechmont, and Mount Bauple). It is widely grown worldwide due to its high oil content and taste (Coleman, 2005). Among the many cultivars of *M. integrifolia*, two of the most popular are the Australian Hidden Valley (HV A) and Hawai'i Agricultural Experimental Station (HAES) cultivars, which are identified using alpha-numeric suffixes such as HV A4 and HAES 660. Their superior nut quality and high yield make them highly sought-after by growers and consumers. However, the South African macadamia industry has recently developed its own hybrid cultivars, including Beaumont and MCT1.

2.2.2. *Macadamia tetraphylla*

M. tetraphylla is indigenous to the Clarence River region of northern New South Wales and the Coomera River region of southeast Queensland (Nagao & Hirae, 1992). Tree seedlings of this species are primarily used as rootstocks for *M. integrifolia* cultivars due to their ability to withstand extreme environments, such as lower temperatures ($\leq 5^{\circ}\text{C}$), than other species. Despite its adaptability, this species has not been widely utilised commercially, likely due to the varying levels of oil (65–75%) and sugar (6–8%), which makes it challenging to achieve a consistent colour during roasting. Table 2.1 shows the key distinctions between *M. tetraphylla* and *M. integrifolia*.

2.2.3. *Macadamia ternifolia*







M. ternifolia is a species native to southeast Queensland's Pine and Kin Kin rivers (Bryen et al., 1998). The species produces small-sized, intensely bitter nuts, making them inedible (Cyanide et al., 2020). The species are characterised by round, small smooth shells, three leaves with spiny margins to each node, and pink flowers.

2.2.4. *Macadamia janseni*

This threatened species is found only in Australia, with only sixty individuals recorded (Akhtar et al., 2006). *M. janseni* is similar to *M. ternifolia* but has larger nuts and is native to Miriam

Vale in south Queensland. Its main characteristics are small and smooth nuts, three leaves from the same node with smooth margins, and the flowers can either be green or pink.

Table 2.1: Differences between *M. tetraphylla* and *M. integrifolia*.

Plant part	<i>M. tetraphylla</i>	<i>M. integrifolia</i>
Leaves	<ul style="list-style-type: none"> • Three to four leaves per node. • The colour of young leaves is reddish/pink or green. • Leaves are 40–30 cm long. 	<ul style="list-style-type: none"> • Three leaves per node. • The colour of young leaves is light green. • Leaves are 20–30 cm and have few spines. 
Flowers	<ul style="list-style-type: none"> • Pink. 	<ul style="list-style-type: none"> • Cream white. 
Fruit	<ul style="list-style-type: none"> • The seed coat is rough and pebbled. 	<ul style="list-style-type: none"> • The seed coat is smooth. 
Kernels	<ul style="list-style-type: none"> • 65–75% oil, 6–8% sugar. 	<ul style="list-style-type: none"> • 80% oil, 4% sugar.

2.2.5. *Macadamia claudieana*

M. claudieana is only found in the Iron Ranges of north Queensland. The nuts are soft and edible. However, the commercialisation of the species has not yet been promoted (Coleman, 2005).

2.2.6. *Macadamia grandis*

This species is originally from northeast Queensland and has not been commercialised (Powell et al., 2014). *M. grandis* has small soft nuts, six leaves from the same node, and creamy

flowers. The Australian government has declared the status of this species as "vulnerable" (Environment Protection and Biodiversity Conservation Act, 1999).

2.2.7. *Macadamia whelanii*

This macadamia species is native to the tropical Sulawesi islands in Indonesia (McConachie, 2009). The nut has a bitter taste and is considered unsuitable for consumption. *M. whelanii* has a big nut twice the size of *M. integrifolia*, five leaves originate from the same node, and the flowers are creamy.

2.2.8. *Macadamia hildebrandii*

This is one of the two macadamia species native to the Sulawesi islands (McConachie, 2009). The species has fire retardant leaves and can grow in nutrient poor areas due to a higher germination power. *M. hildebrandii* is characterised by having a big nut, and inside, they look like an avocado seed, and four leaves originate from the same node.

2.3. Morphology and phenology of Macadamia

The morphology and phenology of macadamia trees are central factors that influence macadamia productivity. The following section examines macadamia tree morphology and phenology and how these affect productivity. This information is important because it provides insights into the ability of the crop to absorb nutrients, water, and sunlight that are crucial for growth and development. Additionally, understanding the phenology of the crop, including flowering, fruiting, and maturity periods, enabled the researcher to evaluate its adaptability to different climates and identify the key factors influencing its growth used in Chapter Six for the climate suitability modelling.

2.3.1. Structure and habit

Commercial macadamia cultivars grown under ideal management conditions may attain a height of over 20 metres (m) with a spread of 15 m at 20 years (Hardner et al., 2009).

Depending on the cultivar, the canopy may be open or dense with upright or spreading forms and single or multiple stems. Mature leaves are sclerophyllous (Figure 2.2b), which allows them to resist collapse after turgidity loss caused by moisture stress; thus, macadamia leaves do not display stress until it is excessive and irreversible (Muthoka et al., 2008).



Figure 2:2: Structure of a ten-year-old *M. integrifolia* tree and leaves growing in Tithandizane cooperative, Malawi.

2.3.2. Flowers

Macadamia trees produce large amounts of flowers; however, only a small proportion, approximately 30%, develop into mature nuts, predominantly due to growing conditions, weather, pollination, and pests and diseases (Pichakum et al., 2014; Nagao et al., 2019). Macadamia flowers are borne in clusters on pendant racemes, typically with between 200 to 400 flowers on a single raceme (Figure 2.3). Racemes are typically produced on mature, less vigorous, shorter stems (Trueman, 2013). An individual flower comprises four perianth lobes with interlocking margins and four stamens opposite and attached to the perianth lobes (Nagao et al., 2019). The pistil consists of an ovary with two ovules and a long style with a small area containing stigma and papilla cells at the tip. Additionally, macadamia flowers are protandrous, meaning the anthers release pollen before the stigma becomes receptive (Queensland Government, 2004a). As such, cross-pollination is key to macadamia yields.

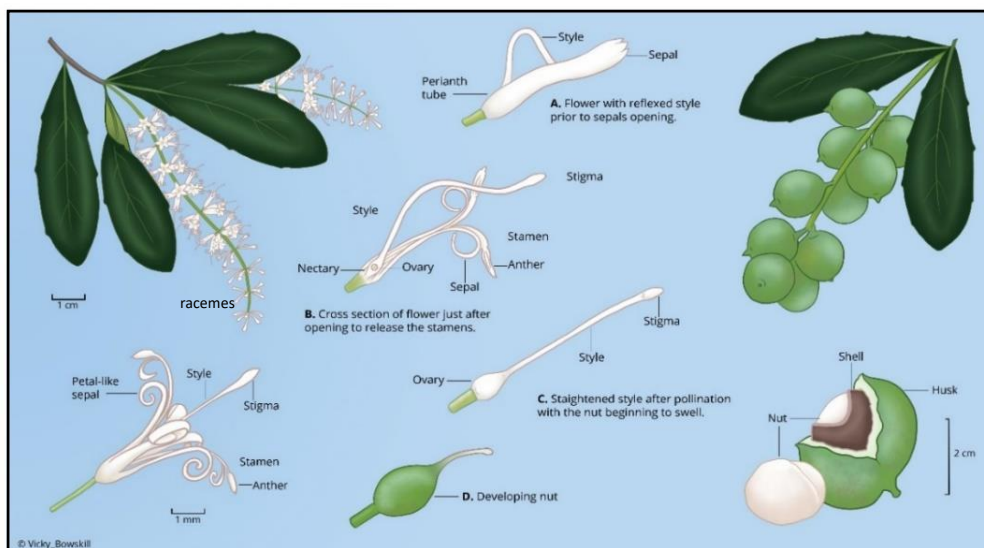


Figure 2.3: A schematic diagram of macadamia floral parts.

2.3.3. Fruit

The macadamia fruit (nut) ranges in size from 1.2 to 2.5 cm and comprises an embryo (nut or kernel), testa (shell), and a pericarp (husk). The nut is connected to the shell by the micropyle, and the shell is connected to the raceme by the pedicel. Following fertilisation, the ovule, nut, and endosperm proliferate (Follett et al., 2009). The nut is covered by a green husk that opens along one suture line from the stalk to the distal end enclosing a single spherical seed with a very hard shell (Yang, 2009). Nuts are borne in a cluster on a single raceme (Figure 2.3). Mature nuts fall off the raceme and drop to the ground with approximately 20 to 30% moisture, which is removed by drying the nut in shell (NIS) under a controlled atmosphere before cracking (Rockle et al., 2019). Initial drying of the nuts to below 10% is recommended to avoid kernel damage and quality loss due to fungal contamination.

2.3.4. Vegetative growth

Macadamia growth and productivity depend on the amount of photosynthetically active radiation (PAR) the trees intercept through their canopies. The leaves convert radiant energy to carbohydrates that are accumulated or used for the tree's seasonal growth and maintenance (Hwang, 1991). The accumulated carbohydrates are stored within the tree in autumn and

summer (Stephenson et al., 2003). During winter and spring, the tree draws on the stored carbohydrates due to insufficient carbohydrate production through photosynthesis to meet the high demands of nut growth and oil accumulation (Stephenson et al., 2003). Developing nuts are strong sinks with high energy demand, as macadamia kernels contain 74% or more oil. Thus macadamia trees require adequate carbohydrate reserves to meet the high energy demands required for oil accumulation (Rengel et al., 2015).

Macadamia trees periodically produce new flushes (leaves) to balance vegetative and reproductive growth for consistent nut production (Wilkie et al., 2010). New flushes are essential for future bearing stems and the leaves as the photosynthesizing source to sustain the crop (Trochoulias & Lahav, 1983). Perdoná & Soratto (2015) found that macadamia leaves are most productive after reaching full size. Subsequently, a macadamia tree must grow new flushes each season to remain healthy and productive. However, during oil accumulation, the flushes become temporarily dormant (McFadyen et al., 2013a). The timing of flush dormancy is critical because immature flushes later in the development phases inhibit raceme production (Nagao et al., 2019).

Vegetative flushing is influenced by temperature and water availability (Pichakum et al., 2014). Major flush growth occurs when temperatures are generally mild, with mean and maximum threshold temperatures ranging between 10 and 30°C (Borompichaichartkul et al., 2009; Pichakum et al., 2014). In contrast, low temperatures ($\leq 10^\circ\text{C}$) result in reduced flush growth (Pichakum et al., 2014). Temperature increases from 15 to 25°C increase tree and nut growth and dry matter production (Trochoulias & Lahav., 1983). Wilkie et al. (2010) reported that flush development decreases as temperatures approach 30°C. As such, investigating the role temperature plays in macadamia growth and development is particularly important for this study because it helps in evaluating the areas suitable for the crop, i.e., current and future geographical areas.

Water stress is another factor that inhibits the vegetative growth of macadamia. Mayer et al. (2006) in their study imposed water stress on macadamia trees during the normal vegetative growth periods and found delayed flush growth until after re-watering the trees. This shows that moisture stress and hotter temperatures during the critical phenological stages of macadamia negatively impact productivity. Understanding this relationship is of utmost importance for the climate suitability modelling study (Chapter Six), particularly in light of the anticipated temperature rises and extreme precipitation events expected in Malawi by the 2050s.

2.3.5. Floral induction to nut maturity

Floral initiation (flower bud formation) is an important component of macadamia production. This is because it influences raceme growth and subsequent macadamia yield potential (Hancock, 1991; Wilkie et al., 2010). Floral initiation is influenced by various factors such as temperature, light, and nutrition. However, floral initiation is temperature sensitive and varies depending on the cultivar and growing location (Moncur et al., 1985, Hancock, 1991). For example, in Malawi and Hawai'i, macadamia floral initiation occurs at warmer night temperatures of 15 to 20°C (Moncur et al., 1985; Britz, 2015). In contrast, floral initiation in Australia occurs under shortening day length conditions at cooler temperatures between 11 and 15°C (Wilkie et al., 2010).

Floral initiation is followed by bud dormancy (Moncur et al., 1985). This dormancy is broken by a combination of warmer temperatures and light rains (Allemann & Young, 2006). The time between floral initiation and anthesis can vary depending on the cultivar and environmental conditions but may range from 137 to 155 days (Britz, 2015). Nonetheless, macadamia flowers are self-incompatible and require insects for efficient pollination (Howlett et al., 2015). According to Tavares et al. (2015), the pollen tube requires up to seven days to reach the ovary. Pollination of the flower is completed when the ovary is fertilised and one ovule starts to develop.

The fruit structures (husk, shell, and endosperm) are formed during the first 100 days after flowering (Jones & Shaw, 1943). Rapid nut development occurs about two weeks after pollination and lasts 16 weeks until the shell hardens (Pichakum et al., 2014). No growth occurs after the shell hardens, and only physiological changes occur within the shell. Growth occurs as a single sigmoidal pattern with a rapid increase in flesh weight about six weeks after anthesis, continuing until 18 weeks (Hancock, 1991). Rapid oil accumulation in the macadamia nuts occurs between 100 to 190 days after flowering, depending on the production region and cultivar (Herbert et al., 2019). The maturity of the nut is achieved when it reaches 72% or more oil content. Warm and moderate climatic conditions hasten maturity, while temperate conditions delay maturity (Herbert et al., 2019).

Flower and fruit abscission continues from anthesis to maturity in three distinct periods. The first abscission period is due to the fall of unfertilised flowers during the first two weeks after anthesis, which may account for over 90% of the flowers (McFadyen et al., 2013b). The second abscission, referred to as the juvenile nut drop, occurs four to eight weeks after anthesis, and over 80% of the initial small immature nuts that set may drop. The third abscission occurs when larger immature nuts drop gradually over a period of nine weeks until maturity at 30 weeks (Refki, 2019). An example of the cyclic, seasonal stages of macadamia development in Malawi is shown in Table 2.2.

Table 2.2: General stages of macadamia development in Malawi.

Month	Development stage
May	Floral initiation
June to August	Flowering
August to September	Fruit set
September to October	Early nut fill
October to December	Late nut fill and shell hardening
December to March	Oil accumulation and harvesting
January to April	Harvesting

Adapted from Carr, 2013.

2.4. Macadamia nut yield and yield components

Macadamia nut yield and yield components are described using kernel recovery, whole kernel recovery, and kernel discoloration.

2.4.1. Kernel recovery

Kernel recovery (KR) refers to the number of nuts obtained from the NIS following shell removal. It is calculated as a percentage of the nut's weight at 1.5% moisture content (MC), with the remainder being the shell (O'Connor et al., 2019). KR is determined by the nut's size, shell thickness, weight, and the shell. Larger nuts contain more kernel than smaller nuts with the same shell thickness. As such, KR is an essential element of the economic profit of macadamias (Wilkie et al., 2010; Bouarakia et al., 2023). The minimum annual acceptable kernel recovery per tree at a mature age (ten years or more) is 33.5 kg tree⁻¹ in favourable regions and 20 kg tree⁻¹ in less desirable areas (Britz, 2015). However, this is under better orchard management practices.

2.4.2. Whole kernel recovery

Macadamia nuts have different sizing styles, including wholes, halves, and pieces (Alam et al., 2019). The weight of each style is expressed as a percentage of the total nut weight. Thus, whole kernel recovery is the weight of first-grade nuts recovered from a weighted NIS and is expressed as a percentage (Radspinner, 1970).

2.4.3. Kernel discolouration

Macadamia kernel discolouration is a disorder in which part or all of the nut's basal portion is stained brown to black (Britz, 2015). In severe cases, the stain is dark over the entire basal part of the nut (Evans, 2020). Commercial nuts with discoloration fall in the second-grade category and are sold at lower prices. Therefore, nut quality (discoloration, visual imperfections, damage, and defective) is an essential determiner of macadamia prices. This is because costs

per unit acceptable kernel increase with the commercial grade kernel (Britz, 2015). Other forms of damage that affect kernel quality include insect damage, fungal contamination, nutritional defects, and immature nuts.

2.5. Climate factors influencing macadamia nut yields

Macadamia productivity is affected by a variety of factors, including spacing, age, and cultivar, as well as soil fertility, topography, insect pests, diseases, and management practices. However, the year to year variation in crop yield is predominantly influenced by climatic factors experienced in the year prior to harvest (Chandler, 2018). Weather factors affect several production related variables, including total yield, kernel recovery, nut quality, style distribution, and profitability. For example, climatic conditions in the macadamia growing regions of Australia are the primary reason for the poor performance of Hawai'ian cultivars, leading to lower yields and unpredictable nut quality (Cull et al., 1986). In Australia, Hawai'ian cultivars produce an average yield of 20 kg of nuts tree⁻¹ compared with 45 kg of nuts tree⁻¹ in Hawai'i. Generally, this is not unexpected as the Hawai'ian cultivars were selected under totally different climatic conditions than those in Australia (Aradhya et al., 1998).

A similar phenomenon has been reported in Malawi, where macadamia nut yields have been as low as 10 kg of nuts tree⁻¹ among smallholder producing areas and 30 kg of nuts tree⁻¹ among commercial estate producers (Makoka, 1991). The low yields and poor quality reflect crop-climate interactions (Eed et al., 2016). This demonstrates that macadamia yield and suitability are subject to a robust cultivar-environment interaction. Currently, no research in Malawi has explored the potential impacts of climate on macadamia growth and productivity under smallholder management systems (Eed et al., 2016). However, it is known that temperature, precipitation, wind, and solar radiation, have the biggest impact on macadamia growth and productivity (Stephenson et al., 2003). Therefore, understanding how these climate factors affect different macadamia cultivars is crucial for increasing smallholder macadamia productivity in Malawi. Furthermore, knowledge of the climatic factors helps in identifying suitable areas for macadamia production and informs recommendations for soil management.

2.5.1. Temperature

Temperature plays a crucial role in the growth and development of plants. Individual plant species have specific temperature ranges within which they can survive and reproduce, represented by minimum, optimal, and maximum temperatures (Hatfield & Prueger, 2015). Perennial crops have a more complex relationship to temperature than annual crops. Hatfield & Prueger (2015) report that many perennial crops have varying temperature thresholds for their phenological events. Higher temperatures above 30°C increase vegetative and reproductive growth in lychees (Menzel & Paxton, 1985), atemoya (Ojeda et al., 2004), and mango (Whiley et al., 1989). Contrarily reduced vegetative growth and reproduction due to higher temperatures ($\geq 30^{\circ}\text{C}$) is reported in avocado pears and macadamia (Trochoulias & Lahav, 1983).

Macadamia is a subtropical crop with a relatively narrow temperature range for growth and development (Moncur et al., 1985). Powell (2009) describes a diurnal temperature envelope for growing macadamia between 14 and 28°C, with optimal growth occurring between 25 and 27°C. Conditions become damaging for the crop when temperatures fall below 1°C or rise above 30°C (Radspinner, 1970). Additionally, macadamia is extremely susceptible to frost damage, especially in younger trees. Hardner et al. (2009) observed that younger trees under three years are more susceptible to frost damage, while trees five years or more old appear to be better able to tolerate frost (Barrueto et al., 2018a). Thus, frost may have little or no effect on mature trees but will damage or kill seedlings. For this reason, macadamia species are unlikely to be found in otherwise suitable areas but routinely incur temperatures below freezing for more than short durations. This is more pronounced in countries that experience very cold winters.

Macadamia is also sensitive to temperature regimes at critical periods related to reproduction (Nagao & Hirae, 1992). Research has shown that small variations in night temperature can

greatly impact the flowering intensity and duration of the flowering season. Nagao et al. (2019) found that low night temperatures (12–14°C) stimulate flower initiation. Pichakum et al. (2014) revealed that the net photosynthesis of macadamia is at a maximum between 16–25°C, and these temperatures also induce raceme formation. Primary vegetative growth is induced with temperatures ranging from 20–30°C (Nagao, 2011). On the other hand, lower diurnal temperature ranges (6–10°C) can slow macadamia vegetative growth, delaying the flowering and fruiting stages, consequently, the nut yields (Stephenson & Gallagher, 1987).

Higher temperatures greater than 30°C are associated with excessive water loss within the macadamia plant (Stephenson & Gallagher, 1986). Excessive water loss results in a disproportional supply of nutrients within the macadamia nut, thereby restricting oil build-up and negatively affecting the nut quality (Britz, 2015). Stephenson & Gallagher (1986) found that kernel recovery in Australia was highest (45%) at 30°C, while very hot temperatures greater than 35°C reduced the kernel recovery by 17%. In a similar research, Perdoná & Soratto (2015) noted that excessive water loss induced by higher temperatures resulted in the loss of racemes and reduced nut retention, leading to lower macadamia yields. This is also consistent with studies from Hawai'i, Malawi, and South Africa, which found that higher temperatures during the early oil accumulation phase were the most critical factor impacting KR (Cull et al., 1986; Britz, 2015). Consequently, temperatures above 30°C adversely affect macadamia KR, oil accumulation, and nut growth.

However, macadamia cultivars can adapt to different temperature ranges depending on the country and the specific locality in which they are grown (Nagao & Hirae, 1992). To date, research on the influence of temperature on macadamia growth and yields has been extensively conducted in major growing areas of Australia, Hawai'i, Malawi, and South Africa under intensive production systems (Hamilton et al., 1983; Wilkie et al., 2010). However, little is known about the temperature variables that influence macadamia productivity under

smallholder farming systems in Malawi. This is possibly why smallholder macadamia yields are still very low per hectare. Therefore, understanding the effects of different temperature variables is vital for cultivar recommendations in an area, as this affects suitability and crop yields.

2.5.2. Precipitation and soil moisture

Macadamia trees thrive in areas with distinct wet and dry seasons (Evans, 2021). Macadamia trees generally require a minimum annual precipitation of 1000 mm for optimal nut growth and yields, with higher water requirements during flowering and fruiting stages (Hardner et al., 2009). Macadamia trees can also tolerate periods of drought due to their hardened leaves and proteoid roots (Hamilton et al., 1983). However, it is recommended not to grow macadamia in areas that receive less than 900 mm of precipitation annually (Perdoná & Soratto, 2015). Irrigation is uncommon in regions such as Hawai'i, Australia, Kenya, and Malawi, where annual precipitation is high (Stephenson et al., 2003). However, insufficient precipitation in Mpumalanga, South Africa, requires an extra 700 mm of irrigation water per season for optimal macadamia yields (Allan, 2007).

Water stress has different effects on macadamia productivity at different phenological stages. Stephenson et al. (2003) noted that water stress due to droughts during the nut maturation period decreased the kernel recovery and nut quality of macadamia, which was correlated with the reduction in photosynthesis. In areas with unreliable precipitation, early nut drops in macadamia occur, resulting in decreased crop yields (Nagao et al., 1994). This is a serious challenge for smallholders in Malawi, whose most critical crop phenological stages coincide with the dry season (May – October) (Zuza et al., 2021b).

Excessive precipitation negatively impacts macadamia kernel recovery and quality (Stephenson et al., 2000; Taylor et al., 2018). Prolonged periods of wet weather can lead to

increased levels of pre-harvest sprouting in macadamia nuts, which can reduce the overall kernel yield and cause discolouration (Stephenson et al., 2000; Stephenson et al., 2003). (Hardner et al., 2012; Britz, 2015). To minimise the impact of wet weather on their crop, farmers can implement appropriate management strategies such as ensuring proper orchard drainage, harvesting mature nuts as soon as possible after they have fallen to the ground, and applying organic mulch around the base of trees (Hancock, 1991; Penter, 2008; Bouarakia et al., 2023). It is also advisable for farmers to adopt macadamia cultivars that are more resistant to wet weather conditions, such as cultivars with good drainage characteristics and good sprouting resistance. Examples of cultivars well-suited to areas with heavy precipitation and humidity include HAES 508, HAES 788, A16, and Beaumont (Allan, 2007).

Individual macadamia cultivars have unique water requirements depending on the growth stage (Carr, 2013). In South Africa, the variety HAES 741 requires 40–55 litres (L) tree⁻¹ day⁻¹, which is 10–30% more water than HAES 344 (35–40 L tree⁻¹ day⁻¹), from the end of flowering to nut maturity for optimal yields (Britz, 2015). In contrast, trees of both cultivars require 20–30 L tree⁻¹ day⁻¹ during the vegetative period in Australia for optimum yields. Nonetheless, water requirement studies for macadamia cultivars are still very scarce globally. Therefore, for optimum yields of macadamia cultivars in specific areas, it is essential to consider how they respond to water availability at different phenological stages, particularly under rainfed conditions like those found in Malawi.

2.5.3. Wind

Wind can positively and negatively impact macadamia growth and yield depending on the intensity and duration of the wind exposure. For example, wind can promote better air circulation around the tree canopy, which can help to reduce the risk of diseases, especially those caused by fungi (Britz, 2015). However, macadamia trees are susceptible to wind damage due to their weak root structure (Quinlan, 2005). Strong winds can cause trees,

flowers, and nuts to fall, leading to complete yield loss. Radspinner (1970) reported that hurricanes Dot and Nina caused substantial damage to macadamia orchards in Hawai'i, resulting in lower yields than expected in those years. In Malawi, the seasonal Chiperoni winds occurring between May and July cause significant yield losses ranging from 15% to 30% (A. Emmott, pers. comm). Therefore, it is necessary to use windbreaks to protect the trees. Once the trees form dense hedgerows, they can provide mutual protection, eliminating the need for windbreaks (Queensland Government, 2004a).

2.5.4. Altitude

Altitude plays a significant role in plant health and growth (Mbiriri et al., 2018). Altitude can impact the type and amount of light plants receive and affects the temperature, moisture, and soil nutrients available to the plants (McDaniel, 2017). As a result, some plant species are adapted to grow well in high altitudes, whereas others grow at middle or lower altitudes. The ideal altitude for growing macadamia depends on the location, with optimal altitudes ranging between 700–3000 m.a.s.l (Hancock, 1991). In general, macadamia trees tend to perform better at higher altitudes due to several factors:

- i. Higher altitudes are typically associated with cooler temperatures, which is beneficial for macadamia trees. This is because cooler temperatures slow down the rate of water loss from the trees, reducing the water stress that can occur during hot and dry periods, especially in low-lying areas.
- ii. Higher altitudes are associated with reduced disease pressure, so some diseases affecting macadamia trees are more prevalent at lower altitudes, including *Phytophthora* root rot, macadamia mosaic virus, and macadamia leaf blight. Moreover, at higher altitudes, the cooler temperatures and reduced humidity levels help reduce the incidence and severity of these diseases, leading to healthier trees and higher yields.

- iii. The growing season for macadamia trees is also extended at higher altitudes due to the cooler temperatures. This longer growing season can provide more time for the trees to develop and produce nuts, leading to higher yields.

In Costa Rica, macadamia is successfully grown at 700–1500 m.a.s.l., in Guatemala at 750–1600 m.a.s.l., and in Malawi at 800–2000 m.a.s.l. (Hancock, 1991), and in Nepal, between 1000–3000 m.a.s.l (Barrueto et al., 2018a). However, in Hawai'i, macadamia grown in lower altitude areas ranging from 700–830 m.a.s.l. result in thick shells and decreased nut yields, attributed to cloud cover that delays flower development (Barrueto et al., 2018a). Similarly, the high-altitude areas of Mphompha (≥ 2500 m.a.s.l.) in northern Malawi have been reported to be the cause of the low macadamia yields, which have been linked to colder temperatures ($\leq 5^{\circ}\text{C}$) and excessive cloud cover (Evans, 2008). Pichakum et al. (2014) reported similar findings in Thailand, where an increase in altitude results in a decrease in macadamia yields, attributed to the reduced number of flowers per raceme due to cold weather conditions. A recent study in Limpopo province, South Africa, has also shown that excessive rainfall in higher altitude areas negatively affects the kernel recovery of macadamia (Bouarakia et al., 2023).

These studies reveal that altitude impacts macadamia yields due to its indirect influence on temperature and precipitation. Therefore, the influence of altitude on temperature and precipitation changes needs to be examined to understand its impact on macadamia suitability. In Malawi, limited studies have been undertaken to explain the suitability of macadamia in relation to altitude. Therefore, such a study is vital for sustainable macadamia production and land use planning.

2.5.5. Solar radiation

The row orientation of a macadamia orchard is known to influence the tree's light interception, an important factor for photosynthesis, affecting tree yields (Britz, 2015). For example, trees in a North-South row direction at latitude 43°N can receive up to 40% more radiation than in the East-West row direction (Evidence, 2016). In Australia, macadamia trees facing the sun

on the northern side produce more vegetative flushes in autumn and summer than on the southern side (Cull et al., 1986). Similarly, Boyton & Hardner (2002) found a higher nut set on the northern side of trees in Australia. McFadyen et al. (2004), using a linear regression model between yield and tree volume, showed increased macadamia yields as light interception increased.

2.6. Non-climatic factors influencing macadamia yields

2.6.1. Soil fertility

Soil fertility is an important factor that directly affects macadamia tree growth and the ability to produce nuts. Macadamia trees are adapted to a wide range of soils but perform best on well-drained soils with high amounts of organic matter (Quinlan, 2005). Although the crop thrives in rocky terrain and steep hillsides, slopes of $\leq 15\%$ are preferable. Avoiding steep slopes to reduce the risk of soil erosion is also advisable. Heavy clay soils are unsuitable for macadamia cultivation because they are prone to waterlogging during extended rainy seasons, resulting in root infections and tree mortality caused by insufficient aeration (Queensland Government, 2004b).

Correct soil nutrition is vital for macadamia production. In Australia, Aitken et al. (1990) found that an inadequate supply of essential nutrients results in nutritional disorders within macadamia trees. Nutrient imbalance in macadamia trees results in increased floral abortion, contributing to yield losses (Stephenson et al., 1997). Consequently, for optimal growth and yields, macadamia trees require a soil pH range of 5–6, adequate levels of soil organic matter (SOM), and essential nutrients (Cull et al., 1986; Bright, 2018).

Macadamia trees are sensitive to soil nutrient levels. Studies have shown that macadamia trees respond well to increases in soil nutrients (Stephenson et al., 1997; Zhao et al., 2019). However, the trees do not respond to nutrient levels above their requirements and may even

show negative impacts at high levels for some nutrients. Adverse effects on parameters such as nut yield and quality are also observed when soil macronutrient levels are too high (Stephenson et al., 2000). Aitken et al. (1990) found that high levels of soil phosphorus (≥ 75 mg kg⁻¹) reduced macadamia yields by 15% in Australia. Stephenson et al. (2002) reported a reduction in macadamia yields by more than 20%, attributed to high total nitrogen (TN) application rates. Moreover, in the same study, high TN levels reduced the percentage of large (≤ 24 mm) nuts by more than 10% and increased intermediate-sized nuts (19–24 mm) by about 10%. Stephenson & Gallagher (1989) reported a similar response to N applied to HAES 660. However, high calcium (Ca²⁺) levels in the soil (≥ 10 mg kg⁻¹) protect macadamia trees from very high temperatures and drought, subsequently leading to higher nut yields (Powell, 2009). This, therefore, shows that the right application rates of essential nutrients is important for enhancing macadamia productivity.

Micronutrients, specifically boron (B) and zinc (Zn), have been identified as being vital for macadamia nut yields (Stephenson et al., 1986). Micronutrients are required primarily during active growth periods and play a significant role in the physiology of the tree, making them a major factor in orchard nutrition management programmes (Evans, 2021). B is mainly required for the normal development of new tissues, pollen, and nuts (Stephenson et al., 1986; Trueman, 2013). Abnormal flower and fruit development are common in macadamia tree crops where B is deficient (Stephenson & Cull., 1986). Zn is required for photosynthesis and phytohormones (auxins) metabolism, which supports fruit quality and disease resistance (Nagao & Hirae, 1992). However, B and Zn are the micro-elements frequently deficient in macadamia orchards globally, and specifically in Africa. Thus, supplementation through inorganic fertiliser application is desirable.

Soil fertility is one of the key constraints affecting macadamia production worldwide. Hence, assessing individual orchards' soil fertility status, especially among small-scale farming communities, to identify underlying nutritional deficiencies is key to improving macadamia

productivity. Hence, soil nutritional assessments of macadamia orchards should be conducted at the end of each harvest season (Smith, 2016). Such analyses are important because they inform the limiting nutrients for macadamia growth and are useful for taking action. Consequently, one of the primary objectives of this study is to assess the soil fertility status of smallholder macadamia farms in Malawi, considering that smallholders still rely on outdated recommendations from studies conducted in the 1990s. By conducting this assessment, this thesis aims to bridge the knowledge gap and provide updated guidance to smallholder macadamia farmers, enabling them to enhance their soil management practices effectively.

2.6.2. Carbohydrate availability in the tree tissue

Carbohydrates influence nut growth and drop in macadamia (Wallace, 1999). Macadamia trees accumulate and store carbohydrates in summer and autumn (Herbert et al., 2019). During spring and winter, the tree draws on the stored carbohydrates due to insufficient carbohydrate production to meet the high energy demands of nut growth and oil accumulation. Macadamia trees require 50 leaves on a branch to support one nut's development (Trueman and Turnbull, 1994). To increase the concentration of carbohydrates, girdling and the application of plant growth regulators such as paclobutrazol and Ethapon-480 and fertilisers can be used. Nagao & Hirae (1992) found that girdling increased the number of racemes when a 3 mm broad girdle was applied to the xylem around the trunk 45 cm above ground level before flower initiation. The same study found that the number of fruit sets increased through girdling of stems with high leaf numbers.

Plant growth regulators, including paclobutrazol, are used in macadamia cultivation to control tree growth and improve yields. When applied to macadamia trees, paclobutrazol inhibits the production of gibberellins, hormones that promote stem and leaf growth (Makoka, 1991). By limiting gibberellin production, paclobutrazol redirects the tree's energy toward the production of flowers and nuts, resulting in higher yields (Trueman, 2011). In addition, the application of paclobutrazol in macadamia increases the partitioning of carbohydrates. Consequently,

paclobutrazol can help regulate the timing of flowering and nut set in macadamia trees, leading to more consistent and predictable crop yields (Rademacher, 2015).

The application of nutrients through manure and inorganic fertilisers, primarily nitrogen and boron, can increase the amounts of carbohydrates in macadamia trees and consequently results in high KR (Wilkie et al., 2010). However, too much TN (e.g., 690 g tree⁻¹ year⁻¹ or more) application tends to cause a reduction in KR. The correct application rates of essential nutrients are key to macadamia growth and yields.

2.6.3. Cross-pollination

Many crops, including apples, olives, grapes, and mangos, have been shown to have increased fruit set and yield through cross-pollination in comparison to self-pollination (Perez et al., 2016). Macadamia is partially self-incompatible and favours cross-pollination over self-pollination (Trueman, 2013). Cross-pollination significantly increases the final nut set and improves the nut size (Meyers, 1997; Wallace, 1999). Furthermore, cross-pollination results in 14 times more fruit retention than self-pollination (Tavares et al., 2015). Britz (2015) also noticed an improvement in yield and kernel quality of "Beaumont" cultivars when cross-pollinated by several different cultivars in South Africa.

Despite the benefits of cross-pollination in macadamia, not all cultivars are compatible. Wallace (1999) found that cross-pollination resulted in larger nuts in 28 out of 30 combinations of pollen sources when using the same maternal parents. This study revealed that cross-pollinated macadamia flowers are more likely to reach maturity than self-pollinated flowers. However, this was not always the case, as HAES 246, fertilised by HAES 814, produced smaller nuts than self-pollinated trees. This demonstrates that cross-pollination also depends on the compatibility of the cultivars. According to Evans (2020), the cultivars HAES 246, 791, and HV A4 are universal pollinators.

However, cross-pollination of macadamia requires mainly insect pollinators rather than wind (see above). Low pollinator populations and activity in the orchard may result in insufficient pollen transfer and directly cause inadequate cross-pollination, which may later affect yield and kernel recovery (Trueman, 2013). However, because insect-mediated pollen transfer in orchards is sometimes restricted to neighboring rows of trees, close inter-planting of various cultivars can enhance cross-pollination (Figure 2.4). Adding beehives is another viable solution that has successfully increased cross-pollination in Australian and Malawian orchards (Howlett et al., 2019). Nevertheless, climate change will also affect pollinators causing phenological mismatches (Jennings et al., 2022).

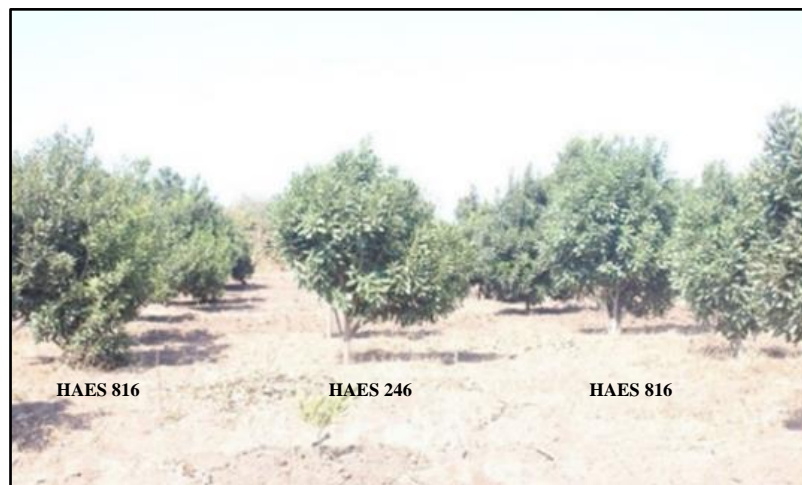


Figure 2.4: Macadamia orchard in Ntchisi district comprising different cultivars planted parallel to each other to facilitate cross-pollination.

2.6.4. Age of orchard

Like any commercial perennial tree crop, macadamia production is determined by the orchard's age for productivity. Macadamia trees typically take several years to reach maturity and start producing nuts. In general, macadamia trees begin to produce profitable nuts when they are around five to seven years old, and they reach peak productivity between the ages of 10 and 20 years, and after 30 years, the yields level out and decline (Nagao et al., 1994; Toft et al., 2019). However, grafted macadamia trees can begin flowering and producing nuts in the second year

of planting, depending on management, soil nutrition, and climatic factors (Wasilwa et al., 2019). Yields in Australian commercial macadamia orchards range from 200 kg ha⁻¹ in four-year-old to more than 3000 kg ha⁻¹ in 20-year-old orchards (McFadyen et al., 2013a). Nevertheless, these yields are based on intensive commercial macadamia production, as opposed to smallholder production in Malawi and Kenya, where yields per ha have been reported to be less than 200 kg (Muthoka et al., 2008; Quiroz et al., 2019).

2.6.5. Pests

Pests are considered a significant threat and limiting factor to macadamia productivity worldwide (Taylor et al., 2018). In 2020, the estimated value of factory-level rejections due to insect pest damage was \$240 ha⁻¹ (INC, 2022). Moreover, annual losses from insect pest damage averaged at \$15.2 million. Macadamia pest damage is divided into direct and indirect losses (Hall et al., 1984). Direct damage occurs when organisms like insects, rats, and squirrels feed on macadamia tree parts or the nut and degrades its value. Indirect damage occurs when organisms like insects or mites feed on other parts of the crop that are not marketed, such as feeding the husk's outer surface.

Three major damaging groups of macadamia insect pests include the false codling moth (*Cryptophlebia leucotreta* Meyr), commonly known as the macadamia nut borer, the macadamia stink bug (*Nezara viridula* (L)), and termites (*Odontotermes badius*) (Chambers et al., 1995). Each group of these three insect pests can make up to 40% of the crop unsaleable (Hall et al., 1984). Secondary insect pests include mites, katydids, red-banded thrips, black citrus aphids, felted coccids, banana-spotting beetle, macadamia leaf miner, and termites.

Nut borers are an important pest of many crops, particularly fruit and cotton, in SSA and the nearby islands in the Atlantic and Indian Oceans (La Croix & Thindwa, 1986). The pest has been recorded on 35 native and cultivated host plants, with cotton in moist equatorial regions (Chambers et al., 1995) and macadamia (La Croix & Thindwa, 1986) in southern Africa most severely affected. This pest lays its eggs on the nut, and the larvae feed and burrow through

the green husk and the shell (Figure 2.5a), occasionally entering the latter and damaging the kernel (de Villiers, 1993a). Damage to the kernels is roughly 2% in low-lying areas (≤ 1000 m.a.s.l.) and approximately 5–7% in higher altitude areas (≥ 1200 m.a.s.l.) (La Croix & Thindwa, 1986).

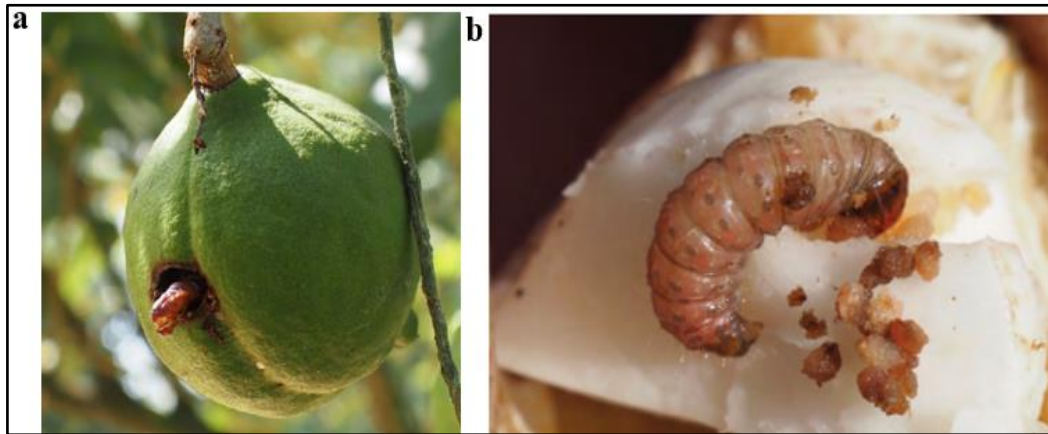


Figure 2.5: a) Macadamia nut borer at an entry point; b) macadamia nut borer larvae (Bright, 2020).

Macadamia stink bugs cause direct damage by inserting their mouthparts through the husk and shell to feed on the macadamia kernel (Mitchell et al., 1965; Follett et al., 2009). The pest feeds on macadamia at any stage of development (Figure 2.6). Kernel injury is usually not detected until the nuts have been shelled and the spotting of the kernels is visible (Taylor et al., 2013). Stink bug feeding also causes premature fruit drops and sunken lesions on kernels of mature nuts (Hall et al., 1984). Secondary fungal infections cause infected kernels to become spongy with or without brown pith-like depressions (La Croix & Thindwa, 1986). Such kernels become shrivelled, soft, and inedible and acquire a translucent appearance, unlike the normal white appearance. In Malawi, damage is severe in low-lying areas (La Croix & Thindwa, 1986). In large monoculture orchards and under higher temperature conditions, the damage by macadamia stink bugs can be as high as 90% if uncontrolled (Follett et al., 2009).

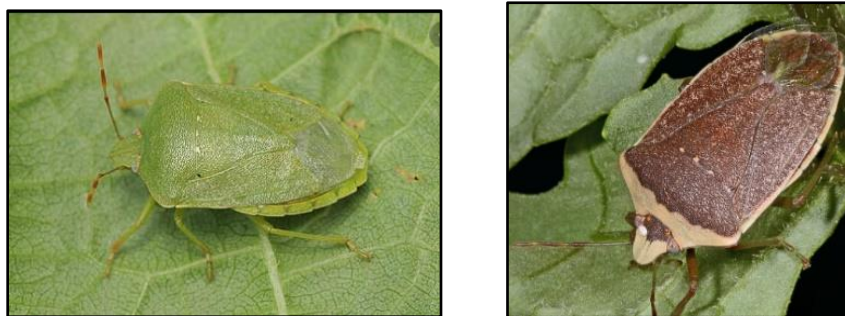


Figure 2.6: Macadamia stink bugs found in a macadamia farm in Malomo cooperative.

A key element in managing nut borers and stink bugs is monitoring population levels so that outbreaks can be anticipated and management decisions made in a timely fashion (Follett et al., 2009). Traps and pheromones are often used to monitor pest population trends (La Croix & Thindwa, 1986). Cultural control methods such as burning the husks immediately after dehusking and burning trash under the trees to produce smoke that repels the insects have been reported to effectively manage these two pests (La Croix & Thindwa, 1986). Chemical control of these two pests has proved difficult and often ineffective, and thus considerable emphasis has been placed on the biological control of the pests (Chambers et al., 1995).

Termites damage macadamia trees at all stages in the life cycle of the tree (Kawate & Tarutani, 2006). Feeding damage on roots and stem bases frequently results in the death of the seedlings and trees. Termites are a big challenge, especially at the seedling stage. To avoid termite damage, it is essential to ensure that seedlings are always watered. Termites can be managed by removing their colonies, i.e., killing the queen and mulching (Bright, 2018, 2019).

2.6.6. Diseases and deficiencies

Several fungal diseases attack macadamia, but most are of minor importance. The major problem on macadamia leaves is chlorosis, common in soils with a pH greater than 6.5 or over-fertilised with phosphorous (Bittenbender and Hiraе, 1990). Zinc deficiencies can be a problem, and the symptoms include small yellowish or slightly mottled leaves, which are bunched together, crop retardation, and poor shoot growth. The common macadamia diseases include husk spot, raceme blight, *Phytophthora* blight, and macadamia root and trunk canker (Bright, 2018).

2.7. Uses of macadamia

Figure 2.7 illustrates the various uses for macadamia nuts and byproducts. Generally, macadamia nuts are consumed both in raw and roasted form. They are also used as additives in the confectionary sector for cakes, ice cream, and macadamia butter. Macadamia halves are mostly used to produce cooking oil and cosmetics such as shampoo, soap, and sunscreens. The cake is used as animal feed.

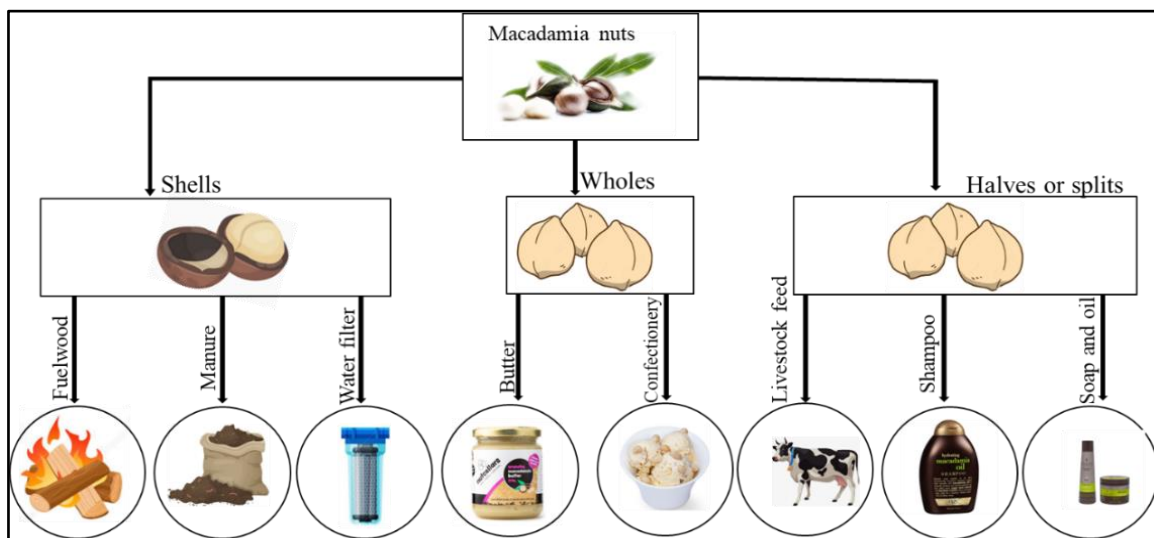


Figure 2.7: Uses of macadamia nuts and shell.

2.7.1. Nutritional uses

Macadamia nuts have the highest total lipid content ($\geq 74\%$) than any nut crop, owing to their high amounts of monounsaturated fats (Table 2.3). The nuts are also rich in carbohydrates, proteins, and dietary fiber and may be consumed raw or roasted, and the oil extracted from the nuts can be used for cooking. Because of the high monosaturated fatty acid content, research has shown that eating macadamia helps reduce cholesterol levels and improves human blood circulation, hence their popularity (Garg et al., 2007).

Table 2.3: Nutrient content of macadamia (%).

Content per 100 g	AMS	USDA	SAMAC
Protein	9.2	7.9	9.4
Fat (total oil)	74.0	75.8	75.0
- Monounsaturated	60.0	59.3	84.0
- Polyunsaturated	4.0	4.0	3.5
- Saturated	10.0	12.1	12.5
Ash	1.3	1.3	1.6
Carbohydrate (total)	7.9	13.8	-
- Sugar	4.6	4.1	4.8
Dietary Fibre	6.4	8.6	7.7

Adapted from Queensland Government (2004b).

2.7.2. Non-food uses

Non-food uses of macadamia include fuelwood derived from shells and timber from wood, which can be used to make furniture and as building blocks. Macadamia nuts and their by-products can also be used as additives for producing tannin leather and cosmetic oils such as shampoo, fragrances, and conditioners. Furthermore, macadamia trees provide ecosystem services such as shade and soil amendment, i.e., shells. The shells can also be fed to livestock and used as a water filter.

2.8. Global macadamia production

Macadamia nut production accounts for less than two percent of the world's tree nut production (INC, 2022). Nevertheless, over the last decade, global macadamia production has more than doubled, with established growing regions continuing to expand their plantings. Moreover, yields for the 2021–2022 growing season increased by more than 66,400 metric tonnes (MT), representing a 5% production increase from the previous season and 131% higher than in 2011 (Figure 2.8). The rising demand for the commodity and the supply shortage in the global market is the driving force for the increased production (Quiroz, 2019).

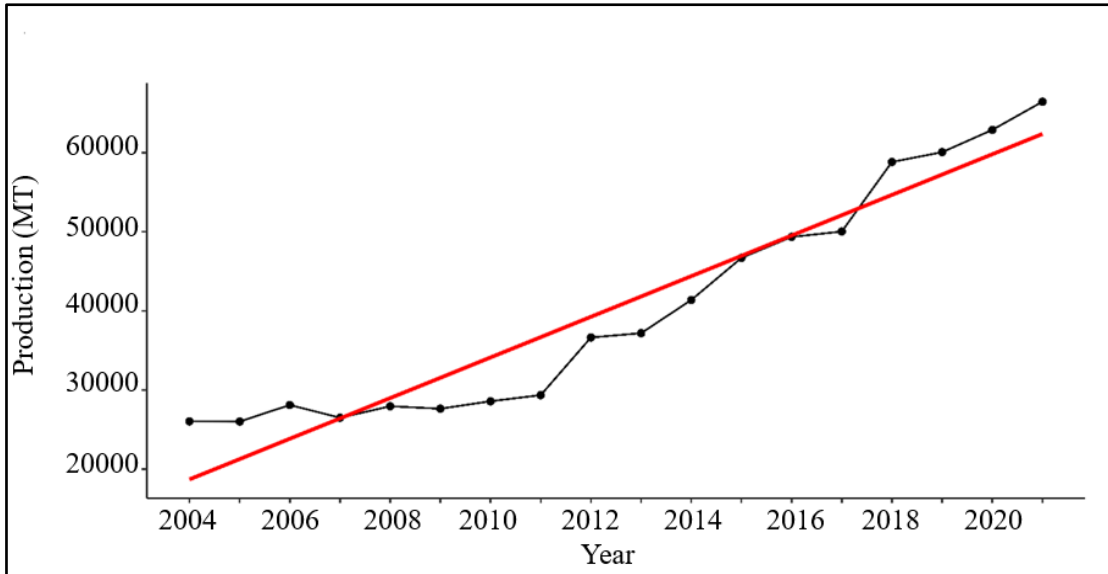


Figure 2.8: Global macadamia kernel production trends (INC, 2022).

South Africa and Australia are the world's leading suppliers of macadamia, accounting for 26% and 24% of the global supply, respectively (Figure 2.9). Interestingly, China's production has grown by over 33% between 2020 and 2021. Africa is the regionally leading producer of macadamia nuts, contributing about 41% of the kernel to global production (INC, 2022). Because of its suitable climate, altitudes, and vast tracts of land for cultivation, Africa will likely continue being a major producer of macadamia in the next decades (Toit et al., 2017).

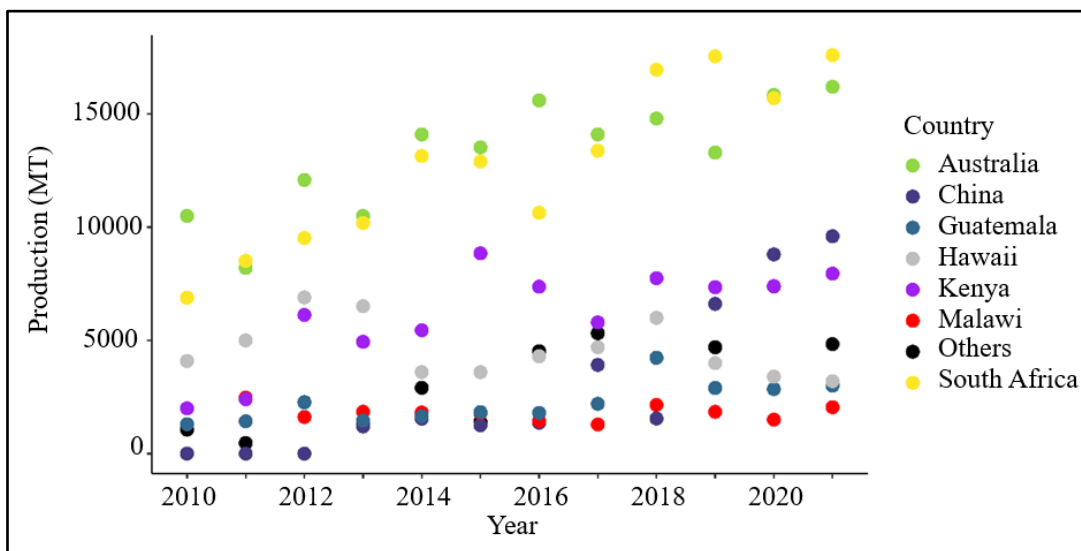


Figure 2.9: Global macadamia production by country for major producers (INC, 2022).

2.9. Global macadamia nut consumption

Named the "queen of nuts," macadamia is gaining popularity among consumers worldwide, with global consumption rising by 56% in the last decade (Figure 2.10). The rapid increase in macadamia consumption is driven by consumers' interest in healthy eating and a deeper understanding of the nutritional benefits of dried nuts (Quiroz et al., 2019). The United States and Australia are the major users of raw macadamia nuts, accounting for 26% and 5%, respectively, while Japan and Germany lead in the consumption of processed macadamia products. China is the major importer of nearly all of the world's NIS macadamia, primarily for snacking and cooking oil. China's annual importation of NIS macadamia is between 50,000 and 60,000 MT annually. Based on these statistics, the consumption of macadamia nuts is expected to continue to outpace supply in the coming decades.

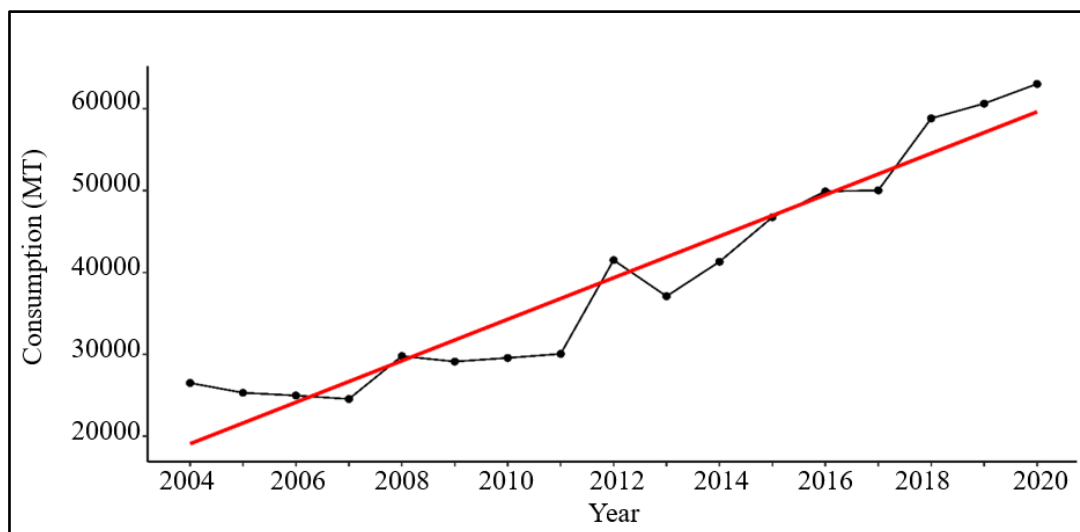


Figure 2.10: Global macadamia kernel consumption (INC, 2022).

2.10. Global macadamia exports

Macadamia nuts are exported either as NIS or shelled. Grade one kernels are primarily used in confectioneries and cereals (Camellia Plc, 2019). Unsound kernel and grade two (halves) fragments are used in the production of animal feed, pharmaceutical quality macadamia oil, and cosmetics (Camellia Plc, 2019). Exports of NIS macadamia rose from 2006 to 2012,

reaching over 31,000 MT. However, due to extreme weather conditions, such as drought in Africa, production declined in the 2013–2014 season (Quiroz et al., 2019). Despite this decline, exports of the crop have been steadily increasing (Figure 2.11).

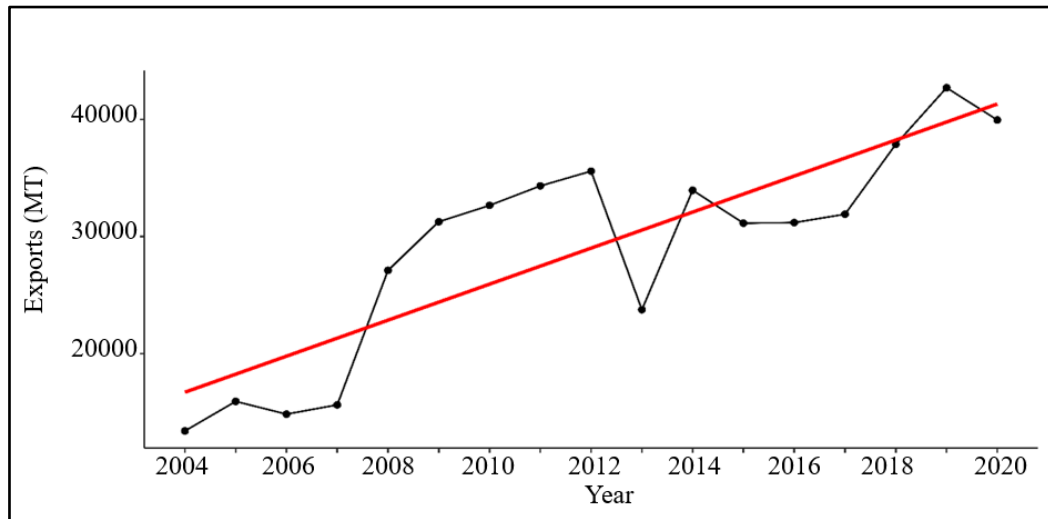


Figure 2.11: Global macadamia kernel exports (INC, 2022).

2.11. Conclusions

This chapter has discussed the factors determining macadamia productivity, from the basics of the macadamia crop to current production trends. It is noted that macadamia nuts have become an essential crop today, and their production has grown tremendously over the past decade. In addition, the strong international demand for macadamia nuts and young orchards reaching maturity, especially in China, Kenya, and Malawi, is expected to continue driving production growth. However, this chapter reveals that macadamia cultivars perform differently in various countries and localities. This is attributed to variations in biotic and abiotic factors, specifically climate, soil nutrition, and producer economics. The majority of research on the impact of these factors on macadamia productivity in Africa has been conducted under large-scale intensive monoculture plantations. In contrast, research on the impact of these factors on smallholder macadamia production is still lacking. This may be one of the underlying potential causes of the observed low yields in smallholder growing areas, especially in Malawi.

Therefore, this Ph.D research seeks to address this knowledge gap. Chapter Three elaborates on the importance of species distribution modelling with respect to abiotic and biotic factors and how it is vital for this research. This will become apparent in Chapter Six, which examines the climatic factors influencing smallholder macadamia production in Malawi and predicts the impacts of climate change on the current production areas of the crop.

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CHAPTER THREE: SPECIES DISTRIBUTION MODELLING AND ITS APPLICATIONS

This chapter presents the scientific literature on the development and application of species distribution models. The chapter's overall goal is to provide a context for examining the climatic factors influencing smallholder macadamia production in Malawi and the potential impacts of climate change on the suitability of the crop (Objective Two). Moreover, this chapter provides information for the sample design, model formulation, interpretation, and evaluation methodology for Objective Two of this thesis.

3.1. Introduction

Species distribution modelling (suitability modelling) is a method used to predict the potential geographical distribution of a species. Over the past decades, species distribution models (SDMs) have become popular in biogeography, conservation biology, ecology, paleoecology, wildlife management, land use planning, and resource management (Araújo & Guisan, 2006; Ghanbarian et al., 2019). SDMs correlate species known occurrence with environmental, demographic, and climatic predictor variables and predict a species' potential distribution in other geographies over space and time (Ahmadi et al., 2023). In other words, SDMs provide critical information about how well suited a given location is for a given species. To achieve this, SDMs use statistical (correlative) or theoretical response curves to identify relationships between species occurrences and predictors (Srivastava et al., 2019; Jin et al., 2022). Therefore, SDMs are an important tool for global change impact assessments for projecting potential future range shifts of species (IPBES, 2016).

Correlative species distribution models are derived using various statistical approaches, including generalised linear models (GLM), Bayesian models, environmental envelopes, ordination and classification methods, locally weighted methods, or a combination of these models (Du et al., 2022). Correlative SDMs use species occurrence data and associated

environmental layers of a given area to estimate the probability of the species occurrence based on the similarity of the environmental conditions in that location with the species' known habitats (de Sousa et al., 2017; Rivrud et al., 2019). The more similar the conditions at a given location are to those of the known habitats, the higher the probability of the species' occurrence (Moran et al., 2022).

In agricultural applications, species distribution modelling studies have mostly focused on higher-value commodities such as avocado, cashew, cocoa, coffee, maize, potatoes, wheat, and tobacco (e.g., Hijmans, 2003; Bunn et al., 2015; Yue et al., 2019; Jennings et al., 2020; Yin & Leng, 2021). Current applications of SDMs on perennial species have mainly focussed on the impact of climate change on range shifts of crops (e.g., Barrueto et al., 2018b; Behroozian et al., 2020; Chemura et al., 2021; Zuza et al., 2021b; Arumugam et al., 2022), species invasion ecology (Zu et al., 2022) and assessment of the impacts of land cover change (Chemura et al., 2022). However, despite advancements in this area, fewer researchers have utilised SDMs in macadamia research. Such research is critical in macadamia-producing countries, as the crop has a long lifespan and requires long-term land use planning considering climate change. Subsequently, this thesis uses species distribution modelling to identify current and future geographical areas for smallholder macadamia production in Malawi. Figure 3.1 illustrates the main stages in species distribution modelling.

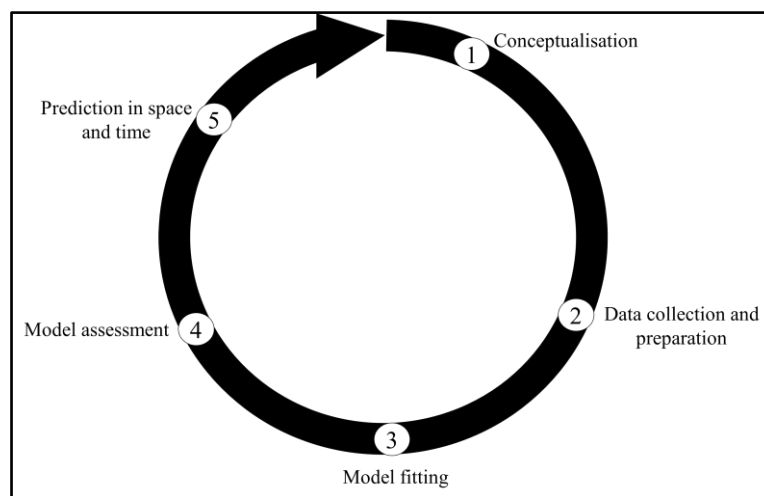


Figure 3.1: The main modelling cycle in species distribution modelling.

3.2. Modelling framework

3.2.1. Conceptual framework

A conceptual framework provides a basis for understanding the ecological processes underlying the distribution of a particular species and helps to ensure that the model is based on a solid knowledge of the species and its environment (Araújo & Guisan, 2006). This framework guides research objectives and shapes study design and model selection decisions. Key considerations during this phase include determining whether species data is available or needs to be collected and selecting an appropriate sampling strategy. Several publications have provided an overview of species distribution modelling (e.g., Peterson & Soberón, 2012; Pecchi et al., 2019). These reviews highlight the central importance of ecological niche theory (Hutchinson, 1957) and the importance of using a conceptual framework to link ecological theory and modelling.

A conceptual framework for an SDM includes assumptions about the factors affecting the species distribution, the relationships between these factors, and the processes that drive the distribution (Austin, 2007). For example, a conceptual framework for a particular coffee species might include assumptions about the factors influencing that species' distribution, such as temperature, precipitation, and soil factors (Chemura et al., 2022). Therefore, to develop an accurate and useful SDM, it is important to thoroughly understand the ecological factors that influence the distribution of the species in question. Subsequently, the modelling framework should be based on the overarching aims of the study and integrate the ecological theory for interpreting the results.

3.2.2. Ecological model

An ecological model serves as a conceptual basis for quantifying environmental factors associated with species distribution and establishes a connection between empirical data and the theoretical framework of the ecological niche (Hutchinson, 1957). The key assumption underlying ecological niche modelling is that environmental factors play an important part in

influencing species distribution and that a reasonable approximation of those variables can be estimated (Austin, 2002). By analysing these variables, predictions can be made regarding the geographical range of a species.

The integration of environmental variables into predictive distribution models, utilising occurrence data as the response variable, enables the identification of a target species' realised environmental niche (Guisan & Zimmermann, 2000). This estimation is referred to as the hypervolume of environmental space, where in the presence of competition, a species can persist indefinitely (Hutchinson, 1957). In contrast, a fundamental niche is a suite of all abiotic environmental conditions within which a species can persist without considering competition (Hutchinson, 1957).

Gradient analysis describes the theoretical foundation for observational studies of species distribution patterns along environmental gradients. Whittaker (1967) proposed that species populations are spread along environmental gradients according to their physiological tolerances, resulting in a continuum of community variation. The gradient theory supports the Gleason (1926) model of plant association, which states that each species is distributed in relation to the total range of environmental factors it encounters and that no two species are similar in these characteristics. This model is now universally accepted as having a fundamental influence on plant distribution. However, the continuum theory (Austin, 1985) proposes that species distribution patterns are arranged according to abstract environmental space, not necessarily geographic distance on the ground or any indirect environmental gradient, and thus provides a theoretical framework for explaining the shape and interrelationship of species responses along direct or resource gradients.

Environmental gradients can be classified as direct, resource, and indirect (Dyakov, 2010). Direct gradients are factors that directly influence plant growth but are not consumed, such as soil pH, humidity, and temperature (Austin, 1985). Resource gradients, on the other hand, include water, nutrients, light, carbon dioxide, and oxygen that plants use for their growth

(Austin, 1985). Indirect gradients, including altitude, aspect, and slope, are complex factors that do not directly impact growth but serve as indicators for direct and resource gradients. These gradients are site specific and cannot be applied to other environments (Dyakov, 2010). However, these indirect gradients are useful in niche modelling where fine-scale data is available and environmental gradients are steep (Austin, 2002).

Fundamental elements and processes that make up an ecological model include abiotic components such as climate, topography, soil type, and water availability and biotic aspects such as biogeographic history, dispersal, competition, community association, and population dynamics (Srivastava et al., 2019). Disturbance processes, like fire and flooding regimes, can also be included in conceptual ecological models, where they play an essential role. However, these elements are often excluded when developing the ecological model because of a lack of data and understanding of biological or disturbance processes affecting the target species distribution (Pecchi et al., 2019).

3.2.3. Data model

A data model in the context of species distribution modelling is a statistical algorithm that predicts a species's spatial and temporal distribution based on environmental data. This model relies on presence-only or presence-absence data and is based on an ecological model that considers environmental predictors affecting the presence of the target species (Jackson et al., 2000; Zurell et al., 2020; Murphy & Smith, 2021). In cases where actual data on environmental drivers are unavailable, proxies are used (Feilhauer et al., 2012; Pease et al., 2022). Direct, indirect, and resource gradients can serve as predictors, with a preference for those closely associated with physiological processes affecting the species. Nevertheless, selecting appropriate predictor variables and determining their relative contribution to the model remains challenging (Thuiller et al., 2004; Zu et al., 2022).

High-quality data that accurately captures the geographical reality is crucial for successful species distribution modelling (Shabani et al., 2018; Roozbeh et al., 2022). However, data

availability and accuracy present key challenges in species distribution modelling, particularly with respect to the availability of geographical information layers (Pecchi et al., 2019; Osborne et al., 2022). Until recently, bioclimatic variables have often been coarse, lacking sufficient data points for adequate interpolation, spatial bias due to sample point locations, or insufficient resolution to pick up microclimatic effects in specific study areas (Yin & Leng, 2021; Hamilton et al., 2022). Nevertheless, recent advancements in GIS and remote sensing, combined with the availability of open-source sharing, means digital terrain data is available at a fine scale, and derived variables (aspect, slope, and topographic location) can be obtained with minimal loss of precision (Shen et al., 2021; Paradinas et al., 2022).

3.2.4. Sample design

Designing an efficient sampling strategy for species distribution modelling is essential to reducing model biases and enhancing model performance (Araujo & Guisan, 2006). Ideally, data for modelling is collected systematically according to a sampling strategy that targets primary environmental gradients crucial for the species and aligns with the study's objectives (Guisan & Zimmermann, 2000). However, because of the high cost of acquiring data from a stratified independent sample design from a field survey, this data type is not commonly used in vegetation modelling (Austin & Meyes, 1996).

While an appropriate sampling design is vital, few studies provide detailed information on the method used. Studies have limited the range of observations along gradients believed to impact the species distribution. For example, Guisan et al. (2006) modelled the Swiss alpine eryngo by limiting their sample resolution to 25 m to match the resolution of the environmental data layers used. Ranjitkar et al. (2016) compiled a presence dataset of potential agroforestry trees in Yunnan province, from which ten tree species were included in their distribution modelling exercise. The basis for selecting these ten tree species was the existing plantation practice in their study area, reflecting farmers' preferences (Ranjitkar et al., 2016). Chemura et al. (2021)

used an area-weighted elimination of presence points sample design to model the distribution of specialty coffee in Ethiopia.

Many studies on species distribution modelling provide limited information about the sampling design used, often only describing the attributes of the dataset used for modelling (e.g., Yin & Leng, 2021). Such information is crucial for assessing the model's accuracy and facilitates the reproducibility of the analysis in other localities. To achieve this, researchers should provide their sampling designs to facilitate replication in other settings.

3.2.5. Environmental predictors

Prior to modelling a species potential distribution, it is recommended to pre-select predictors, as including redundant or irrelevant variables can lead to errors in most modelling systems (Ahmadi et al., 2023). Thus, the appropriate selection of environmental predictors is critical to the model's performance and potential use in prediction and explanation (Williams et al., 2012). However, this aspect is often overlooked compared to the selection of modelling methods, which can hinder the overall effectiveness of the model.

Deciding which environmental predictors to use and their relative contributions to species distribution modelling is a challenging task (Koch et al., 2019; Chemura et al., 2022). To tackle this issue, some researchers limit their analysis "a priori" to a few justifiable or easily measurable predictors (e.g., Wang et al., 2021; Morera-Pujol et al., 2023). Another approach is to use the Pearson correlation coefficient to select environmental predictors while assessing multicollinearity through the variance inflation factor (de Sousa & Solberg, 2020; Roozbeh et al., 2022; Ferrarini et al., 2023). Decision trees and artificial neural networks are alternatives (Gobeyn et al., 2019). These utilise parsimony (the minimum number of variables with the best possible fit) to evaluate the best classification of the predictor. The main advantage of these methods is their ability to estimate a distribution function empirically through resampling of the observed data while being unaffected by autocorrelation (Williams et al., 2012).

Recognition of direct, indirect, and resource variables can also significantly influence how each variable is used in the modelling approach (Olden & Jackson, 2002). Indirect variables such as altitude and latitude can only have a correlation with species through their relationships with variables such as temperature and precipitation (Cruz-Cárdenas et al., 2014). Since the correlation between indirect and direct variables can vary by site and is not necessarily linear, the shape of a species' response to indirect variables cannot be predicted (Austin et al., 1996). In contrast, there exist hypotheses about the shapes of species responses to direct and resource variables. For instance, plants' response to soil nutrients is expected to follow a hyperbolic curve, with species abundance increasing to a threshold beyond which further increases are inhibited. Therefore, when evaluating SDMs, it is important to consider whether a species' response to environmental predictors aligns with known ecological theories. For this reason, this thesis utilises environmental predictors with respect to altitude. This is because Malawi has varying altitudinal gradients that influence the weather experienced in the various districts in the country.

Bioclimatic modelling studies developed to predict changes in the geographic distribution of potential habitats under projected future climates use derived climate variables considered important to plant physiological function and known occurrences of the species to estimate the conditions that are suitable to maintain viable populations (e.g., Woldeyohannes et al., 2020; Zuza et al., 2021b). Once bioclimatic models are characterised, they can be applied to a variety of questions in ecology, evolution, land use planning, and conservation.

3.2.6. Model formulation

Ecologists rely heavily on collaboration with statisticians to incorporate new statistical theories and techniques into ecology, such as the use of generalised additive models (GAM) by Yee & Mackenzie (1991). The various approaches and techniques discussed in Nieto-Lugilde et al. (2018) demonstrate that the full array of statistical methods has yet to be integrated into species distribution modelling.

Model formulation (fitting) is an important aspect of species distribution modelling. In this process, a model is chosen to predict a particular type of response and estimate model coefficients together with an optimal statistical approach with regard to the modelling context (Descombes et al., 2020). Modelling methodology considerations also include the type of response variable, its theoretical distribution, data adequacy and reliability, sample design, and study objectives (e.g., Shabani et al., 2018; Waldock et al., 2022; Brunton et al., 2023).

3.3. Species distribution model algorithms

Species distribution model algorithms are statistical techniques used to predict the distribution of a particular species in a given area. These algorithms are typically based on data about the species' habitat requirements, climatic conditions, and land use patterns (Thuiller et al., 2004; de Sousa et al., 2020). Some common algorithms used in species distribution modeling are highlighted in Table 3.1.

Table 3.1: Commonly used techniques in species distribution modelling and agricultural applications

Class	Model	Description	Key references
Regression	Generalised linear model (GLM)	GLM is a regression analysis algorithm that assumes the dependent variable follows an exponential distribution. It estimates the relationship between the dependent and independent variables using a linear equation, accommodating distributions like binary, Poisson, and normal.	McCullagh and Nelder, 1989
	Generalised additive models (GAM)	GAM extends GLM to accommodate non-linear relationships between the dependent and independent variables, using a smooth function to model their relationship. It assumes the dependent variable follows an exponential distribution and is ideal when the relationship between variables is undefined.	Hastie and Tibshirani, 1986
	Multivariate Adaptive Regression Splines (MARS)	Non-parametric regression methods that automatically model non-linearities and interactions between a response variable and some set of predictors. MARS can handle noisy and complex data and is useful for predicting the outcome of a system that is poorly understood.	Friedman 1991
Envelope	Bioclim	A machine learning approach that defines a multi-dimensional environmental space where a species can occur using only occurrence data. Bioclim compares the values of the environmental variables at that location of the species to the percentile distribution of the values from known locations.	Busby, 1991
Machine learning	Maximum Entropy (Maxent)	This algorithm predicts species occurrences by analyzing the spread of distributions while considering the environmental variables of known locations. It uses only presence data and compares species locations to all available environments in the study area.	Phillips et al., 2006

	Artificial Neural Networks (NNET)	ANN is a complex model system of artificial neurons that can exhibit complex global behavior, such as selecting a habitat based on multiple environmental variables. This is determined by the connections between the neurons and associated functions.	Hopfield, 1982
Ensemble (Tree models based on classifiers)	Random Forest (RF)	RF is an ensemble classifier built of several decision trees that uses Breiman's random forest algorithm for classification and regression. It generates training data from bootstrap replications by randomly changing the predictive variable sets over the different tree induction processes.	Breiman, 2001
	Support vector machine (SVM)	This is a universal learning technique based on structural risk minimisation and statistical learning theory for cogent predictions. It maps the original data into a high-dimensional feature space where a hyperplane is constructed from training data and uses a kernel function to transform the data into an SVM.	Vapnik et al., 1997
Distance	Domain	Using the Gower metric distance, this approach computes the environmental distance between a site of interest and the nearest presence record.	Carpenter et al., 1993
Bioclimatic modelling	BIOMOD (NNET, GAM, GLM, RF)	A general framework for predicting species distributions from climate data using GLM, RF, GAM, and ANN by evaluating them and then selecting the best accurate model to make future projections or retaining all of the predictions from the different models and projecting them all into the future.	Thuiller, 2003; 2004
Ensemble models		Ensemble modelling is when many separate models are built to predict an outcome using various modelling algorithms or training data sets. Ensemble models are motivated by the desire to lower the prediction's generalization error. Causes of generalization error in models are variance, low accuracy, noise, and bias. The ensemble approach combines multiple models, thereby increasing model accuracy in predictions.	Segurado & Araújo, 2004

3.4. Presence-only versus presence-absence species distribution models

Different modelling techniques are available to generate species distributions. A key distinction among the modelling methods is the type of response variable used, specifically whether they utilise presence-only data or a combination of presence and absence data (Brotons et al., 2004; Leroy, 2022; Praveen et al., 2023). Presence-only models allow the use of data where knowledge of absences is insufficient or unavailable (Carpenter et al., 1993; Roozbeh et al., 2022; Molgora et al., 2023). Such models depend on defining environmental conditions at locations where a species is present and comparing these to the environmental conditions of background areas (Landau et al., 2022; Song et al., 2023). Examples of presence-only algorithms include Bioclim and Domain.

Conversely, algorithms such as GLMs and GAMs and machine learning algorithms such as RF and SVM require high-quality presence and absence data to rank habitat suitability based on species presence and absence distributions (Zurell et al., 2020; Shipley et al., 2022). The basic assumption of these models is that species have a preferred range of environmental conditions and that the presence or absence of a species is related to those conditions (Taylor et al., 2023). These models can be used to make predictions about where a species is likely to occur in areas where no data is available and can help identify areas important for conservation or agriculture.

Models based on only the presence of species have become more common, attributed to the increasing number of datasets made accessible through digitised records from Herbaria and Natural History Museums. However, a major limitation of these models is their inability to accurately predict the probability of a species' presence, as they lack reliable information on how it occurs in a certain area (Vieira et al., 2022). Moreover, the lack of absence records is considered a data error because it limits the creation of models that accurately distinguish between suitable and unsuitable habitats, particularly the identification of the attributes of unsuitable habitats (Segurado & Araújo, 2004).

As an alternative, background pseudo-absence points (background points) from environmental predictors are used in studies employing binomial models where presence-only data is available (Powell et al., 2014). Additionally, for ecological models used in agriculture, treating areas without current production as entirely unsuitable is inappropriate (Chemura et al., 2016). Further, determining whether a species is absent in a specific location is difficult and rare, so absence data may not accurately represent natural occurrences (Zuza et al., 2021b; Gouveia et al., 2023).

3.5. Comparative studies on species distribution modelling

The introduction of new techniques to the field of species distribution modelling, along with the availability of digitised data from various sources, has resulted in many studies comparing the performance of various modelling techniques. These studies often examine the differences in model predictions for potential species distribution under current and future climate scenarios (see Hu et al., 2019; Chemura et al., 2020; Radomski et al., 2022; Marchetto et al., 2023).

However, it is difficult to compare the rapidly expanding availability of new modelling techniques, and the comparison of methods undertaken by different researchers is rarely, if ever, comparable (Austin, 2002). This is especially difficult with crops as the absence in an area does not mean that the area is unsuitable for a crop. To address this issue, artificial datasets with clearly defined relationships are used to compare model performance, assuming that "truth" is unknown in models developed using real data (Austin, 2007). A large comparison of modelling techniques by Norberg et al. (2019), coupled with several previous studies on modelling uncertainty using the same datasets, has provided the most comprehensive investigation to date on the relative merits of different modelling techniques over a wide range of conditions (Guo et al., 2015; Lin et al., 2015; Ochoa-Ochoa et al., 2016; Watling et al., 2015; Zelazowski et al., 2018).

Austin & Meyers (1996) found that GAMs are more flexible in predicting species distribution than GLMs. Similarly, Hirzel et al. (2001) revealed that GLMs are robust to the quality and quantity of data and thus produce equivalent results. Franklin (2002), in their study, found that classification trees like RF are sensitive to outliers and less accurate than GLMs. Moreover, in the same study, Franklin (2002) reported that different models with similar accuracy levels may produce vastly different spatial predictions when using random predictor variable selection. Tsoar et al. (2007) compared the performance of six presence-only models and found that Domain had the highest accuracy ($AUC \geq 0.75$) while Bioclim had the lowest accuracy ($AUC \leq 0.65$).

Coetzee et al. (2009) applied seven different modelling methods: GLM, GAM, ANN, GBM, RF, and MARS, to predict the distribution of birds in South Africa. The evaluation results indicated that the GBM, RF, and GAM models outperformed the other models attaining AUC values of ≥ 0.95 . Nonetheless, GBM was the model that best summarised the overall patterns in range change for all the models used.

Kutywayo et al. (2013) evaluated two SDMs: BRT and GLM, using presence-only data of coffee white stem borer in various coffee producing areas in Zimbabwe. Their objective was to evaluate the models' ability in predicting the distribution of the pest. The study found that BRT and GLM models had similar performance statistics regarding specificity (0.72) and AUC (0.79). However, the models exhibited differences in sensitivity (0.81 vs. 0.76) and kappa values (0.53 vs. 0.47), with BRT performing better than GLM in both aspects. Interestingly, in areas projected to be suitable for the pest under future climate scenarios, the BRT model's predictions were lower than those of the GLM model.

Ren-Yan et al. (2014) used six species distribution model algorithms: Bioclim, Domain, MD, RF, Maxent, and SVM to analyse the distribution patterns of five tree species in China. To obtain an accurate and stable comparison of the predictive performance of these algorithms, the authors generated background pseudo-absent points for models requiring absences. The results indicated that MD, RF, Maxent, and SVM exhibited higher prediction accuracy (AUC

≥ 0.95) and were more stable than Bioclim and Domain. Hence, the study highlights the significance of selecting appropriate SDMs for different modelling activities to ensure high prediction accuracy and model stability.

Norberg et al. (2019) assessed the predictive performance of 33 variants of 15 SDMs at species and community levels for five species-rich communities in five regions globally. Their findings reveal significant differences in the prediction ability of the models, particularly in communities with rare species. Nevertheless, none of the models in the study performed well for all prediction tasks. Implying that cross-validation is required to fit a small set of models to determine which models perform best for each study.

Despite claims of superiority for any specific species distribution modelling technique, independent evaluations of models have often been unable to demonstrate the pre-eminence of any single one (Segurado & Araújo, 2004; Araújo & New, 2007; Marmion et al., 2009; Hao et al., 2020). Studies have demonstrated that projections from alternative models may be so varied that even the simplest assessment of whether species distributions should be expected to contract or expand for any given climate scenario is compromised. For example, when comparing different modelling techniques, Thuiller et al. (2004) found differing projections in potential climate change induced shifts in the distribution of European plants. Similar observations have been reported by Araújo et al. (2006), Jones et al. (2013), de Sousa et al. (2017), Chemura et al. (2019), and Hao et al. (2020). Such prediction variability is not surprising given that bioclimatic envelope models are correlative and sensitive to the data and statistical functions used to describe the species distributions with climate factors.

A solution to the intermodal variations is the use of ensemble models. The idea of ensemble modelling dates back to 1969 when J.M. Bates and C.W.J. Granger published their influential article 'The Combination of Forecasts' (Bates & Granger, 1969). The authors provided crucial

information that individual predictions contained some independent information while a combination of predictions lowered the mean error. This proves that ensemble models are better at predicting species distributions than individual model results. However, better-combined predictions are based on better individual predictions with improved data availability (Araújo & New, 2007). Recent studies on modelling techniques reveal that ensemble models are the most capable performers than individual SDMs (e.g., Akyol et al., 2020; Woldeyohannes et al., 2020; Zuza et al., 2021b; Mudereri et al., 2021). These studies show that the ensemble modelling approach is a robust novel method that outperforms individual SDMs, including when sample size and location error influence the accuracy of model predictions.

Kaky et al. (2020) assessed the predictive performance of eight single algorithm methods (Maxent, RF, SVM, Maxlike, BRT, CART, FDA, and GLM) to an ensemble modelling approach. Based on the AUC and TSS, ensemble modelling, Maxent, and RF achieved the best predictive performances, while SVM and CART performed the poorest. In addition, the authors found a high similarity in habitat suitability between Maxent and ensemble predictive maps. Demonstrating that single algorithm methods can also produce distribution maps of comparable accuracy to ensemble methods.

Chemura et al. (2021) used a combination of RF, BRT, and SVM algorithms in an ensemble modelling approach to predict the suitability of specialty coffee in Ethiopia. While the individual models for each growing area of specialty coffee demonstrated satisfactory results with an AUC value of 0.93 or lower, the ensemble model exhibited exceptional performance with an AUC value of 0.94 or higher.

It is evident from the previous discussions that when deciding on modelling techniques, one must first examine the data type (presence or absence) and secondarily consider other factors, including study objectives, data quality and accuracy, and scale. Additionally, the availability

of statistical packages, the level of ecological knowledge, and the statistical skill of the analyst should all be considered.

3.6. Predicting species distributions under changing climates

Human influence has warmed the atmosphere, ocean, and land (IPCC, 2021, 2023; UNEP, 2022). This warming is attributed to the increases in the concentrations of GHGs since around the 1750s. Global temperature analyses strongly indicate an increased warming trend in the past decades (Figure 3.2). According to IPCC (2021) findings, each of the last four decades has been successively warmer than any decade that preceded it since 1850. For example, the average global surface temperature during the first two decades of the 21st century (2001–2020) was 0.99°C (0.84 to 1.10°C) higher than the average temperature recorded between 1850 and 1900 (IPCC, 2023).

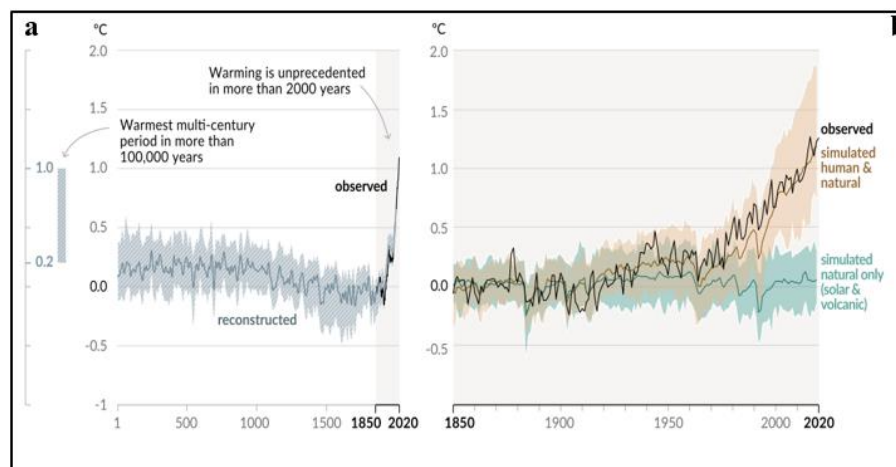


Figure 3.2: a) Change in global surface temperature (decadal average); b) Change in global surface temperature (annual average) as observed and simulated using human & natural and only natural factors (IPCC, 2021).

Temperature prediction studies reveal that global temperatures will continue to increase until mid-century under all emission scenarios (IPCC, 2007, 2021; UNEP, 2022). It is expected that global warming of 1.5°C and 2°C will be exceeded over the 21st century unless significant reductions in CO₂ and other GHG emissions occur in the next decades (Figure 3.3).

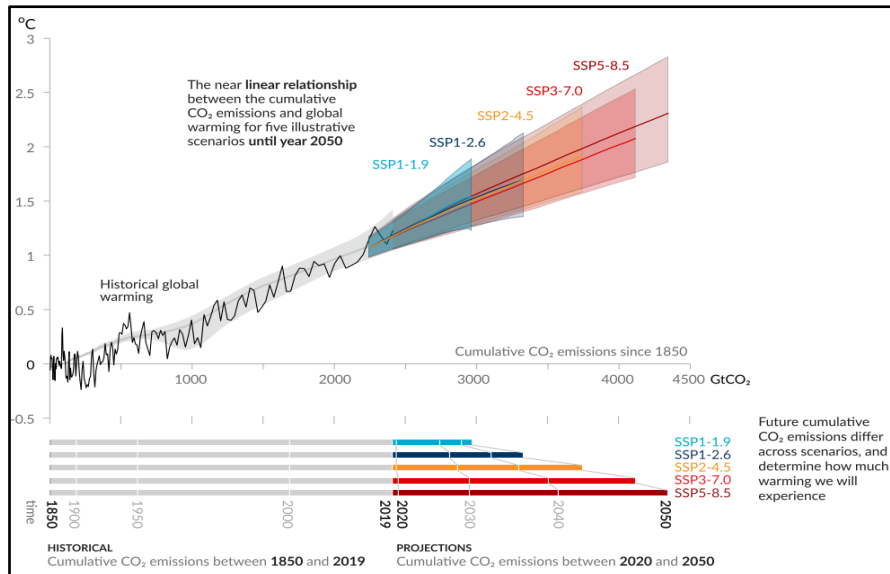


Figure 3.3: Near-linear relationship between cumulative CO₂ emissions and the increase in global surface temperature (IPCC, 2021).

Mean average precipitation over land has increased worldwide since the 1950s (IPCC, 2021). Further, the frequency and severity of heavy precipitation events have intensified over the earth's surface (95% confidence interval), with human-induced climate change being the primary contributor. At the same time, human-induced climate change has resulted in greater agricultural and ecological droughts in some regions due to increased land evapotranspiration (Mcgree et al., 2014). The reductions in global monsoon precipitation are partly attributed to human-induced aerosol emissions from the Northern Hemisphere (IPCC, 2007). According to Cowan et al. (2017), human influence has also increased the likelihood of extreme events such as heatwaves, droughts, fires, very cold weather, and flooding on a global scale and in specific regions worldwide. Nevertheless, the increase in warming has led to substantial increases in monsoon precipitation throughout South and East Asia and West Africa (IPCC, 2021).

Climate change is already altering species habitats and ecosystems, and the long-term consequences are predicted to be substantial (IPCC, 2021; UNEP, 2022). The severity of these effects are projected to increase in direct proportion to the degree of global warming (UNEP,

2019; IPCC, 2023). Thus, species will have to adapt to these changes or migrate to newer areas for survival. Failure to adapt by the species will certainly result in extinctions, as already seen in the past (Pimm et al., 2014; IPCC, 2023).

Climate change is a major threat to SSA. This is due to high present day temperatures, reliance on rainfed agriculture, and low adaptive capacity, especially among smallholder farmers (Mataya et al., 2020; Chapman et al., 2020; FAO, 2022b). Rising temperatures are predicted to shorten the growing season for various staples in the region, such as cassava, maize, and rice (Calzadilla et al., 2013; Jennings et al., 2022; Chemura et al., 2022). In addition, extreme temperatures coupled with heatwaves and increased diurnal ranges will likely cause damage to crops and lower yields (Linnenluecke et al., 2018; Chapman et al., 2020; Manuel et al., 2021). Higher temperatures are also expected to increase the incidences and severity of crop pests and diseases (Warnatzsch & Reay, 2019; Jennings et al., 2022).

Precipitation amount, intensity, and variability also impact crop yields (Niang et al., 2015; Mittal et al., 2017; Grüter et al., 2022); however, uncertainty in the magnitude of precipitation projections makes adapting to changing precipitation patterns challenging (Jones et al., 2015; Warnatzsch & Reay, 2019; Mataya et al., 2020). Therefore, evaluating changes in the suitable areas for the production of specific crops under climate change conditions can provide scientific knowledge and support for future land use planning, particularly for crops with high initial investments and long term benefits like macadamia.

Species distribution models are useful for predicting how climate change can impact different species (Jarvie & Svenning, 2018; Rather et al., 2020). By analysing how a species' range may shift under various climate scenarios, scientists can gain insight into the potential implications of climate change on biodiversity and land use planning (Chemura et al., 2022). The procedure entails fitting statistical models of current climate data to species distributions and then

projecting species potential distributions into the future using future climate simulations. However, these projections rely on the niche conservatism (NC) assumption. Niche conservatism refers to the tendency of species to retain some of their niche related traits over time (Wiens, 2004). Numerous modelling studies have demonstrated the assumptions of NC for different species worldwide (see Hwang, 1991; Barrueto et al., 2018c; Rather et al., 2020; Shen et al., 2021; Vieira et al., 2023).

There is currently a substantial body of literature predicting species geographical distribution of plant species under climate change from global (e.g., Yin & Leng, 2021; Jennings et al., 2022) to regional (Teslić et al., 2019; Almazroui et al., 2020) and national (Zuza et al., 2021b; Chemura et al., 2022; Jin et al., 2022) scales. Despite a great deal of variability in the predicted impact of climate change arising from factors such as different models, species, regions, emission scenarios, and timeline of projected climate, the models all indicate an overall decline or loss of suitable habitat for the vast majority of species if effective policies are not enacted.

3.6.1. General Circulation Models (GCMs)

General circulation models simulate the Earth's climate using three-dimensional grids (IPCC, 2007, Table 3.2). GCMs are based on the fundamental physical laws that govern the Earth's climate system, such as the conservation of energy and the laws of thermodynamics. Principally GCMs are used for weather forecasting, understanding the climate, and predicting the future climate under climate change scenarios (Melo-Merino et al., 2020). GCMs are typically used to simulate the Earth's climate over long periods of time, such as decades and centuries (IPCC, 2021). GCMs, consider a wide range of variables, such as temperature, precipitation, wind, humidity, and atmospheric composition. Hence, GCMs are an essential tool for climate research, as they allow scientists to study the effects of different factors on the Earth's climate (UNEP, 2022).

Table 3.2: General circulation models available at WorldClim.

Country	Modelling centre	GCM
Australia	Commonwealth Scientific and Industrial Research Organisation	ACCESS1-0-AC
China	Beijing Climate Center	BCC-CSM1-1-BC
USA	National Center for Atmospheric Research	CCSM4-CC
France	Centre National de Recherches Météorologiques	CNRM-CM5-CN
USA	Geophysical Fluid Dynamics Laboratory	GFDL-CM3-GF
USA	NASA/GISS (Goddard Institute for Space Studies)	GISS-E2-R-GS
South Korea	National Institute of Meteorological Research	HadGEM2-AO-HD
UK	Met Office Hadley Centre	HadGEM2-CC-HG HadGEM2-ES-HE
Russia	Russian Academy of Sciences, Institute of Numerical Mathematics	INMCM4-IN
France	Institut Pierre-Simon Laplace	IPSL-CM5A-LR-IP
Japan	Atmosphere and Ocean Research Institute (The University of Tokyo)	MIROC-ESM-CHEM MI MIROC-ESM-MR MIROC5-MC
Germany	Max Planck Institute for Meteorology	MPI-ESM-LR-MP
Japan	Meteorological Research Institute	MRI-CGCM3-MG
Norway	Bjerknes Centre for Climate Research, Norwegian Meteorological Institute	NorESM1-M

This thesis utilises bioclimatic variables from [WorldClim version 1.4](#), based on the 17 downscaled GCMs corresponding to the IPCC's Fifth Assessment Report (AR5, Table 3.3). Since there are no established criteria for assessing how each GCM predicts future climate accurately, relying on multiple GCMs in species distribution modelling can provide more reliable results (IPCC, 2007; de Sousa et al., 2017). Moreover, studies on species distribution modelling in SSA have shown that individual GCMs may simulate atmospheric processes

differently and produce varying outcomes for temperature and precipitation (Mittal et al., 2017; Warnatzsch & Reay, 2019; Chemura et al., 2022). Thus, highlighting the need to use more than one GCM when conducting distribution modelling exercises.

Table 3.3: Bioclimatic variables available in WorldClim.

Covariate	Bioclimatic variable	Unit
Bio 1	Annual Mean Temperature	°C
Bio 2	Mean Diurnal Range (Mean of monthly)	°C
Bio 3	Isothermality (BIO2/BIO7) x 100	-
Bio 4	Temperature Seasonality (Std. Dev x 100)	-
Bio 5	Max Temperature of Warmest Month	°C
Bio 6	Min Temperature of Coldest Month	°C
Bio 7	Temperature Annual Range	°C
Bio 8	Mean Temperature of Wettest Quarter	°C
Bio 9	Mean Temperature of Driest Quarter	°C
Bio 10	Mean Temperature of Warmest Quarter	°C
Bio 11	Mean Temperature of Coldest Quarter	°C
Bio 12	Annual Precipitation	mm
Bio 13	Precipitation of Wettest Month	mm
Bio 14	Precipitation of Driest Month	mm
Bio 15	Precipitation Seasonality (cv x 100)	-
Bio 16	Precipitation of Wettest Quarter	mm
Bio 17	Precipitation of Driest Quarter	mm
Bio 18	Precipitation of Warmest Quarter	mm
Bio 19	Precipitation of Coldest Quarter	mm

3.6.2. Representative Concentration Pathways

The impacts of climate change on the environment and society are determined by the earth system's response and how humans adapt through changes in lifestyle, economy, technology, and policy (Jubb et al., 2013). Because these responses are uncertain, future scenarios are used to assess the implications of various options. Representative concentration pathways provide

four distinct 21st century pathways of GHG emissions and atmospheric concentrations, air pollutant emissions, and land-use change (van Vuuren et al., 2011). These pathways are characterised by radioactive forcing (extra heat the lower atmosphere will retain as a result of additional greenhouse gases, measured in Watts per square metre (W/m²) (van Vuuren et al., 2011; de Sousa et al., 2019). Each RCP represents a diverse range of climate outcomes and is neither a forecast nor a policy recommendation. The pathways consist of one mitigation scenario leading to a very low forcing level (RCP 2.6), two medium stabilisation scenarios (RCP 4.5 and RCP 6.0), and one extremely high baseline emission scenario (RCP 8.5). In this Ph.D research, only RCP 4.5 and 8.5 are used for the 2050s period (Table 3.4). This is because these are the most widely used scenarios.

Table 3.4: Characteristics of Representative Concentration Pathways by the 2050s.

Scenario	Radioactive forcing (W/m ²)	GEI concentration by the year 2100 (ppm CO ₂ equivalent)	Temperature change (°C) by 2050s		Publication
			Mean	Range	
RCP 2.6	2.6	~490	1.0	0.4–1.6	(Riahi et al., 2007).
RCP 4.5	4.5	~650	1.4	0.9–2.0	(Fujino et al., 2006).
RCP 6.0	6.0	~850	1.3	0.8–1.8	(Clarke et al., 2007).
RCP 8.5	8.5	~1370	2.0	1.4–2.6	(Van Vuuren et al., 2007).

RCP 2.6 is the most ambitious and effective mitigation scenario, aiming to keep temperatures below 1.5°C by the 2050s. Unfortunately, recent reports indicate that the international community is falling short of the Paris climate goals, with no credible pathway to limit warming to 1.5°C (UNEP, 2022). RCP 4.5 is a stabilisation scenario and assumes that GHG emissions will peak in the 2040s and then gradually decline, leading to atmospheric concentrations of CO₂ at around 540 parts per million (ppm) equivalent by the end of the 21st century (Fujino et al., 2006). This pathway is consistent with efforts to limit global warming

to below 2°C above pre-industrial levels. The RCP 6.0 pathway assumes that GHG emissions will continue to rise throughout the 21st century but at a slower rate than under the RCP 8.5 (Jubb et al., 2013). This pathway leads to a stabilisation of atmospheric concentrations at around 670 ppm CO₂ equivalent by the end of the century, resulting in a warming of about 3°C above pre-industrial levels. Emission scenario 8.5 arises from little effort to reduce emissions and represents a failure to curb warming by 2100 (Woetzel et al., 2020). This pathway results in a warming of about 4.5°C above pre-industrial levels, with significant impacts on global ecosystems and human societies.

3.7. Accuracy methods for evaluating SDMs

Assessing the predictive accuracy of models is a critical step in the development process of distribution models (Allouche et al., 2006; Araújo & New, 2007). A quantitative performance assessment of the model may aid in uncovering aspects needing improvements and assist in determining model suitability for the specific application (Shabani et al., 2018; Norberg et al., 2019). Additionally, it enables the researcher to investigate the impact of different data and species' properties on the degree of accuracy of the generated maps by the model (Kadmon et al., 2003; Allouche et al., 2006).

SDM accuracy is assessed based on two main factors: discrimination capacity and reliability (Pearce & Ferrier, 2000). Discrimination capacity evaluates a model's ability to differentiate occurrence versus absence sites. This approach involves the construction of a confusion matrix that tallies the number of true positives, false positives, false negatives, and true negatives (Pearce & Ferrier, 2000). Reliability implies harmony of the predicted occurrence probabilities and proportions of sites occupied by the species (Pearce & Ferrier, 2000; Shabani et al., 2018). Several methods are available for measuring accuracy, including AUC, Sensitivity, Specificity, Kappa statistic, True Skill Statistic, and thresholds.

3.7.1. The area under the ROC curve

The AUC is a non-parametric measure for evaluating the performance of binary classification models (Bradley, 1997). It measures the trade-off between sensitivity (true positive rate) and specificity (true negative rate) over a range of threshold levels, making it a threshold-independent measure of model performance (Bradley, 1997; Heikkinen et al., 2006; Bobrowski et al., 2017). The AUC ranges from 0.5 to 1.0, where 0.5 corresponds to models that perform no better than random chance, and 1.0 corresponds to perfect discrimination. As suggested by Swets (1988), the AUC is classified as excellent (0.9–1.0), very good (0.8–0.9), good (0.7–0.8), fair (0.6–0.7), and poor (0.5–0.6).

3.7.2. Sensitivity and Specificity

Sensitivity represents the proportion of correctly predicted presence records and, thus, quantifying omission errors. In calculation, the following equation is used:

$$\text{Sensitivity} = \frac{\text{Number of positive sites correctly predicted}}{\text{Total number of positive sites in sample}}$$

$$S = \frac{A}{A + C}$$

Equation 3.1

Where:

A: Denotes the number of correctly predicted presence cells in which the species was found.

C: Denotes the number of cells in which the species was found, but the model predicted absence.

Specificity represents the proportion of correctly predicted absences and, thus, the quantification of commission errors. The following equation is used in calculating sensitivity:

$$\text{Specificity} = \frac{\text{Number of negative sites correctly predicted}}{\text{Total number of negative sites in sample}}$$

$$SP = \frac{B}{B + D}$$

Equation 3.2

Where:

B: Denotes the number of cells in which the species was not found, but its presence is predicted in the model.

D: Denotes the number of cells correctly predicting absence.

It is worth noting that, when compared across models, sensitivity and specificity are independent of one another and of occurrence, representing the proportion of sites where the species was recorded as present.

3.7.3. Kappa

Cohen's Kappa statistic defines the accuracy of predictions relative to the accuracy that might have resulted by chance alone (Cohen, 1960). It is based on the optimal threshold that can make the best of information in the mixed matrix to measure the model's performance. Generally, the kappa statistic ranges from -1 to $+1$, where $+1$ indicates perfect agreement between predictions and observations, and values of 0 or less indicate agreement no better than random classification (Tsoar et al., 2007). The interpretation of kappa values can be categorised as excellent ($0.85-1.0$), very good ($0.7-0.85$), good ($0.55-0.7$), fair ($0.4-0.55$), and fail (< 0.4) (Ren-Yan et al., 2014).

3.7.4. True Skill Statistic

Allouche et al. (2006) introduced the true skill statistic (TSS), which is independent of occurrence data but threshold-dependent. In contrast to the AUC measure, the TSS converts a continuous prediction into a binary one (i.e., those areas predicted as suitable versus not suitable for the species) and provides a measure of map accuracy (Bobrowski et al., 2017). The TSS value can accommodate values between 0 and 1 . The TSS is an alternative to Cohen's Kappa when a threshold-dependent performance measure is needed. Additionally, TSS assesses both omission and commission errors. The following equation is used for calculating TSS:

$$\text{TSS} = \frac{AD-BC}{(A+C)(B+D)} = \text{Sensitivity} + \text{Specificity} - 1 \quad \text{Equation 3.3}$$

3.7.5. Thresholds

A variety of threshold selection techniques exists, including taking 0.5 as a threshold (default), which is widely used in ecology (Pearson et al., 2002), or specifying a specific degree of

sensitivity of specificity (e.g., 0.90%) (Cantor et al., 1999). The third category of threshold selection identifies a threshold value that maximises the percentage of correctly classified points, sensitivity plus specificity, or Kappa (Norberg et al., 2019).

3.8. Evaluation dataset

Model evaluation is commonly carried out by testing predictions on the data used to build or train the model, termed cross-validated training data, and is usually derived by partitioning the training data (Berrar, 2018). The preferred method of model evaluation is cross-validation (Austin, 2007), with 80% of the data used in training the model and 20% for testing model prediction (Guisan & Zimmermann, 2000; Berrar, 2018; Hao et al., 2020), even though many theoretical contributions and practical alternatives have been reported (Hand, 1986, 1997; Vapnik, 1995; Schiavo and Hand, 2000; Berrar, 2018).

Cross-validation estimates how well a model will perform on new data, which is important in statistical modelling as the goal is to make predictions on unseen data (Stone, 1974; Isaksson et al., 2008). In SDMs, cross-validation is crucial as limited and biased data can affect the model's reliability and robustness (Guisan et al., 2006). Cross-validation tests the model's performance on independent validation data, providing a more accurate estimate of its predictive performance and helping avoid model overfitting (Williams et al., 2009; Mayer et al., 2019; Mudereri et al., 2021).

The collection of additional data for model evaluation rather than splitting the dataset has recently been recommended (Lloret & Lloret, 2020; Mudereri et al., 2021; Waldock et al., 2022). Other scholars have questioned the practice, arguing that it risks comparing different sampling strategies instead of evaluating the model (Descombes et al., 2020). However, predictions on partitioned datasets are not truly independent, as biases inherent in the training data are retained in the test data (Barry and Elith 2006). Thus, showing that cross-validation

is a reliable performance estimation technique. For this reason, this thesis uses cross-validation to evaluate the predictive performance of the individual SDM algorithms included in the ensemble suitability model for macadamia in Malawi.

3.9. Model limitations

Niche models derived from statistical correlations with environmental variables have certain assumptions that can significantly impact their predictions (Guisan & Zimmermann, 2000). For instance, such models require a representative sample of the range of values of the key predictor variables that define the target species' habitat (Hirzel et al., 2006). Additionally, the absence of data is often assumed to represent areas with a negative species-environmental relationship. However, it is important to recognise that unoccupied areas of suitable habitat may exist due to factors other than environmental relations, such as biogeographic history, large-scale disturbance, or dispersion constraint (Botkin et al., 2007). Furthermore, it is inappropriate to treat areas without current production as unsuitable for agricultural applications of niche models (Zuza et al., 2021b). This is because the absence of the crop in an area of interest does not necessarily imply that it is unsuitable; rather, it could be due to a lack of introduction. Therefore, caution should be exercised when interpreting model results, and their limitations should be considered to avoid overgeneralisation or erroneous predictions.

Developing species distribution models for regions with complex topographical terrains, such as Malawi, is challenging due to the complex local and regional climate gradients (IPCC, 2014). Hence, caution must be exercised when interpreting model results for local effects on future distribution predictions. For agricultural planning, it is crucial to consider soil nutrition and socioeconomic factors as their combination influences land suitability (Heikkinen et al., 2006; Chemura et al., 2016). Knowledge of specific crop cultivar requirements should also be considered because cultivars are likely to respond differently to climate change. Furthermore,

studies should focus on evaluating the effect of climate change on the trait combination of the various crop cultivars available in different microclimates.

Model building is another limiting factor in species distribution modelling studies, attributed to the different uncertainties incurred during the process (Heikkinen et al., 2006). However, automated model calibration (cross-validation) reduces these uncertainties as it is embedded with novel modelling frameworks. The automated model calibration approach eliminates sources of uncertainty, such as collinearity and model overfitting, which are associated with other model building methods, such as the "priori selection of a set of explanatory variables" (Marmion et al., 2009). Consequently, automated model calibration results in higher accuracy levels of model predictions.

Spatial autocorrelation is frequently encountered in ecological data, and many ecological theories and models implicitly assume an underlying spatial pattern in the distribution of species and their environment (Legendre & Fortin, 1989). Spatial autocorrelation is the lack of independence between pairs of observations at given distances in time and space (Tobler, 1970; Segurado & Araújo, 2004; Paris et al., 2020). Spatial autocorrelation is the most challenging source of bias in species modelling (Dormann et al., 2007). This is because patterns of spatial autocorrelation can produce false-positive outcomes in the analyses (Diniz-Filho et al., 2003; Dormann et al., 2007). According to Segurado et al. (2006), spatial autocorrelation can inflate model predictions up to 90 times.

Several studies have discussed the importance of measuring spatial autocorrelation when evaluating problems in geological ecology, such as latitudinal gradients in species richness (Badgley & Fox, 2000; Jetz & Rahbek, 2001), the relationship between local and regional richness (Fox et al., 2000), spatial patterns in community structure (Leduc et al., 1992) and spatial synchrony in population dynamics (Koenig & Knops, 1998). Therefore, it is essential

to identify the magnitude and structure of the spatial autocorrelation before undertaking any species distribution modelling exercises.

3.10. Conclusions

This chapter emphasizes the importance of species distribution models (SDMs) in predicting the impact of climate change and changes in land use on plant habitats. These changes are predicted to result in range shifts, local extinctions, and displacement of plant species. For perennial crops, it is predicted that average increases in temperatures and shifts in precipitation may result in losses of suitable growing areas. However, this chapter reveals that SDMs can be used to estimate species' potential range shifts in response to different environmental factors. While individual SDMs can determine a species' distribution, ensemble modeling approaches are preferred because of the uncertainties associated with using single SDMs.

Additionally, this chapter emphasizes that the choice of the modelling approach is determined by the study objectives, the nature, quantity, and quality of available data, and personal preference based on the skills and experience of the researcher. It is established that research on climate change impacts on macadamia suitability globally and in Malawi is still lacking. However, climate change threatens macadamia production. Because of the longevity of macadamia, it is thus important to utilise species distribution models to provide an understanding of important weather factors influencing productivity and project impacts of climate change on production. Such analyses are important because these can facilitate in land use planning.

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CHAPTER FOUR: MACADAMIA NUT PRODUCTION AND MARKETING IN MALAWI: A HISTORICAL AND CURRENT PERSPECTIVE

Abstract

Macadamia nuts are a valuable contributor to Malawi's food security, income generation, and export diversification. The country is one of the leading global producers of macadamia nuts, with a thriving industry worth \$30 million and a 3% market share. However, the production is dominated by commercial producers, accounting for 90% of production, while smallholders contribute only 10%. Despite this imbalance, the smallholder subsector can potentially drive future growth of the country's macadamia sector due to its low-input requirements, high returns per unit area (\$10.7–15 kg⁻¹ ha⁻¹) when compared to crops like tobacco (\$1.4–2.55 kg⁻¹ ha⁻¹), and large tracts of suitable land owned by smallholders that can be utilised for expansion. These make macadamia a profitable commodity with the potential for poverty reduction and wealth creation among farming communities. This chapter examines the historical and current trends in macadamia nut production in Malawi, analyses the country's value chain, and discusses the challenges smallholder macadamia producers face for informed policymaking. The synthesis of the smallholder macadamia subsector highlights its significant contributions to rural economic growth and livelihood improvement. The findings are intended to inform policymakers and stakeholders about the potential for smallholder macadamia nut production in sustainable rural development in Malawi.

4.1. Introduction

Malawi is a landlocked country in southern Africa, bordered by Mozambique, Zambia, and Tanzania (Figure 4.1). The country's terrain is highly varied, featuring the lows of the Great Rift Valley, which contains Lake Malawi and the Shire river, as well as high grounds with elevations ranging from 1000 to 1500 m.a.s.l., and peaks as high as 3000 m.a.s.l. The country has a total area of 118,484 km², with 80% (94,449 km²) dedicated to settlement and agricultural production. Water bodies cover the remaining area, particularly Lake Malawi.

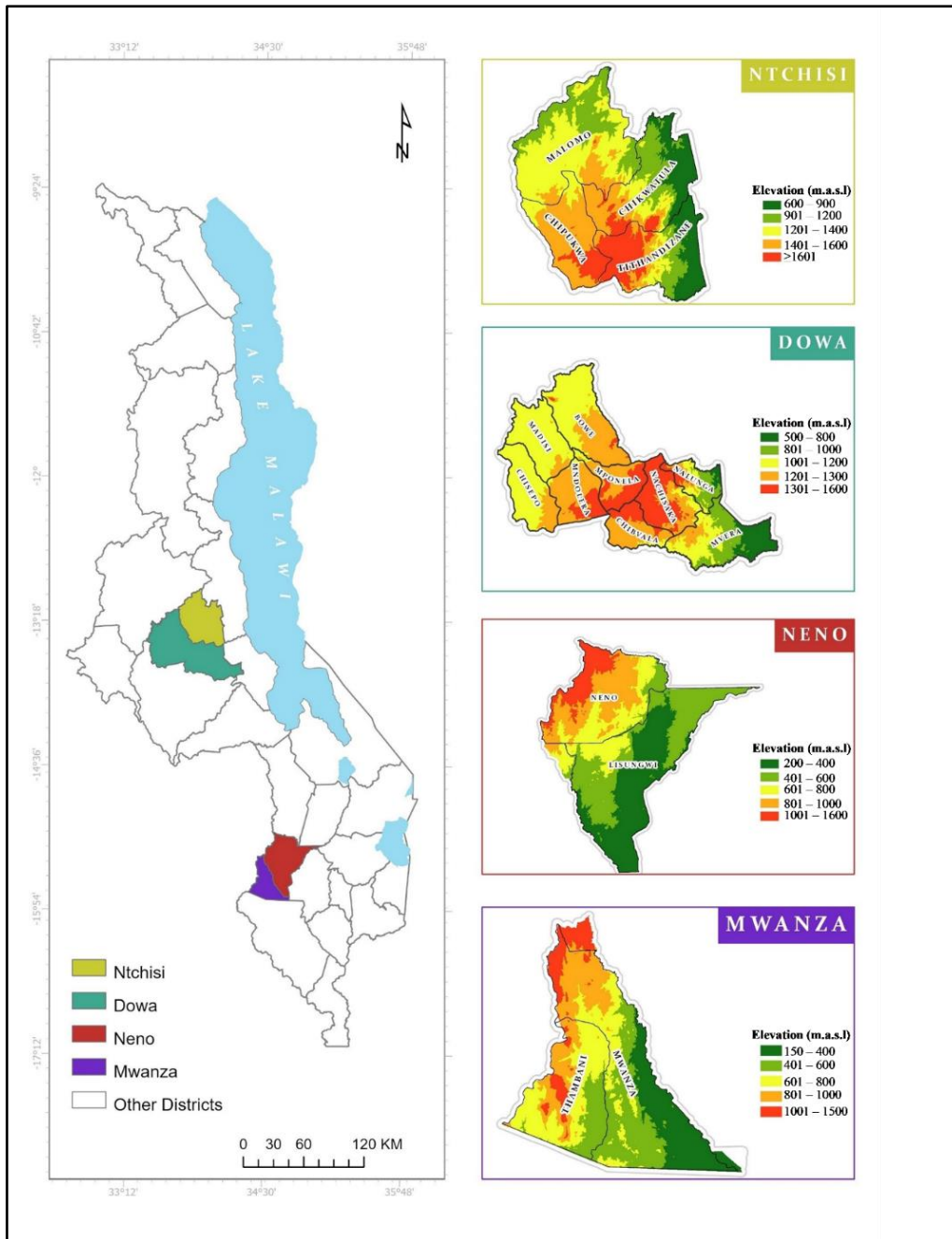


Figure 4.1: Geographical location and topography of Malawi.

Malawi's population has been rapidly growing and is estimated to be over 22.8 million (www.imf.org/en/Countries/MWI). Nearly 83% of the population lives in rural areas (McBride & Moucheraud, 2022). Agriculture remains the core source of income for the majority of Malawians, accounting for over 90% of the population and contributing to approximately 82.5% of the country's foreign exchange earnings (Government of Malawi, 2022). The economy of Malawi is valued at \$12.6 billion by Gross Domestic Product (GDP, Figure 4.2).

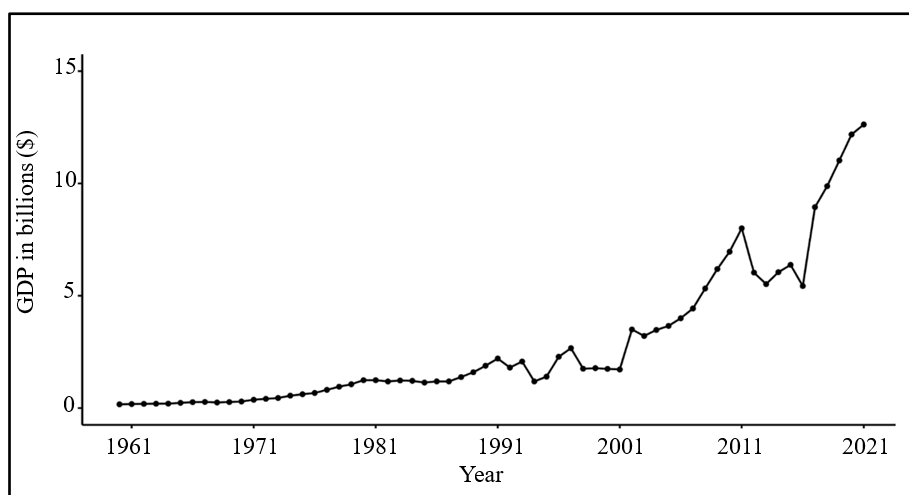


Figure 4.2: Malawi GDP performance ([Data sourced from World Bank](#)).

4.2. The role and structure of the agriculture sector in Malawi

Agriculture is a crucial sector globally, providing the primary source of income and livelihood for many of the world's poorest populations (WFP, 2021). This is particularly true in SSA, where agriculture is a key driver of economic activities (FAO 2022a). The sector accounts for 30–40% of Africa's GDP and almost 60% of its export earnings (FAO, 2022b). Malawi's economy relies heavily on agriculture, with the sector contributing over 30% of the country's GDP and employing more than 85% of the labour force (Government of Malawi, 2018, 2022). The sector is also key to realising the country's long-term economic development plan (National Planning Commission, 2022) and reaching several SDGs, especially those on food security and climate action.

Agriculture provides a livelihood for the vast majority of Malawi's rural populations (Kishindo & Mvula, 2017; Tuni et al., 2022). Crop production mainly concentrates on maize as a primary food source and cash crop. Maize is the country's most dominant crop, occupying around 80% of the cultivated land (Shah et al., 2021). This renders maize the centre of agricultural policies and public expenditures in the country (Government of Malawi, 2020). Moreover, Malawi's food security is characterised by maize harvests and access to maize (Dougill et al., 2020).

Tobacco is an essential cash crop in Malawi and has been one of the country's main agricultural exports for several decades. Despite declining global demand for tobacco products and increasing international pressure to reduce tobacco use, tobacco production remains a vital economic activity in Malawi (Government of Malawi, 2022). Many smallholder farmers depend on tobacco for their livelihoods, and the crop provides a significant source of income and employment for the country's rural population (Prowse, 2022).

Malawi's agricultural sector comprises commercial estate and smallholder producers. The distinction is principally reflected in the tenure systems under which land is cultivated. The commercial estate subsector encompasses large-scale commercial estates ranging from 100 to over 10,000 ha, with land tenure systems primarily based on leasehold or freehold (Joseph et al., 2023). Commercial estate producers are fully engaged in the multiplication of certified seed and cash crop production for domestic and export markets and are classified as having high input and high productivity (Nkhono-Mvula et al., 2023). Tobacco has been Malawi's main cash and export crop since the 1800s, falling under the estates subsector (Wineman et al., 2023).

Smallholder farmers in Malawi, estimated to be two million farm families, cultivate about 4.5 million hectares of land in the country (Dougill et al., 2020; Makate et al., 2023). The subsector is characterised by small-scale, subsistent farming, with the average smallholder farm size being less than 0.8 ha (NSO, 2020; Government of Malawi, 2022). Despite small landholdings, smallholder farmers collectively occupy 80% of the agricultural land in the country. Furthermore, smallholder production contributes approximately 25% of the country's GDP, 95% of the total agricultural labour force, and nearly 70% of agricultural produce, especially maize and tobacco (Drope et al., 2016; Government of Malawi, 2020, 2022).

Despite the important contributions of the smallholder subsector to Malawi's food security and economy, production volumes from each farmer are small, and many are food insecure annually (WFP, 2018; Salima et al., 2023). This is attributed to three key factors. First is the

utilisation of traditional crop production practices, such as the use of handheld implements for farming and over-reliance on seasonal precipitation (Poole, 2017; Tuni et al., 2022). Secondly, limited access to inputs and finance for the farming venture leads to low use of fertilisers and chemicals such as pesticides and herbicides (Makoka, 2009; Burke et al., 2022). Lastly is the lack of crop diversification among the smallholders (Fatch et al., 2023). These factors make Malawi's smallholder farmers increasingly vulnerable to natural and economic shocks, with climate change expected to worsen the situation (Mataya et al., 2019; Burke et al., 2022). Therefore, the subsector must prepare and adapt for sustainable food security and economic development in the country.

4.3. Climate change and agriculture in Malawi

Climate change, caused by human activities, has become an undeniable reality. Evidence shows that agricultural production is already being affected by climate change. This is especially true in many parts of Africa, particularly among smallholder farming households (Woetzel et al., 2020; Agyekum et al., 2022; FAO, 2022b). SSA is currently one of the most vulnerable regions to climate change (Niang et al., 2014; Rivrud et al., 2019; Dougill et al., 2020). Malawi is particularly vulnerable to climate change within SSA due to high poverty levels, limited finances and technology, and a heavy reliance on a predominantly rainfed agricultural sector (Mataya et al., 2019; Warnatzsch & Reay, 2020; Khonje et al., 2022). Moreover, Malawi is exposed to complex, interconnected climate systems, the most important being the monsoons, El Niño Southern Oscillation (ENSO), and cyclones. These climate systems are likely to increase their influence on extreme weather outcomes as a result of warming due to climate change.

Climate change threatens Malawi's economic growth, long-term prosperity, and the livelihoods of an already vulnerable population (Hermans et al., 2021; Nyagumbo et al., 2022). Localised droughts and floods reduce crop yields or result in total crop failure, worsening Malawi's food

security (Jennings et al., 2022). Furthermore, there has been a significant increase in extreme weather events, such as heatwaves, droughts, flash floods, and tropical cyclones in the country, from just one during the 1970s to over 40, dominated by floods between 2000 and 2022 (Trocaire, 2006; Mkusa & Hendriks, 2021; Otto et al., 2022). Climate change projections for Malawi suggest possible yield losses of 50% of maize, 45% of tobacco, 12% of groundnuts, 22% of soybeans, and 9% of potatoes by the 2050s, with adverse implications on food security (Warnatzsch et al., 2020; Bezner et al., 2022; Jennings et al., 2022). However, such climate models have not been developed for tree crops like macadamia and coffee in the country.

4.3.1. Changes in Temperature

Climate change in Malawi is consistent with trends in the broader SSA region and globally. Regarding temperature related extremes, the frequency of hot days and nights has increased over the past decades (Mittal et al., 2017; World Bank, 2022). Between 1960 and 2020, Malawi's average number of hot days has increased by 30.5 days per year, particularly during the dry season (Jennings et al., 2022). Warm night average days have also increased by 41 days over the same period (Khonje et al., 2022; McGill, 2022). However, every degree day above 30°C results in a 1 to 1.7% reduction in maize yields (Lobell et al., 2009). Similarly, temperatures above 30°C result in increased flower abortion and premature nut drop of macadamia, thus reducing the nut yield and quality (Nagao et al., 1994).

Malawi's temperature data shows a ~0.9°C increase between 1960 and 2005 (Figure 4.3), at an average rate of 0.21°C per decade (Sutcliffe, 2014; World Bank, 2019). Future warming trends are anticipated based on global and regional climate model projections, with likely increases of 0.9–1.5°C by the 2030s, 1.1–2.6°C by the 2050s, and up to 5°C by the 2090s based on high risk climate scenarios (Bezner et al., 2022). Results of 34 climate models provide with higher certainty that temperatures in Malawi will likely increase by 1.5°C, 2°C, and 2.3°C by 2030, 2050, and 2070, respectively, above the temperatures of the pre-industrial periods (Dougill et al., 2020; Kavwenje et al., 2022).

Temperature increases in Malawi are predicted to be the most severe during the dry season, especially from September through November (Jennings et al., 2022). However, such temperature increases will coincide with crucial macadamia phenological stages such as flowering and nut development, resulting in flower abortion and premature nut fall, leading to lower macadamia yields and affecting the nut quality (Zuza et al., 2021b). Moreover, Almazroui et al. (2020) have predicted annual temperature increases across Malawi of 1–2°C for the 2050s compared to 1981–2010 for December to February and June to August. This warming is projected to be severe in Malawi's central and southern regions (Warnatzsch & Reay, 2019; Kavwenje et al., 2022). Such warming will likely have detrimental effects on the agricultural sector if there is low policy implementation effectiveness by the government (Jennings et al., 2022). Some detrimental impacts will include crop failure, increases in crop pests and diseases, and a reduction in suitable areas for various crops.

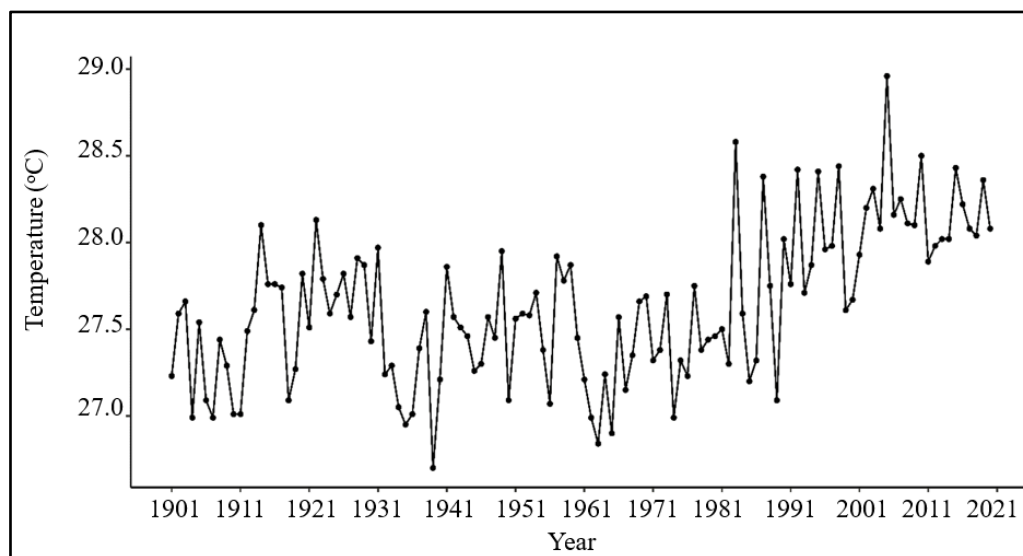


Figure 4.3: Historical average annual temperatures for Malawi (Data sourced from [World Bank Group Climate Change Knowledge Portal](#)).

Furthermore, higher temperatures (+2 to 5°C) are projected to increase aflatoxin contamination levels of agricultural produce, especially in nuts and cereals (Warnatzsch & Reay, 2019). However, studies on the projected impacts of increases in temperature in Malawi have been limited to important staple and cash crops, especially maize (Stevens & Madani, 2016;

Warnatzsch & Reay, 2019; Jennings et al., 2022), tea (Bunn et al., 2017), sugarcane (Dougill et al., 2020), groundnuts, cassava, and soybeans (Mittal et al., 2021; Jennings et al., 2022).

Because macadamia is sensitive to changes in temperature, it is vital to undertake countrywide studies on how the suitability of the crop will fare with projected temperature increases for land use planning purposes. Barrueto et al. (2018) found that future temperature increases will alter the suitability for macadamia production in Nepal. Studies on coffee suitability in the different growing regions globally have shown that predicted increases in temperature will reduce the areas suitable for the crop (Bunn et al., 2015; Chemura et al., 2021; Cassamo et al., 2023). Similar findings have been reported on other important crops in various countries: potatoes (Wang et al., 2021), oil-tea (Wu et al., 2022), bananas (Holanda et al., 2022), and canola (Everest et al., 2022). This, therefore, stresses the importance of suitability studies on land use planning, especially for perennial crops (30–50 years) that require high initial investments, like macadamia.

4.3.2. Changes in Precipitation

Malawian agriculture, particularly smallholder production, is rainfed (Maliro et al., 2017; FAO, 2022a). However, crops are sensitive to water availability, especially during the growing season (Omuto & Vargas, 2018). Short dry periods can be damaging if they occur at critical times of the crop's growth (Brandreth, 2015). For example, during the 2015–2016 growing season, a severe drought caused by El Niño events resulted in extensive maize, groundnuts, and tobacco crop failures in Malawi. As a result, food prices surged, and up to 2.8 million people in the country faced severe food insecurity (MVAC, 2018).

Malawi's agricultural sector is vulnerable to shifts in precipitation patterns, and the frequency of extreme precipitation events, such as droughts and floods, worsens the situation (Murray et al., 2016; Bezner et al., 2022). Droughts and flooding have become more common in the

country, leading to declines in crop productivity and directly impacting the nation's food security. According to Dougill et al. (2020) and informal interviews with farmers, most regions in Malawi have experienced declining precipitation levels over the 1960–2022 period, notably in southern and northern Malawi. The decreases are evident for annual and seasonal precipitation (March to December), while slight increases are evident for the highest precipitation months of January and February (Pohl et al., 2017; Mittal et al., 2017; Jennings et al., 2022).

"Historically, in the winter months of May to July, we used to have a lot of Chiperoni rains in this part of Neno, but now this is becoming increasingly uncommon."
(Emmanuel Junior Zuza [EJZ]_01).

Over the past six years, Malawi has experienced devastating effects from tropical storms Ana, Idai, Kenneth, and, most recently, Freddy, resulting in massive flooding, destroyed property, and communities becoming homeless and food insecure. Despite these climatic shocks, farmers who have diversified into several crops, particularly perennial crops, have reported being somewhat resilient (HIMACUL manager, pers. comm). This is due to reliance on more than one crop and the adoption of climate-smart agriculture technologies such as agroforestry, terracing, and conservation agriculture.

"Macadamia smallholders were better off in terms of resilience to cyclones Ana and Idai. This is because the macadamia trees and crops under the tree were not severely affected by the cyclones. Farmers were able to harvest some of their field crops, in addition to macadamia. The staples were used for food, and macadamia was sold for income. On the other hand, non-macadamia smallholders lost half or all of their entire crop, which rendered them food insecure." (HIMACUL manager).

However, climate change projections of precipitation in the country are coupled with large uncertainties, partly due to the high variability of historical precipitation and the lack of clear trends (Figure 4.4). About 50% of the 34 climate models analysed by Mittal et al. (2017)

indicate that precipitation changes are likely to be less than 5%, while the other 50% disagree on whether the future climate will be wetter or drier and to what extent. The large disagreement among the models indicates low confidence in projections of future precipitation patterns in Malawi. Nonetheless, a less predictable rainy season for smallholder farmers makes planning challenging. This is because farmers rely on knowing when the wet season will begin to sow their crops, apply fertilisers, and harvest during dry periods. Thus, less predictability makes crop yields more variable and vulnerable to post-harvest losses.

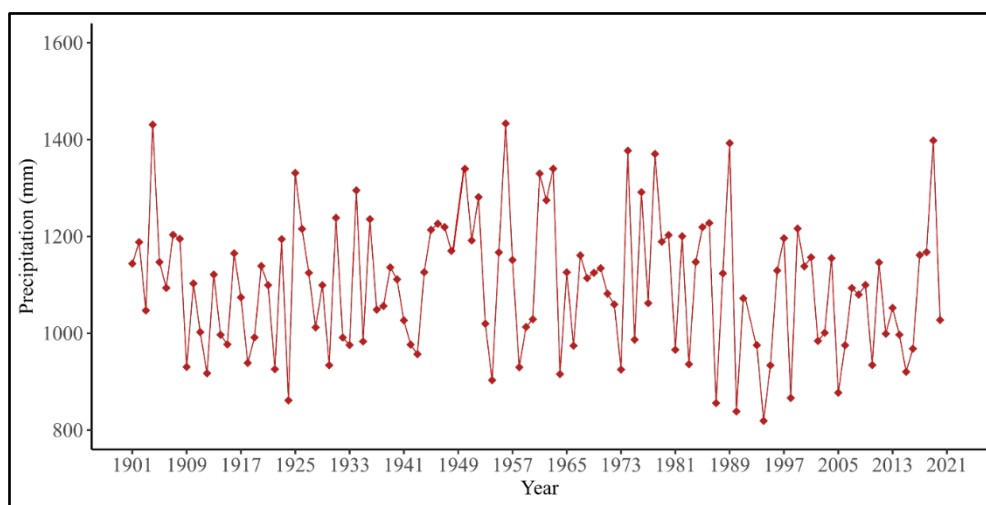


Figure 4.4: Historical annual average precipitation for Malawi (Data sourced from [World Bank Group Climate Change Knowledge Portal](#)).

Projections from GCMs also indicate that Malawi will experience a decrease in the average number of precipitation days and an increase in the duration and intensity of precipitation by the 2050s (de Sousa Pinto, 2015; Nandolo et al., 2022). Seasonal distribution of precipitation will become stronger, with the rainy season receiving a higher proportion of rain and the dry season receiving less (Kavwenje et al., 2022). It is projected that the reduction in precipitation will be more pronounced in the southern region of the country (−5.1%) than in the central (−2.8%) and northern (−1.8%) regions. The combination of these changes suggests more variable precipitation patterns, with a higher likelihood of both dry spells and intense precipitation events, which will be associated with droughts and flooding.

By the 2050s, climate models also predict a 10% increase in drying from September to November of +5 to +10 consecutive dry days compared to 1976–2005 (de Sousa Pinto, 2015; Kavwenje et al., 2022). From December to February, the projections show a small increase in precipitation in Malawi, up to 4% over the same period (Mittal et al., 2017; Kavwenje et al., 2022). Therefore, understanding projected shifts in the amount and distribution of precipitation is crucial for future planning of activities that rely on water availability, such as agriculture.

4.4. The status of food security in Malawi

FAO's World Food Summit (1996) defined food security as the condition where "all people, at all times, have physical and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life." This definition describes the "Four Pillars" of food security: availability, access, utilisation, and stability. Food availability refers to a country's capacity to provide sufficient food to its population through sustainable production, stock levels, and importation (including food aid). Access is a household's ability to acquire adequate food from its local market place. This highlights the significance of purchasing power, applicable to both countries and households on the global market. Food utilisation refers to the appropriate use of food in terms of adequate nutrition and proper preparation and storage. Stability refers to the capacity of individuals to always have access to food, despite sudden shocks such as droughts and economic crises.

Food insecurity is a serious challenge in Malawi, as most agricultural production falls short of its potential due to various factors, including climate change, soil fertility, and management practices (Diro et al., 2019). Maize is a critical aspect of food security among Malawians, with access to and sufficient output of this staple being vital determinants (Makombe et al., 2010). This is reflected in a common Malawian saying: "*Ngati sunadye nsima ndiye kuti siunadye tsiku limenelo*" (meaning if you have not eaten maize thick porridge in a day, you are starving). According to the WFP, as of 2021, an estimated 7.7 million people in the country were food insecure and in need of assistance.

Climatic shocks, primarily by precipitation variability and higher than normal temperatures, result in many smallholders failing to meet their daily subsistence needs. Nearly 80% of rural communities in Malawi are net buyers of maize, but their purchases are hindered by high import prices and weak purchasing power (Government of Malawi, 2018c). Smallholders are the most vulnerable to chronic and transitory food insecurity due to their limited capacity to cope with climatic and economic shocks. For example, the 2017–2018 growing season saw a 22.1% decline in maize production from 3,464,139 MT to 2,697,959 MT due to severe droughts and flooding coupled with fall armyworm (*Spodoptera frugiperda*) damage (MVAC, 2018). This decline was also reflected in other crops, including common beans (5.5%), groundnuts (12.1%), potatoes (8.9%), and soybeans (18.9%). Consequently, 1,062,674 rural Malawians required humanitarian assistance to meet their food and nutritional needs.

As Malawi's population and food demand continue to grow, there is a rising need to increase food availability by making smallholder production more sustainable to maintain per capita production. Despite the recent bumper yields of maize, acute and chronic food insecurity are still major challenges the smallholder producers face (Stevens & Madani, 2016; Nyirenda et al., 2021; Mkusa & Hendriks, 2022). Moreover, by the 2050s, cereal crop production in Malawi is projected to decline by 14%, and climate change will likely have a greater impact (Warnatzsch et al., 2020; Jennings et al., 2022). Current observable events suggest that the frequency of extreme weather in Malawi is also increasing. More droughts and floods have occurred in the last two decades (2000–2020) than in the past three decades before (1970–2000) (Government of Malawi, 2018b; Jennings et al., 2022).

To achieve key SDGs related to food security by the 2030s, notably "No Poverty," "Zero Hunger," "Reduced Inequalities," "Responsible Consumption and Production," and "Climate Action," agrifood systems in Malawi must be made more efficient, inclusive, resilient and sustainable (FAO, 2021). The transformation of agrifood systems can be made possible by implementing climate-smart agriculture practices (Mccarthy et al., 2011; FAO, 2021). CSA

practices support the FAO Strategic Framework 2022–2031, which considers the interlinkages in agricultural productivity, environmental impact, and social sustainability. Consequently, CSA practices are a viable option for achieving food security and resilience to climate change at the community level. Some of the CSA strategies include crop diversification, regenerative agriculture, agroecology, conservation agriculture, and agroforestry (Mccarthy et al., 2011; Hermans et al., 2020; Zuza et al., 2021b).

4.4.1. Crop diversification in Malawi

Crop diversification is an important component of Malawi's National Agricultural Policy. For example, crop diversification reduces the reliance on maize as a staple, enhancing food security in the country. Additionally, crop diversification offers economic benefits by expanding income opportunities for farmers. This is because by cultivating a diverse range of crops, farmers can tap into various markets and diversify income sources, which aligns with the Vision 2063 National Development Plan. Moreover, crop diversification addresses the concern of nutritional diversity among many Malawians. Crop diversification is defined in two ways: horizontal and vertical. Horizontal crop diversification refers to adding crops to an existing cropping system, whereas vertical crop diversification refers to adding high-value crops to an existing system that can be processed and exported for income generation (Adjimoti et al., 2017). Crop diversification can help improve the farming system's productivity, resilience to climate variability and change, and nutrition security (van Vagt, 2018; de Sousa, 2020).

Numerous factors, which vary by country, may lead households to diversify their cropping portfolio. The most common factors include the need to reduce risk, diversify income sources, seasonality, labour markets, pests and diseases management, farmland biodiversity promotion, responding to changing consumer demands or changes in government policy, and, as a climate change coping mechanism (De & Chattopadhyay, 2010; Gajigo, 2013; Rehima et al., 2013; Zuza et al., 2021a).

Crop diversification has been a central focus of the agricultural policy agenda in Malawi, as evidenced by the inclusion of this objective in various national plans and strategies such as the Malawi Growth and Development Strategy II (2011) and III (2017), the National Agriculture Investment Plan (NAIP) (2016), and most recently, the Malawi 2063 policy (2022). The main objectives of these policies are to increase the share of agricultural GDP from crops other than tobacco and maize, enhance resilience to climate change by diversifying production, and improve food and nutritional security for Malawians (Government of Malawi, 2022).

However, to achieve these objectives, farmers need access to resources and market incentives to adopt a range of alternative crops. As such, diversifying crops helps farmers spread market and production risks across multiple crops, thus contributing to the NAIP's second goal and Malawi 2063's first goal of improving Malawians' wellbeing and livelihoods now and in the future. Additionally, crop diversification can improve food and nutritional security by contributing to improved dietary diversity in Malawi. Hence, crop diversification is key to ensuring food security and resilience to climate shocks in Malawi.

4.4.2. Crop diversification with legumes

Nutrient deficiencies are one of the major factors limiting productivity on smallholder farms in Malawi, as soil fertility is low and farmers have limited access to amendments such as inorganic fertilisers and manure (Snapp et al., 2014). Smallholder farmers' limited use of fertilisers and continuous monocropping results in lower yields and nutrient depletion (Waddington & Karigwindi, 2001). Nitrogen is a particularly limiting factor, and smallholders find themselves in a poverty trap where increasing nutrient and soil organic matter (SOM) depletion may eventually result in non-responsive degraded soils (Tittonell & Giller, 2013; Burke et al., 2022). However, legume diversification in rainfed cereal production has been shown to positively affect SOM and N through crop residue incorporation and biological nitrogen fixation (Nalivata et al., 2017; Ngwira et al., 2020).

Legumes fix, on average, 30–40 kg of freely available atmospheric N for every metric tonne of dry shoot matter produced (Setiyono et al., 2010). This can help improve soil fertility, especially when crop residues are incorporated into the soil, increasing crop yields in the subsequent crop (Peoples et al., 2009; Komarek et al., 2021). Additionally, legumes provide nutritional benefits by adding protein to cereal-based diets (Bezner Kerr et al., 2018). Incorporation of legumes into maize-based systems can also help reduce biotic stresses in cereals such as Asiatic witchweed (*Striga asiatica* (L.) Kuntze) and promote biodiversity in farms, which can lead to an increase in beneficial insects such as parasitoids and predators, reducing the need for synthetic pesticides and providing additional cash income if markets are available (Tiftonell & Giller, 2013; McCarthy et al., 2021).

4.4.3. Diversification through agroforestry

Climate emergencies and rural poverty, especially in developing countries, including Malawi, call for a shift to new paradigms regarding farming practices and the relations between farmers and nature (Cialdella et al., 2023). Agroforestry is an agricultural system that combines trees with crops, trees with livestock, or trees with both crops and livestock on farmlands (McCarthy et al., 2011). Agroforestry practices provide countless benefits that contribute to household income (Cerda et al., 2014), develop local and national economies (de Sousa et al., 2019), food security (de Sousa et al., 2017), advance cleaner biofuel energy (Amores, 2015), provides an array of ecosystems services (Somarriba et al., 2013; Chemura et al., 2020), act as a climate change mitigation and adaptation strategy (Garrity et al., 2010; van Noordwijk et al. 2014; McCarthy et al., 2021) and control of pests and diseases (Avelino et al., 2004; Haggard et al., 2011). In addition, farmland trees contribute significantly to the global tree cover (Gassner and Dobie, 2022). Because of these various goods and services, agroforestry systems offer a sustainable form of agriculture and land use (Figure 4.5).



Figure 4.5: Summary of benefits from agroforestry systems (Worms, 2022).

A given agroforestry system is centred on a single species known as a "flagship species" (Gassner et al., 2022). This is the species the farmer values the most, typically because it contributes the most to their livelihood. Additional "flotilla species" are added to provide agroecological services such as nitrogen fixation (Gassner et al., 2022; van Noordwijk et al., 2023). The types of flotilla species are determined by the needs of the flagship species (Dobie et al., 2022). In many agroforestry systems, the flagship species is either an annual crop, a perennial crop, or an animal species.

Flotilla species may consist of trees, shrubs, or annual crops. Common crops grown in agroforestry systems in Africa include well-known staples such as maize, cassava, groundnuts, and rice; cash crops like banana, cacao, coffee, macadamia, and vanilla; fertiliser tree species such as *Faidhebia abida*, *Gliricidia sepium*, *Leucaena leucocephala*, pigeon peas, and *Sesbania sesban*; live mulch grasses like Napier grass; timber species such as bamboo and eucalypts species; fuelwood species and fodder crops.

Agroforestry systems are also beneficial in creating microclimates that buffer supra-optimal temperatures, as has been reported in semi-arid Kenya and Malawi (Lott et al., 2009). Subsequently, agroforestry systems can reduce the damaging effect of high-temperature

exposure of intercropped systems and prevent higher evapotranspiration rates, reducing moisture stress in crop fields.

Among Cameroonian communities, agroforestry is utilised for income generation opportunities through village nurseries and the production of fruits and nuts for trade. Through entrepreneurial opportunities such as processing and out of season fruit, indirect employment opportunities have also improved among the Cameroonian communities, resulting in increased income generation (Asaah et al., 2011).

Studies in Malawi have shown that agroforestry with fertiliser trees like *Sesbania sesban* increases soil fertility and crop yields over time (Koech et al., 2020). Smallholder macadamia agroforestry systems have proven beneficial by providing growers with a supplement for cereal-based diets and income generation through crop sales and fuelwood, thereby reducing deforestation (Brandreth, 2015). In addition, macadamia-based systems are less susceptible to extreme drought and flooding, enhancing resilience and contributing to climate change adaptation among producers in Malawi (Zuza et al., 2021a). As such, it can be concluded that macadamia agroforestry systems offer more benefits than traditional monoculture systems.

4.5. The history of macadamia production in Malawi

The origins of macadamia tree planting in Malawi are not well documented. However, old trees (greater than 80 years old), thought to be the first introductions and still surviving to this day, can be found in Thyolo (Bvumbwe), Ntchisi (Kalira), and Rumphi (Mphompha) districts. These macadamia trees were introduced from Hawai'i in the early 1940s for macadamia research activities (Makoka, 1991). The macadamia research was commissioned to meet the needs of the Malawian government and commercial estate industry demands. The main research questions included:

- Evaluating macadamia cultivars from Hawai'i for growth, yield, and adaptation under Malawi field conditions.

- Development of the macadamia value chain for the estate's sector as a substitution for tung (*Aleurites moluccanus* L.) plantations.

Macadamia research trials were initially conducted at Bvumbwe Agricultural Research Station in southern Malawi and later expanded to other locations, including Kalira Extension Planning Area in the central region and Lunyangwa Agricultural Research Station (LARS) in northern Malawi (Hancock, 1991). At the time, the macadamia nut subsector was dominated by commercial estate producers, specifically Naming'omba Tea Estate Limited and Kawalazi Estate, which were managed by multinational corporations based in the United Kingdom (Emmott, 1989), prior to the country's independence (1964).

The decline of the tung oil industry in the mid-1950s led to the growth of the macadamia nut industry in Malawi (Phiri, 1991). Prior to this, macadamia trees were commonly used by commercial estate producers as boundary markers to prevent land encroachment by neighbouring villagers (Allen, 1987). Although the hectareage of macadamia was often large among the estate producers, it was still regarded as a minor crop in the overall estate production systems (Hancock, 1991). Moreover, during these early years, macadamia crop management was limited (Casey, 1983), and there was little investment in technology for macadamia production and processing; for example, dehusking was performed manually because dehusking machines were considered inefficient as they damaged the nuts (Phiri, 1991).

By the beginning of the 1980s, three commercial estates in Malawi were operational, producing more than 311 metric tonnes of marketable kernel annually (AfDB, 1998). Approximately 95% of all this produce was processed at Naming'omba and Kawalazi factories (Hancock, 1991). Due to the drought during the 1988–1989 rain season, macadamia kernel yields dropped to 150 MT (TNA, 1991). During the 1990s, macadamia hectareage steadily increased to over 2000 ha (Phiri, 1991). Despite the relatively small hectareage, the crops' contribution to the country's economy during these years was significant and contributed to the country's foreign exchange earnings (A.Emmott, pers. comm).

Smallholder macadamia production began simultaneously with the commercial estate sector production but intensified in the 1990s (Parshotam, 2018). Production was primarily concentrated near Bvumbwe, Kalira, and Lunyangwa research stations (Phiri, 1988). Smallholders got their seedlings either from commercial estate producers or research stations. Nevertheless, total production by smallholders was still small and insignificant. Although smallholders, especially those close to Naming'omba, had access to the factory, many ended up removing most of their trees because of reduced and low payments by the factory (Phiri, 1989).

Smallholder growers around Kalira EPA also had to deal with significant marketing difficulties, which further demotivated the farmers. For one, the Ntchisi road did not exist back then, so it took a long time to transport the nuts to Naming'omba factory, thus delaying farmer payments when they most needed it. As a result, farmers sold their nuts to "middlemen" at reduced prices (Makoka, 1991). In 1991, David Emmott and Timothy Kanthiti started promoting smallholder production of macadamia trees in Neno district. As a result of Emmott's initiatives, smallholder macadamia production spread to Mwanza, a district west of Neno (A. Emmott, pers. comm).

Realising the potential of smallholder macadamia production to Malawi's economy and its increasing global demand, the government of Malawi implemented a feasibility study on the suitability of smallholder macadamia production within the country (AfDB, 2009). The study was conducted from 1985 to 1989, but the report was only finalised in 1994 by FAO (AfDB, 2009). Coincidentally, the feasibility study on macadamia was coupled with significant reforms in the agricultural sector, including deregulating particular crops (coffee, tea, macadamia, and tobacco) and liberalisation of prices in 1995 (Chirwa, 2004). These reforms were implemented to stimulate the growth and development of the agricultural sector and to diversify the export base of Malawi.

Because of macadamia nuts' market potential and food value, the African Development Bank funded the Malawi government in 1998 to implement the MSDP (AfDB, 2009). The geographical focus of the MSDP project included five districts, i.e., Dowa, Mzimba, Ntchisi, Nkhatabay, and Rumphi. The project aimed to improve the wellbeing of smallholders by providing income-generating activities while increasing foreign exchange earnings for the agricultural sector. MSDP's specific goal was to promote and develop smallholder production of 1200 ha of macadamia intercropped with 2500 ha of food and cash crops. However, the project's implementation was delayed and only began in 2001 (AfDB, 2009).

The project managed to distribute over 132,000 macadamia tree seedlings, developed 1320 ha of macadamia fields by smallholder farmers, established 320 demonstration plots on farmers' fields, dug 88 boreholes for nursery clubs, and 3650 farmers were trained in good management practices of macadamia, and grafting and ten demand-driven farmers' cooperative societies were established. Despite the potential and the keen interest from smallholder farmers, the MSDP project is regarded as unsuccessful and resulted in many farmers neglecting their macadamia trees after project completion and opting for more profitable crops such as tobacco and groundnuts with established markets and support from the government. The following are some of the reasons the MSDP project is considered unsuccessful (Parshotam, 2018):

- The government of Malawi failed to provide adequate support and continuity once the MSDP project concluded, resulting in a lack of access to macadamia extension services for farmers. Moreover, extension staff were relocated to other districts, leaving farmers without the necessary support and guidance.
- The absence of an established market structure for macadamia nuts created challenges for farmers in terms of selling their produce. This led to farmers selling their nuts at lower prices, ultimately causing some farmers to remove their macadamia trees and switch to crops with readily available markets, like tobacco and groundnuts.

- Sub-optimal infrastructure development (roads, boreholes, and storage sheds) and not all infrastructure works had been completed by project closure, e.g., warehouses and nurseries. This led to contractors abandoning the projects and denying farmers from accessing the facilities.
- Limited access to processing facilities close to smallholder farms forced farmers to travel long distances, often exceeding 600 km, to process their nuts. This led to delayed payments for their produce. Farmers also incurred transportation costs, increasing their overall production expenses and demotivating them.

With funding from the European Union, the Malawi government implemented the Farm Income Diversification Programme Phase I from 2008 to 2011 to revive smallholder macadamia production in former MSDP impact areas. However, the project was also unsuccessful, as farmers in northern Malawi were given macadamia tree seedlings that were unsuitable for the areas, and there was no market outlet in the area to process, market, and export the macadamia nuts (Parshotam 2018). During the same period (2004), David Emmott, a farmer, created the Neno Macadamia Trust ([NMT](#)) and later the Highlands Macadamia Cooperative Union Limited.

4.6. The Neno Macadamia Trust

NMT was founded in 2004 by David Emmott to coordinate support for the Malawian smallholder macadamia subsector. The initial support was focused on the district of Neno and later widely through HIMACUL (K. Mkengala, pers. comm). The Trust works with HIMACUL primary cooperatives to improve their production techniques, provides financial support for the establishment of macadamia tree nurseries, and facilitates market linkages for farmer produce (Zuza et al., 2021a). Additionally, NMT supports the establishment of community-based processing facilities to add value to the raw macadamia nuts, helping farmers to maximise the value they receive for their macadamia nuts. The overall aim of NMT is to

enhance local communities' livelihoods and contribute to the development of the smallholder macadamia subsector in Malawi (A. Emmott, pers. comm).

4.7. Highlands Macadamia Cooperative Union Limited

HIMACUL is a Malawian smallholder-owned macadamia cooperative and works with seven district level primary cooperatives. It operates in Dowa, Mwanza, Neno, and Ntchisi districts but previously included Rumphu district. The main focus of HIMACUL is the promotion of macadamia agroforestry and nut trading with its member farmers (Chandler, 2018; Zuza et al., 2021a). Over 3465 HIMACUL registered farmers cultivate approximately 1000 hectares of land in Malawi. Most of these farmers are smallholders with at least 20 macadamia trees. With financial assistance from NMT, HIMACUL has implemented its five-year plan to intensify macadamia activities in their primary cooperatives from 2016 to 2021, as well as a Plan Vivo payment for ecosystem services (Brandreth, 2015).

Plan Vivo payments support sustainable land use projects, such as reforestation, conservation, and agroforestry (Plan Vivo, 2013). To ensure the long-term success of these initiatives, payments are made over several years (Plan Vivo, 2013; Muttaqin et al., 2019). Plan Vivo certification is crucial as it enables communities and landowners to earn carbon credits through the implementation of sustainable land use practices (Kelsey Jack & Jayachandran, 2019; Drucker et al., 2023). However, payment amounts are project-dependent and typically calculated based on the number of verified carbon credits generated. In the case of HIMACUL, the Plan Vivo framework encourages smallholder macadamia farmers to adopt sustainable land use practices that promote both climate and ecosystem benefits while improving their livelihoods and wellbeing (Brandreth, 2015).

4.8. The current status of macadamia production in Malawi

Macadamia is a thriving crop in Malawi, which competes with other crops for land. Over the years, the total macadamia hectarage has increased significantly, with a growth rate of 83%, from 5280 ha in 1996 to over 10,000 ha in 2021. Notably, smallholders manage around 1500

ha of the total land under macadamia production, representing a 35% increase in mature crops and a fourfold increase in immature trees (Evans, 2020). Understanding the distribution of mature and immature trees is vital in determining the current and future potential of the macadamia industry in the country.

In addition, there has been an upward trend in annual plantings, with 2019 recording the highest annual establishment in 20 years at 1202 ha (Figure 4.6). Since 2016, there has been an average of 980 ha yearly. Furthermore, there has been a noticeable increase in new macadamia establishments in Malawi's northern and central regions, which accounts for almost half of the expansion during the period. This growth in the industry demonstrates the potential for Malawi to become a significant player in the global macadamia market.

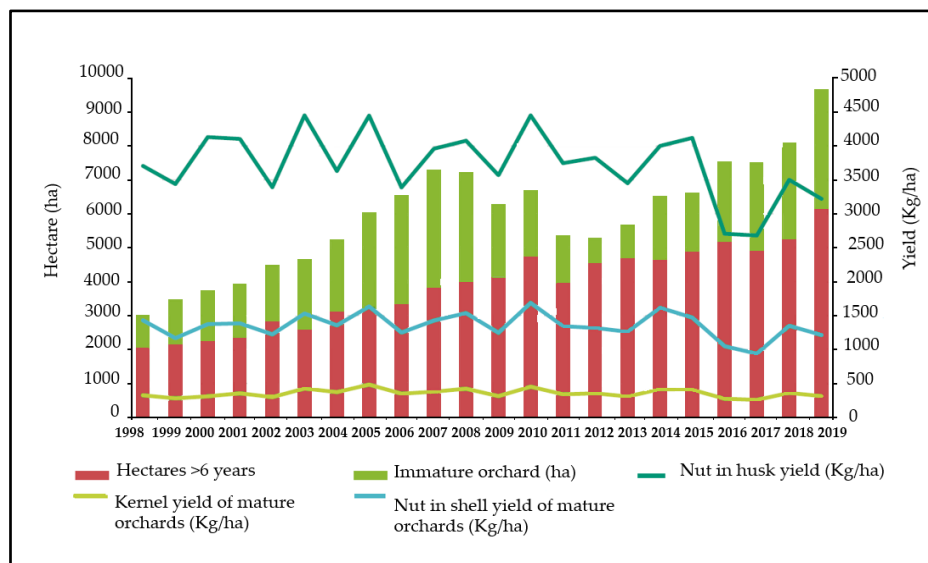


Figure 4.6: Malawi macadamia establishment with nut in husk, shell, and kernel (Evans, 2020).

Currently, there are seven major commercial producers of macadamia nuts in Malawi who also facilitate with processing and marketing of the crop (Conforzi Estate, Naming'omba Tea Estate Limited, Eastern Produce, and Plantation General International, Kawalazi Estate, Sable Farming, Tropha Estates in Mzimba district), alongside some 3850 smallholder farmers spread across the country. Similar to the macadamia industry in Kenya, the Malawian macadamia industry is built around commercial estate producers. These firms perform the greatest share

of the industry's value chain activities (Evans, 2021). Commercial estate producers also provide growers with research and extension services, develop new macadamia products and markets for existing and new products. Overall, commercial estates are essential players in determining the characteristics of the Malawian macadamia value.

In terms of production numbers, smallholder macadamia trees total over 300,000 compared to over one million under the commercial estate subsector (Evans, 2020). These numbers are expected to increase in the next decade due to more government and private sector involvement in the macadamia value chain (Evans, 2020). This is, in addition, to the increase in popularity of the crop among smallholders in Chitipa, Dowa, Mwanza, Mzimba, Neno, Ntchisi, and Rumphi districts. Recently commercial estate and smallholder activity has commenced in Kasungu, Lilongwe, and Mchinji districts (Figure 4.7).

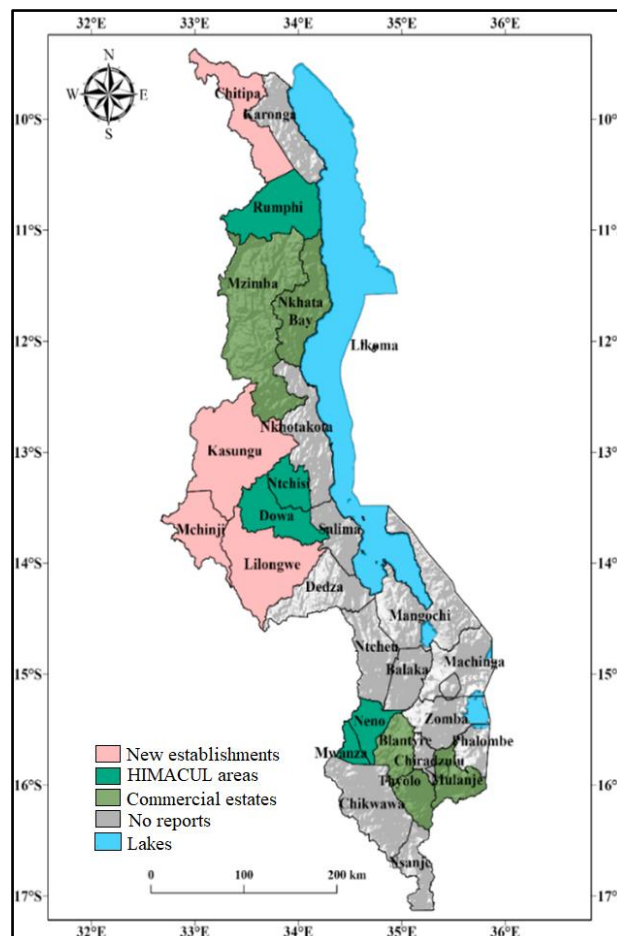


Figure 4.7: Macadamia growing areas in Malawi.

4.8.1. Macadamia production trends in Malawi

Historically, Malawi was one of the world's leading macadamia producers, ranking as the third largest in the mid-1980s (Evans, 2008). However, the country is currently the seventh largest producer, contributing only 4% of global production (Figure 4.8). Over the past decade, Malawi's macadamia production has grown by 53.5%, attributed to increased smallholder tonnage and access to processing facilities (Evans, 2020). With the bulk of smallholder young orchards only starting to produce or not yet producing, the Malawian crop is expected to double in volume in the next two to five years (Evans, 2020). This shows that the country has a strong competitive advantage and can reclaim its previous rankings if managed properly. Nonetheless, extreme weather events, including heatwaves, droughts and floods, and pests like stink bugs and nut borers, have resulted in significant yield reductions in some years (2016, 2017, 2019, and 2020).

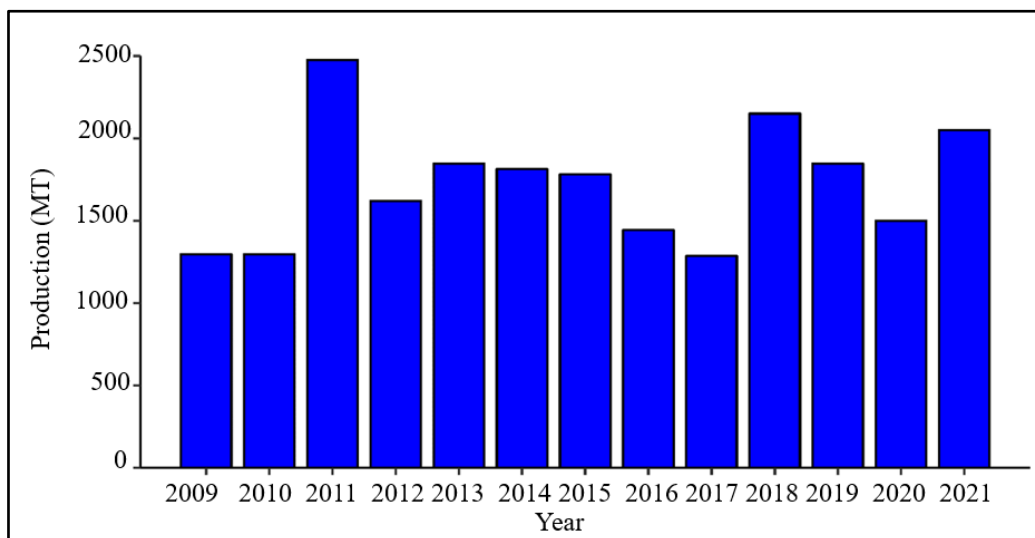


Figure 4.8: Malawi's macadamia kernel production trends (INC, 2022).

4.8.2. Macadamia nut consumption in Malawi

Malawi's macadamia nut production is almost entirely for export, with approximately five percent of the nuts consumed locally (Parshotam, 2018; Zuza et al., 2021a). The primary export destinations are South Africa, the United Kingdom, and the United States. However, the trend

of macadamia nut consumption is changing in Malawi as domestic demand has recently increased (Chandler, 2018). Moreover, macadamia nuts are now widely available in local shops nationwide.

4.8.3. Macadamia nut export from Malawi

Malawi is currently the world's seventh-largest exporter of macadamia nuts, accounting for 4% of global trade on a five-year average (INC, 2022). The primary export market for Malawi's macadamia nuts is South Africa (95%), where the nuts are mainly used for the international snacking market (www.trademap.org). However, with the increasing demand for nuts and their products in countries such as China and Vietnam, Malawi is expected to expand its NIS export markets in these regions. In addition, between 2014 and 2019, Kyrgyzstan and Malaysia, which traditionally imported kernels, began importing NIS macadamia from Malawi (www.trademap.org). This presents an opportunity for Malawian farmers to access a larger market for their produce.

4.9. The Malawian macadamia value chain

Malawi's macadamia value chain encompasses several key players, including producers, aggregators, processors, influencers, and supporting organisations. Figure 4.9 shows a visual mapping of Malawi's macadamia value chain actors. This section is important as it details areas that need improvement to ensure productivity among smallholders.

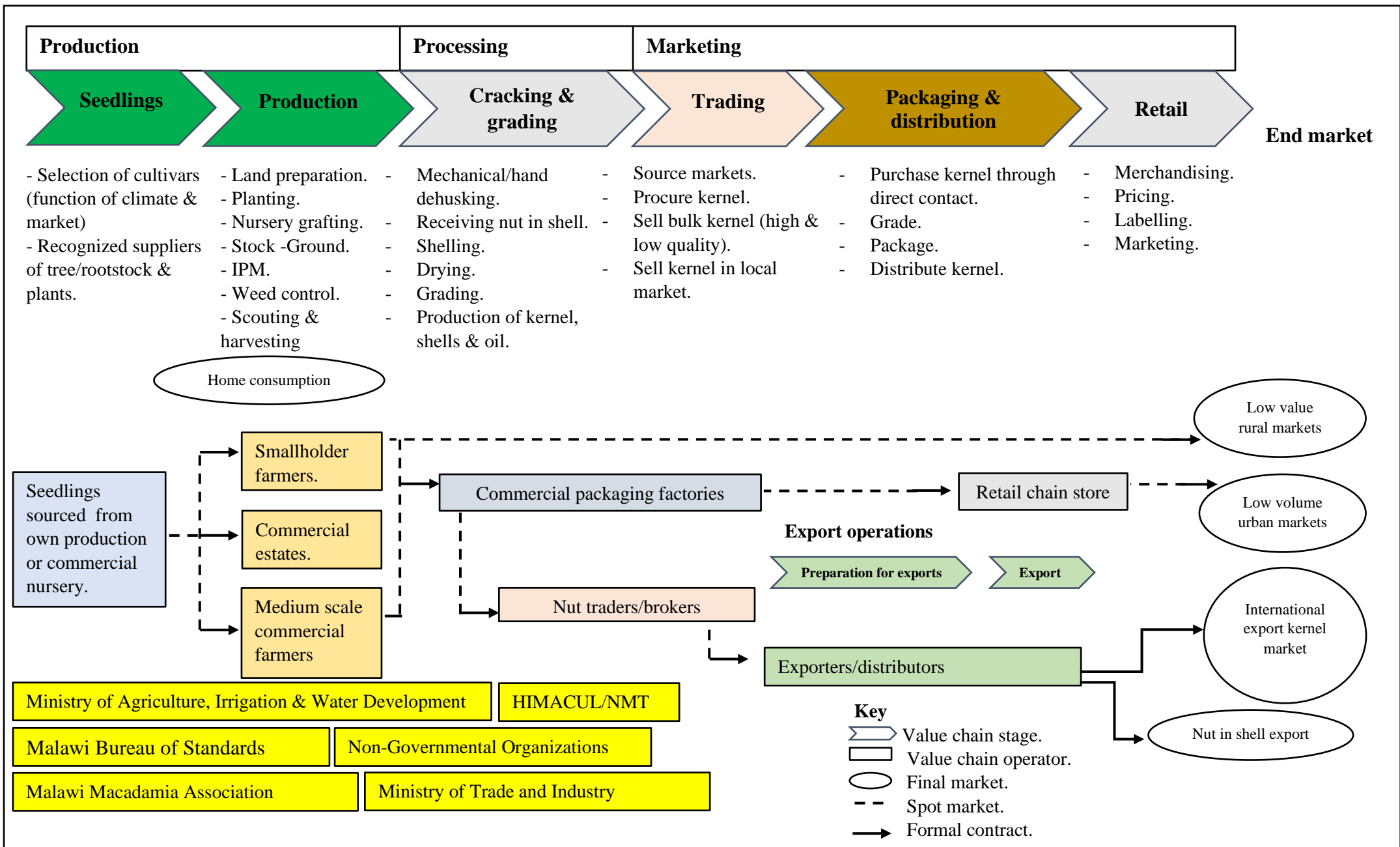


Figure 4.9: Summary of Malawian macadamia value chain actors and their roles.

4.9.1. Producers

Commercial estate producers dominate macadamia production more than smallholders in Malawi. Until recently, smallholder production was concentrated in the southern and central regions of the country (Parshotam, 2018). However, in 2013, the establishment of a macadamia factory by Tropha Estates in the northern region led to an increase in smallholder planting in the region, particularly in the districts of Chitipa, Mzimba, Nkhatabay, and Rumphu (Zuza et al., 2021a). Macadamia production has also started to take shape in Mchinji, Lilongwe, and Kasungu districts, attributed to the conversion of tobacco estates to macadamia estates.

The bulk of the macadamia expansion in terms of area and volumes predominantly emanates from existing farmers expanding primary operations, while new entrants contribute very little growth into primary production (Toit et al., 2017; Zuza et al., 2021a). Smallholder macadamia farming units vary in size and range from small (≤ 0.1 ha) to larger profitable farms (≥ 10 ha). However, the majority (90%) of smallholder macadamia producers individually do not produce sufficient volumes (≤ 200 kg ha⁻¹) to justify the time and capital investment involved in the processing and market development.

4.9.2. Input suppliers

The lack of access to farm inputs such as quality-improved tree seedlings, fertilisers, plant growth regulators, and pest and disease control chemicals is one of the primary causes of low macadamia productivity in Malawi. Rural women with limited access to input face an even worse situation. Among smallholder macadamia producing areas, inputs are sold through farm input supply or agrodealer shops commonly found in trading centres. However, with rapid land degradation, soil fertility loss, and high pest and disease incidences, the relevance of agricultural input supply shops cannot be overemphasized.

To facilitate access to farm inputs, HIMACUL provides input loans (inorganic fertilisers) to their member cooperatives and individual clubs, which are repaid at the end of each harvest season. The in-grower smallholders linked with the estate producers have reported the same arrangement. Macadamia tree seedlings are mainly sourced from HIMACUL and commercial estate nurseries. In addition, some HIMACUL members produce their seedlings through grafting techniques for their use and sell the excess to other non-members.

4.9.3. Nut vendors or middlemen

Macadamia nut vendors, or middlemen, are unregistered buyers of macadamia nuts. These vendors buy macadamia nuts from farmers at farm gate prices and sell them again to registered traders or processors. The central role of vendors is buying and assembly of macadamia nuts. Vendors do this through door to door buying and use buckets as standard measures at pre-established non-negotiable prices. Vendors are predominantly men, as buying requires heavy lifting, walking long distances, and spending long periods away from home.

Often vendors are perceived as dishonest because they buy macadamia nuts at much cheaper prices from farmers than HIMACUL and commercial estates and usually buy the crop without any quality specification. For example, farmers have reported instances when vendors bought the crop while it was still not adequately dried during financial hardship, such as when school fees and other household necessities were due, especially during the lean season months of January and February.

4.9.4. Highlands Macadamia Cooperative Union Limited

HIMACUL is the majority shareholder of [Liberation Foods](#), the first Fairtrade, farmer-owned nut company in the UK, and a member of the International nut cooperative. HIMACUL conducts and coordinates the activities of its seven district level cooperatives, including

agricultural advisory services, provision of tree seedlings and inputs, nut aggregation, bulking, drying, grading, and transportation to processors and trading.

4.9.5. Macadamia Processors or Marketers (Commercial Estates)

The Malawian macadamia industry receives very little assistance in terms of infrastructure development from the government of Malawi (Khan, 2016). The industry predominantly consists of privately owned processing facilities that perform the complete and fundamental processing procedures, covering cleaning, sorting, drying, dehusking, shelling, grading, roasting, and packaging. The core responsibility of processors is to identify buyers and negotiate a price for the nuts. Processors also act as traders by aggregating small amounts of the crop through seasonal vendors. Moreover, commission tariffs from macadamia are determined by processors because of the non-existence of governing authorities in the Malawian macadamia value chain.

Malawi has seven macadamia nut processors, mainly engaged in dehusking and packaging raw nuts (Irish Aid, 2012). The processors only produce 5% of the roasted macadamia for the domestic market, while the remaining 95% is exported to South Africa. However, processors have reported interest in supplying macadamia snacks to retailers globally (R. Saunders, pers. comm). One way to accomplish this would be to use retailer packaging of the nuts in Malawi. While this is feasible for the Malawian value chain, its potential is questionable for international retailers and would require a scoping study on their interests. Another potential solution, especially among smallholder producers, is fair trade certification. This would ensure that smallholders get premiums for their nuts.

4.9.6. Government of Malawi

The main influencers in Malawi's macadamia value chain under the mandate of the Government of Malawi are the Ministry of Agriculture, Irrigation and Water Development, the

Malawi Bureau of Standards, and the Ministry of Industry, Trade, and Tourism. The Ministry of Agriculture, Irrigation, and Water Development is responsible for various tasks within the value chain, which are outlined below:

- Provision of agricultural extension services (Department of Agricultural Extension Services).
- Research (Department of Agricultural Research Services).
- Provision of irrigation services such as drilling boreholes (Department of Water and Irrigation).

The Malawi Bureau of Standards (MSB) is the national standards organisation of the Republic of Malawi. MSB is responsible for the standardisation and quality assurance of processed and sold products within and outside Malawi. The Ministry of Industry, Trade, and Tourism is mandated to facilitate the trade of goods and services within Malawi and in international markets. They are also responsible for the promotion of the Malawi National Export Strategy.

4.9.7. Malawi Macadamia Association

The Malawi Macadamia Association (MMA), established in 2022 (previously known as the Tree Nut Growers Association of Malawi), is a trade association responsible for promoting the growth and development of the macadamia industry in Malawi (MMA, 2022). The association is involved in several activities along the macadamia value chain, including:

- Promotion of macadamia farming: The association promotes macadamia farming in Malawi by helping to increase the number of farmers growing macadamia trees and increasing the overall supply of macadamia nuts.
- Facilitation of market access: The Association is responsible for helping to connect farmers with buyers, both domestically and internationally, to help ensure that

macadamia nuts are sold at a fair price and that farmers receive a fair return for their crops.

- **Quality control:** The Association also oversees the quality control of macadamia nuts produced in Malawi, ensuring that the nuts meet the standards required by buyers and are of high quality.
- **Capacity building:** The Association provides training and support to farmers and other stakeholders in the macadamia value chain, helping to build capacity and improve the industry's sustainability.
- **Representation:** The Association also serves as a representative body for the macadamia industry in Malawi, advocating for the interests of farmers and other stakeholders and engaging in discussions with the government and other relevant organisations.

4.9.8. Non-Governmental Organisations (NGOs)

Various non-governmental organisations (NGOs) play different roles in the macadamia value chain. GIZ is one of the prominent NGOs working in Malawi to improve the macadamia value chain through the inclusion of more smallholder farmers in macadamia production as a way of diet and income diversification, training smallholders in farm business management, and facilitation of linkages between public and private actors within the value chain. AgDevCo, a social impact investor and fund manager, is another important NGO in Malawi's macadamia value chain. The organisation has invested over \$1.5 million in Tropha Estates to develop a 518 hectare irrigated macadamia hub farm and a 1,000 MT processing facility.

4.9.9. Wholesalers, retailers, and the value-adding sector

Malawian macadamia nuts are mostly sold to South African traders, who pack and distribute the kernels to the European snacking market (Scheepers, 2018). Macadamia kernel mainly finds its way to the UK, EU, and US markets as an ingredient in candy. Recently, packers of snacking foods have begun to roast and flavour macadamia nuts, after which they are sold on

the snacking market locally and internationally (A. Emmott, pers. comm). Sound kernel unsuitable for the snacking markets is processed into oil or macadamia butter. Macadamia oil is used as a salad dressing, cooking oil, and in the cosmetic industry as a base for lotions and creams. Macadamia butter is used as a spread or base for pesto and flavouring (Mayer et al., 2006).

Macadamia shells have various applications in Malawi, including being processed into briquettes, pressed board wood products, and carbonated shells for purifying water. In unprocessed form, macadamia shells are used as mulch in gardens and fuel in the boilers of the macadamia processing plants and for cooking or warming water.

Despite the private sector's considerable investment in processing facilities for macadamia nuts, no finished products are produced within Malawi. Most nuts are sold in their raw form in local and international markets. Because of the limited value addition, Malawi nuts fetch low market prices. To increase the profitability of macadamia nuts, there is a need for value addition. Recently, Nutcellars, a UK based start-up organisation, has started value addition of macadamia nuts sourced from HIMACUL farmers into various products such as butter and chocolate. This highlights the potential of further processing the crop in Malawi.

4.10. Analysis of macadamia value chain constraints in Malawi

Macadamia production has been identified as a potential source of income for smallholders in Malawi due to its growing demand as a high-value, export-oriented crop. However, developing a sustainable macadamia value chain in the country faces several constraints and opportunities that need to be considered. The following is a synthesis of the current study findings and previous studies.

4.10.1. Low productivity

Several factors are responsible for the low productivity of Malawian macadamia farmers. Based on desk research, some of these factors are summarised below.

4.10.1.1. Access to quality tree seedlings

Lack of access to high-quality tree seedlings is a significant challenge for many macadamia smallholders in Malawi. This is attributed to the limited availability of certified tree seedling suppliers in the country and thus unable to meet the growing demand for macadamia tree seedlings from smallholder farmers (Toit et al., 2017; Zuza et al., 2021a). Furthermore, the high cost of macadamia tree seedlings (\$3.50 per seedling) represents a significant barrier for many smallholder farmers in the country. As a result, many smallholders view macadamia production as costly, with a few tree seedling suppliers taking advantage of the high-demand situation. Nevertheless, organisations such as HIMACUL and some commercial producers are taking steps to increase nursery production, making it more accessible and affordable to smallholder farmers.

4.10.1.2. Availability of adaptable macadamia cultivars

Macadamia cultivar yields among smallholder farmers in Malawi remain very low ($10 \text{ kg tree}^{-1} \text{ year}^{-1}$) compared to commercial estate producer yields ($30 \text{ kg tree}^{-1} \text{ year}^{-1}$). A contributing factor is the lack of empirical evidence supporting the suitability of existing cultivars for smallholder growing areas (Toit et al., 2017; Zuza et al., 2021b). This lack of information makes it difficult to expand the industry, as the performance of different cultivars under different smallholder growing areas is poorly understood. Therefore, local cultivar performance studies for the smallholder growing areas in Malawi are needed to increase productivity. This is because the success of macadamia tree yields depends on its interaction with the growing area's environment.

4.10.1.3. Climate change

Malawi's good arable land and favourable weather conditions make macadamia production a promising industry. Part of the reason why the sector does not live up to its full potential is the impact of climate variability and change (Zuza et al., 2021b). Changes in climatic conditions result in low and unstable productivity of macadamia trees (Quiroz et al., 2019). Smallholder farmers argue they are less resilient to sudden climate shocks due to a lack of government support for climate adaptation strategies. However, HIMACUL has been advocating for agroforestry, mulching, intercropping, and basin making around the tree to facilitate moisture conservation and soil temperature reduction to address the issues of drought and higher temperatures. In turn, this may result in increasing macadamia productivity.

4.10.1.4. Pests and Diseases

Pests and diseases such as the macadamia nut borers pose significant challenges in the smallholder macadamia production subsector in Malawi. These can result in yield losses of up to 100% and impact crop quality (La Croix & Thindwa, 1986; Schoeman, 2014). Furthermore, insect damage is the second cause of Malawi's low macadamia kernel recovery and a major contributor to low quality (Evans, 2008). As such, the management of pests and diseases is key for sustainable smallholder macadamia production.

4.10.1.5. Lack of agricultural extension services

The availability of agricultural extension staff and macadamia experts in the Malawian macadamia value chain is limited, and this has gotten worse since the Farm Income Diversification Programme (FIDP) and AfDB projects were phased out (Toit et al., 2017). Consequently, macadamia activities have become unsustainable, resulting in many smallholders not reaping the long-term benefits of the crop.

However, for macadamia nuts to remain viable in Malawi as a long-term initiative, providing smallholder farmers with the necessary agricultural extension services and technical support is

essential. Currently, cooperative extension services are a viable option; for example, HIMACUL has successfully trained its lead farmers in macadamia good agricultural practices, who in turn train other farmers (K. Mkengala, pers. comm), and the estates have implemented an agricultural extension to their in-grower farmers (farmers growing macadamia inside the commercial estates).

4.10.1.6. Inadequate farm equipment

Compared to large-scale producers, many smallholder macadamia farmers in Malawi have limited access to production equipment and machinery such as sprayers, planters, dehuskers, and shakers. As a result, there is an urgent need to provide smallholders with basic farm equipment and machinery. This can be accomplished by providing credit to farmers or farmer cooperatives.

4.10.2. Low-quality nuts

The quality of macadamia nuts is very important as it determines the price of the produce. The low quality of smallholder macadamia nuts makes it difficult to get higher prices from the processors. Some of the reasons for low-quality nuts include the following:

4.10.2.1. Immature harvesting

Immature harvesting is a larger issue that has influenced macadamia nut quality for years, causing smallholders' reputations to suffer (Evans, 2021). According to smallholder farmer interviews, when new processors began operations (around 2010), there was a lot of hostility from pioneering processors and producers. Feeling threatened by newcomers, these pioneers adopted a predatory attitude, such as using middlemen to buy the crop without considering quality issues, such as maturity, or offering higher prices than cooperatives, resulting in many uncertainties (Irish Aid, 2012).

4.10.3. Processing capacity

Macadamia processing requires sophisticated infrastructure and equipment (storage sheds, drying racks, a good road network, and a processing factory close to production areas) to be profitable. Macadamia processing companies in Malawi are privately owned, with limited access for smallholder farmers, making it costly for smallholders due to distance. Smallholder cooperatives travel over 600 km to have their nuts processed (Parshotam, 2018). This challenge can be solved through smallholder aggregation of NIS macadamia, and, in the future, the government of Malawi and NGOs can invest in building factories for processing the nuts for the smallholders.

4.10.4. Crop theft

Crop theft is another factor that has caused many smallholders to abandon their farms. It is also a contributing factor to low-quality macadamia. Nut theft predominantly occurs at the community level. However, stealing macadamia compromises the viability of flowers, which become damaged by the action of knocking nuts off the tree by shaking branches or beating the trunk (Quiroz et al., 2019). To address this challenge, the creation of traceability systems is key. This can ensure that only registered macadamia smallholders trade their nuts.

4.11. Opportunities for the macadamia sector in Malawi

There are several opportunities for the growth of the macadamia sector in Malawi, and these include the following:

1. Growing demand: The global demand for macadamia nuts is increasing, and Malawi has the potential to tap into this growing market.
2. Support from government and development organisations: The government of Malawi has expressed support for developing the macadamia value chain, and several NGOs are working to support smallholder farmers in the sector, such as GIZ and AgDevCo.

3. Potential for value addition: There is potential for value addition in the macadamia value chain, such as through the production of macadamia oil and other macadamia-based products.
4. Diversification of crops: Macadamia production can allow farmers to diversify their crops, reducing their dependence on traditional staple crops and improving their overall income.

4.12. Conclusions

Chapter Four explores the agricultural sector in Malawi, focusing on the macadamia industry, its organisational framework, and governance structure. Established by the commercial estate subsector, the macadamia industry competes with other crops for resources such as land and inputs. Despite the limited involvement from the Malawi government, private companies have made substantial investments in the macadamia industry, leading to large, horizontally integrated individual processors to take the lead in crucial activities along the Malawian macadamia value chain, such as production, processing, and marketing. The chapter further provides a comprehensive analysis of the major factors impacting macadamia productivity, especially among smallholder producers, including limited access to quality macadamia tree seedlings, the impact of weather patterns and climate change, insect pests and diseases, and a lack of agricultural extension services.

Despite the identified challenges, the chapter recognises the significant growth potential for the macadamia industry in Malawi. Addressing the identified constraints and capitalising on the available opportunities is crucial to fully realise this potential. Therefore, there is a need for increased public-private partnerships and investment in the macadamia subsector. This can help to improve the infrastructure and provide the necessary support to smallholder farmers through technical assistance and capacity-building programs. The Malawi government can

also play a crucial role in promoting the industry by implementing supportive policies and investing in research and development programs that target the challenges faced by the sector.

Moreover, the chapter emphasizes the importance of enhancing supply chain management practices, particularly in the processing and marketing stages, to increase the competitiveness of the macadamia industry and ensure that smallholder farmers receive fair prices for their produce. A well-functioning market information system can also help reduce risks for producers and processors and improve price transparency. Finally, the chapter underscores the importance of promoting sustainable agricultural practices such as agroforestry and integrating social and environmental considerations into business decision-making. These efforts will ensure the industry's long-term viability and contribute to the overall growth and development of the agricultural sector in Malawi.

In conclusion, the macadamia industry in Malawi holds immense potential for growth and development, and this potential can only be fully realised by addressing the challenges faced by the sector through collaborative efforts between the government, the private sector, and civil society. Therefore, this chapter identifies the areas that must be addressed to ensure that smallholder macadamia production is profitable. These include an understanding of the socio-economic characteristics of the smallholder farmers, climatic factors influencing production, and soil fertility factors hindering yields. As such, this shows how this study aims to provide solutions that can assist smallholder farmers.

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Graphical Abstract



Farmer stands in front of her macadamia field



Focus group discussions



Farmer interviews



CHAPTER FIVE: CHARACTERISATION OF SMALLHOLDER MACADAMIA HOUSEHOLDS, CROPPING SYSTEMS, CULTIVAR PREFERENCES, AND PERCEIVED CONSTRAINTS TO PRODUCTION IN MALAWI

Abstract

Macadamia nuts play a crucial role in the nutrition and livelihoods of smallholder producers in Malawi. Using cross-sectional data from 144 HIMACUL farmers, this study reveals that the majority of smallholder macadamia farmers (62%) are over the age of 50, and farming is their primary occupation. The study finds that yield-related attributes, particularly high yielding potential (38%), nut quality (29%), and extended flowering patterns (15%), are the most important characteristics that determine farmer preference for macadamia cultivars. The most preferred macadamia cultivars found in over half of the farmers' fields are HAES 660 (18%), 800 (10%), 791 (9%), 816 (8%), and 246 (7%), respectively. These findings emphasize the importance of considering smallholder preferences when promoting and introducing macadamia cultivars. Furthermore, the current study reveals that efforts to control pests and diseases, creation a conducive marketing environment, and strengthening and main streaming agricultural extension services for more technological and input support require a strategic institutional framework. In conclusion, the results of this study contribute to the understanding of farmer demographics, preferences for macadamia cultivars, and the challenges they face for sustainable smallholder macadamia production in Malawi. These findings can be used to support smallholder macadamia production in Malawi in the future.

5.1. Introduction

Horticulture plays a vital role in providing food and income for many households in Malawi (Kachule & Franzel, 2009; Chagomoka et al., 2014). Despite utilising only a small fraction of the country's arable land ($\leq 5\%$), the horticulture industry has enormous potential to contribute to both national food security and economic growth (Government of Malawi, 2020). Malawi

is renowned for its diverse fruit crops, including bananas, citrus species, coffee, macadamia nuts, and tea. Bananas and citrus are particularly important, forming a staple part of the diet in rural and urban areas, with approximately 95% of their total production consumed within the country (Government of Malawi, 2020). Additionally, coffee and tea are major products consumed locally and exported (Government of Malawi, 2022).

Malawi is also a major global producer of premium-quality macadamia nuts (Evans, 2021). The crop is well-established and grown on commercial estates and smallholder landholdings across the country (Eed et al., 2016; Zuza et al., 2021b). Because the crop's returns are higher and more stable (~\$14 to 15 kg⁻¹), the country's macadamia industry is rapidly expanding, with farms previously used for tobacco production being converted or diversified to macadamia production (Government of Malawi, 2018).

However, smallholder macadamia trees are less productive than those grown on commercial estates (Zuza et al., 2021a). Several key factors contribute to this disparity, including poor management practices, adverse weather conditions, limited access to high-quality macadamia tree seedlings, soil nutrient deficiencies, pests, and diseases (Toit et al., 2017; Evans, 2020; Zuza et al., 2021a). Previous studies suggest that smallholder macadamia productivity can be improved by introducing new generation cultivars with higher yield potential and greater resilience to pests and diseases (Chandler, 2018; Evans, 2021). Furthermore, implementing good agricultural practices and improving soil fertility can significantly boost the productivity of smallholder grown macadamia trees.

Recent studies indicate that new generation macadamia cultivars have a significantly higher yield potential ($\geq 45 \text{ kg tree}^{-1} \text{ year}^{-1}$) than old generation cultivars ($\leq 30 \text{ kg tree}^{-1} \text{ year}^{-1}$) (Khan, 2016; Evans, 2021). However, their adoption by Malawian smallholders has been slow due to various socioeconomic factors such as lack of awareness, misconceptions about the costs and benefits of the cultivars, and farmer preferences (Toit et al., 2017). Despite this, it remains

essential for smallholders to adopt the new generation cultivars for the long-term growth of the macadamia industry in Malawi. Moreover, macadamia processors in the country are currently advocating for new generation cultivars in response to market demands.

The adoption of new agricultural technologies, including new cultivars, is rarely immediate, particularly for high-value perennials (Pierpaoli et al., 2013; Moyo et al., 2021). New agricultural technologies are often associated with risks and uncertainties regarding the appropriate application, scalability, environmental compatibility, and, most importantly, farmers' perceptions and expectations (Pierpaoli et al., 2013). Subsequently, when working in agricultural systems such as those found in Malawi, it is vital to identify the factors that may influence the adoption of new technologies (Gardner et al., 2019). Previous studies have shown that household characteristics, perceived benefits, market availability, input costs, and long versus short term benefits influence the adoption of an agriculture technology (Etwire, 2013; Reimer & Fisher, 2014; Etten et al., 2021).

Research has shown that Participatory Rural Appraisal (PRA) can help overcome challenges that prevent farmers from adopting new agricultural technologies (Hermans et al., 2020; Ayetigbo & Adesokan, 2023). By incorporating farmer knowledge and perspectives into the planning and management of research development initiatives, PRA increases the likelihood of farmers adopting newly developed agriculture technologies (Banla et al., 2018; Annika et al., 2019). This approach has been successfully applied in different countries, leading to the development of diverse groundnut varieties with desirable attributes for Malawian farmers (Freeman et al., 2002; Moyo et al., 2021) and improved variety adoption of potatoes, barley, pearl millet, and maize for Bolivia, Ecuador, and Peru (Danial et al., 2007).

Therefore, this study examines smallholder farmers' socioeconomic statuses, cropping systems, cultivar preferences, and constraints to macadamia production. The information gathered provides insights into the socioeconomic factors affecting smallholder cultivar preferences and

macadamia production. Additionally, the findings are expected to guide the recommendations of macadamia cultivars for smallholder growing areas and inform future Malawi cultivar acquisition and breeding programs.

5.2. Methodology

This section discusses the following: study sites, research design, target population, sample size, sampling procedure, data collection, research instruments, and data analysis methods.

5.2.1. Study location

This study focuses on smallholder macadamia farmers who are members of the seven primary HIMACUL cooperatives (Figure 5.1). HIMACUL farmers were selected because they are a good representation of smallholder macadamia producers in Malawi (Toit et al., 2017). The farmers were selected on the basis that they actively traded macadamia nuts with HIMACUL, owned at least one hundred macadamia trees, and had at least two consecutive harvests from their macadamia orchards. Consequently, 144 smallholder farmers were chosen, representing 45% of the target population.

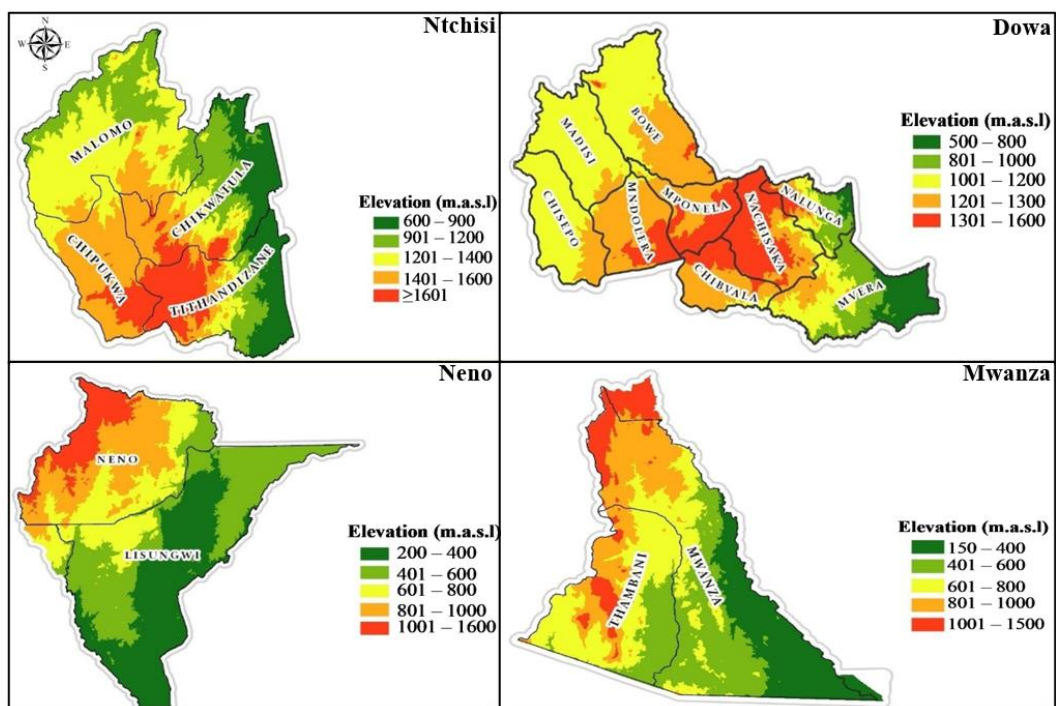


Figure 5.1: Map of districts showing the study sites and elevations.

Dowa district covers an area of 3041 km² with altitudes varying between 700 to 1500 m.a.s.l. The district consists of a hilly eastern region growing crops like bananas, beans, macadamia, sugarcane, and vegetables and a low plain western region focused on groundnut, maize, tobacco cultivation, and livestock production. The district has seven Extension Planning Areas (EPAs), with macadamia cultivation concentrated in Nachisaka EPA. The average annual temperature in the district ranges from 10–32°C (Table 5.1), and the annual precipitation varies from 800–1500 mm. The broad range in annual precipitation is attributed to the district's location. Consequently, precipitation is influenced by the prevailing winds and variations in elevation among the district areas.

Ntchisi district spans 1655 km² and has altitudes ranging from 900 to over 2000 m.a.s.l. The district's primary cash crops are groundnuts, macadamia nuts, soybeans, tobacco, and vegetables. The eastern areas are hilly, while the rest is mostly flat. The agroecology of Ntchisi's EPAs varies significantly from other macadamia growing districts. For example, areas in Tithandizane cooperative range from low-lying hot and dry land on the Rift Valley escarpment to cool and wet areas on the Rift Valley ridge. Precipitation varies between EPAs, with Malomo receiving low precipitation (800–1200 mm) compared to Chikwatula and Tithandizane (1200–1500 mm). The average annual temperature is 8°C in winter and 35°C in summer (Clarkson, 2010).

Mwanza district covers an area of about 826 km². The topography of the district is predominantly mountainous, especially on the western side, with flat alluvial plans on the central side. It has elevations ranging from 600 to 1200 m.a.s.l. The average annual temperatures vary from 15°C in high altitudes and 40°C in lower altitudes. Annual precipitation varies between 600 and 1000 mm. The district has two EPAs, Mwanza and Thambani, and its primary cash crops are tangerines, oranges, lemons, potatoes, and cotton, with macadamia becoming popular recently. Macadamia is mainly grown in Mwanza EPA.

Neno district, covering approximately 1469 km², has a varied landscape, with hilly areas exceeding 2000 m.a.s.l. in the Kirk range and flatter areas in Lisungwi and the Shire Valley (800 and 1000 m.a.s.l.), creating a stark contrast in agroecological conditions within the district. The district has two EPAs: Lisungwi and Neno, known collectively as Neno cooperative. The temperature ranges from 15°C in high-altitude areas to 35°C in the Shire Valley's low-lying areas, with an annual average precipitation of 800–1200 mm. The popular cash crops among smallholders are fruits, especially macadamia, tangerines, oranges, and lemons, alongside pigeon peas and chillies.

Table 5.1: Annual average climate conditions of the study areas.

District	Cooperative	Annual precipitation (mm)	Average annual min temp (°C)	Average annual max temp (°C)
Ntchisi	Chikwatula	1200–1500	10	30
	Malomo	800–1200	11	35
	Tithandizane	1200–1800	8	25
	Mphaza	1000–1500	12	32
Dowa	Nachisaka	800–1500	10	32
Neno	Neno	800–1200	15	35
Mwanza	Mwanza	600–1000	15	40

5.2.2. Research design

The present study uses a descriptive survey design based on Al-Hamdan & Bani's (2022) framework to investigate smallholder macadamia farmers' characteristics, behaviours, and patterns in Malawi. The descriptive design is particularly appropriate for this study for several reasons. Firstly, it enables the researcher to address the who, what, where, and how of the phenomenon under study. Secondly, by collecting quantitative and qualitative data, the descriptive study design allows for a more comprehensive understanding of smallholder macadamia production systems in Malawi. For example, quantitative data describes the demographic characteristics of the smallholders, while qualitative data explores their attitudes and beliefs. Thirdly, the descriptive design was selected as it is relatively inexpensive and feasible, given the limited resources available (Piñeiro et al., 2020). Lastly, the descriptive

design was chosen because it is useful for identifying patterns and trends that inform future studies (Irhza et al., 2023; Mlangeni et al., 2023).

5.2.3. Target population

The term "target population" refers to the particular group of individuals relevant to a study. According to Holden et al. (2018), a population is a group of individuals with similar characteristics. The target population of this study was 317 smallholder macadamia farmers who are active members in this context trading macadamia nuts with HIMACUL. There are other smallholders who are active among the HIMACUL cooperatives but not yet trading nuts.

5.2.4. Sample size and sampling procedure

The study used purposive sampling to select a sample of 144 participants, which is a good representation, according to Thoai et al. (2018), as the population was less than 10,000. Purposive sampling is a non-probability sampling method that involves the researcher selecting participants most relevant to the research question (Sexton, 2022). This sampling approach was chosen because the target population was small, and the researcher sought specific information from the participants. The sample selection criteria was based on the researcher's knowledge, and the sample size was determined by considering factors such as organisation type, purpose, and previous research in the area.

5.2.5. Validity

Validity refers to the accuracy and meaningfulness of conclusions drawn from research results. Sarcheshmeh et al. (2018) suggest that the standard procedure for assessing the content validity of a measure is to consult with professionals or experts in the relevant field to assist in determining question content, correcting wording, sequencing issues, and improving overall study quality. For this thesis, the researcher consulted the industrial supervisor (Andrew Emmott), HIMACUL manager (Ken Mkengala), and two macadamia value chain experts (Dr.

Wayne Hancock, Southern Cross University, Australia, and Nichorus Evans, GFA Consulting Group, Spain). These specialists confirmed that the cases were relevant to the topic of the study.

5.2.6. Reliability

Reliability measures the degree to which a research instrument yields consistent results after repeated trials (Saunders et al., 2019). The researcher conducted a pilot study to assess the reliability and validity of the survey questionnaire. The aim was to ensure the questions were clear and easily understood, the response options were exhaustive, and the questionnaire was completed within a reasonable time. This preliminary testing also allowed the researcher to assess whether the collected variables could be easily processed and analysed. The pilot study was based on a sample of 10% of the respondents. Any question found to be interpreted differently during the pilot study was rephrased so that all respondents would have the same understanding. Prior to the actual collection of data, questionnaires were modified based on the opinions expressed by respondents during pre-testing.

5.2.7. Data collection procedure

Prior to conducting fieldwork in Malawi, ethical approval was obtained from the Open University Human Research Ethics Committee (HREC/3306/Zuza). Primary data was collected from the seven primary HIMACUL cooperative members. Due to Covid-19 travel restrictions, research assistants (RAs) conducted the interviews in place of the researcher. The RAs were recruited according to the regulations set by the Open University. They were required to be university graduates with relevant training and experience conducting surveys and focus group discussions (FDGs). The team consisted of three males and two females.

The questionnaire was structured to address specific objectives and was based on methods for examining agricultural problems and assessing farmers' knowledge, perceptions, and practices

(Bellon, 2001). Both closed and open-ended questions were used to generate data on demographic characteristics, cropping systems, preferred macadamia cultivars and attributes, and production constraints.

Seven focus group discussions (FGDs) with farmers were conducted in two phases in each cooperative. In the first phase, gender-specific groups were formed to obtain participants' opinions on cropping systems, preferred macadamia cultivars, and factors influencing production. In the second phase, male and female participants were mixed to obtain their views on the same aspects. This separation was intended to address cultural norms that may make it difficult for women to express themselves in the presence of their husbands or village elders. The FGDs were conducted in community buildings and facilitated by local research assistants fluent in Chichewa, the local language. They also transcribed and translated the recordings into English to ensure accuracy and consistency. The FGD technique is widely used as a qualitative data collection approach in social science research that provides a large context validity of general scientific information (Kraaijvange et al., 2015; Singh et al., 2023).

Data was collected in September 2021 and was analysed using R[®] Statistical Computing Software version 4.2.2 (R Core Team, 2022). The original questionnaire was in English, but the questions were translated into the local language, Chichewa.

5.2.8. Theoretical model of farmer preference for macadamia cultivars

Farmer preference for macadamia cultivars in Malawi can best be assessed by combining the Random Utility theory (Manski, 1977) with Lancaster's (1966) theory of consumer demand. From the random utility theory, a farmer faces a choice set C that has j macadamia cultivars as elements. The farmer's task is to select cultivars that maximise their utility function U . To select the utility maximising cultivar, the farmer's decision rule is to compare U_1, U_2, \dots, U_j and

select the outcome that gives the maximum utility. Given the utility functions, farmer i only selects a cultivar j over cultivar k in time t if and only if:

$$U_{ijt} > U_{ikt}, \forall j \neq k \forall k \in J \quad \text{Equation 5.1}$$

Each farmer is assumed to have a latent utility function U_{ijt}^* that cannot be observed directly.

What is directly observable to the researcher is the choice U_{ijt} , where $U_{ijt}^* = 1$ if $\max(U_{i1t}^*, U_{i2t}^*, \dots, U_{ijt}^*)$, and 0 if otherwise (Bell et al., 2014).

From the Lancasterian (1966) theory, it can be argued that farmers do not derive utility from a cultivar in its entirety but rather from its fundamental characteristics. This implies that even if all other macadamia characteristics are identical, a farmer may benefit more from cultivating a pest resistant cultivar than a high yielding one. In this regard, it is the cultivar's individual features that provide value to the farmer rather than the cultivar as a whole. Thus, it is clear that the selection of a cultivar is based not on its entirety but rather on its characteristics.

To comprehensively understand farmers' preferences for macadamia attributes, one must consider the various cultivars' attributes and how these influence the farmers' decisions. However, when the smallholders planted their macadamia trees in Malawi, there were limited options for planting materials, and the farmers had no knowledge of the cultivars' characteristics (W. Hancock, pers. comm). Hence, choice in this context must consider the farmers' "preferred cultivar" based on their collective and individual experiences over the last ten years. This study uses two consecutive harvests and owning a ten year old macadamia orchard as part of the criteria for selecting the interviewed farmers. This is because trees are fully matured at this age and can show their full range of attributes.

However, a model that only accounts for macadamia characteristics is unlikely to adequately explain farmer preferences for macadamia cultivars. In essence, the characteristics of the

farmer and the cultivar influence the probability that a farmer will prefer one cultivar over others. Therefore, any model that attempts to quantify the probability of a cultivar being chosen as the preferred option should incorporate farmer and farm attributes. Existing literature on farmer preference for crop varieties suggests that factors such as agroecology, age, gender, access to agricultural extension services, education levels, and household size influence farmer preferences.

Therefore, to better understand farmer preference for macadamia cultivars, it is essential to incorporate these attributes into the model and examine how they condition the probabilities of different cultivars being selected as preferred options. However, some factors that influence farmer preferences may be unknown to the researcher, and therefore, the farmer's utility function from cultivars cannot be fully understood. To account for these unknown factors, the utility function can be expressed as follows:

$$U = \beta'x + \varepsilon \quad \text{Equation 5.2}$$

With β' being the marginal utilities of the various attributes discussed above, x being the observed factors, and ε being an error term that accounts for the unobserved factors that are assumed to be random (Train, 2003). The statistical distribution of the error term (ε) in equation 5.2 determines the distribution of the probability that a farmer will choose any of the j macadamia cultivars in equation 5.1.

The multiple response nature of the farmer's choice task presents a statistical complexity that the researcher must explicitly account for. Given that the farmer can select up to five cultivars based on their characteristics, the probability of selecting one cultivar and another cultivar can be determined jointly. Consequently, the distribution of error terms for the j cultivars can be jointly normal. In such a case, proper analysis of farmer preferences requires a multivariate framework of the Seemingly Unrelated Regression (SUR) type, in which the interrelationships

between the j cultivars are explicitly jointly modelled (Fiebig, 2001). Given their attributes, it is also possible that some cultivars can serve as substitutes. To identify such interrelationships between cultivars, it is crucial to evaluate farmer preferences within a multivariate framework considering the joint distribution of preferences.

A further complication of the model is the discrete outcome nature of the dependent variables, which are binary indicators of whether or not a farmer selects cultivar j as one of their preferences. The binary nature of the dependent variables necessitates additional assumptions regarding the error term distribution in equation 5.2. Since the outcome variables are not continuous, the SUR cannot provide accurate estimates of the model's parameters. Subsequently, a multivariate model with binary outcomes is the most suitable for assessing farmer preferences for macadamia cultivars. Continuing with the assumption of multivariate normal distribution of the errors for the j cultivars (equation 5.2) can be operationalised as follows using a multivariate probit model:

$$y^* = \beta'x + \varepsilon_i$$

Equation 5.3

$$y_i = 1 \text{ if } \beta'_i x + \varepsilon_i > 0, \text{ otherwise } y_i = 0 \text{ if } \beta'_i x + \varepsilon_i \leq 0$$

Where: y^* is the binary outcome, and the other variables and parameters are as previously defined. Notice that the error terms are assumed to be multivariate, normally distributed with a mean zero, a variance of one, and a square simultaneous correlation matrix (Cappellari & Jenkins, 2003). One desirable attribute of this multivariate model is that it collapses to j univariate probit models when the multivariate normal distribution assumption does not hold, still allowing for empirical estimation of the farmer's preference for the individual cultivars.

5.2.9. Empirical model

Implementing the theoretical model above (equation 5.3) requires good variation in the dependent and independent outcomes, preferably from a large enough sample size. However, this study's sample does not allow empirical estimation of the model (preference models for

more than 10 cultivars require at least 3000 individuals for empirical analysis (Byrne et al., 2015; Moyo et al., 2021). Therefore, empirical estimation of the model becomes difficult as the model cannot converge regardless of how it is specified. However, the study ran one probit that explains farmer preference for the cultivar HAES 660. Based on the descriptive analysis, HAES 660 is the cultivar that farmers prefer the most. The model is specified empirically as follows:

$$y_i = \beta_0 + \beta_1sex + \beta_2age + \beta_3cooperative + \beta_4education + \beta_5landsize + \beta_6droughtresistance + \beta_7nutsizesize + \beta_8yield + \beta_9windresistance + \varepsilon_i$$

Where: y_i is a dummy variable equal to 1 if the farmer chose cultivar HAES 660 as their preferred cultivar and 0 if otherwise; β_n are parameters to be estimated; ε_i is an error term assumed to be normally distributed, and the sex, age, cooperative, education level, land size (hectares or ha), drought resistance (dummy), kernel quality (dummy), yield (dummy), and wind resistance (dummy) are farmer, farm and cultivar attributes theorised to affect the choice for the cultivar.

5.3. Results

5.3.1. Gender and age of farmers

The male population constituted 58% of the participants, while the remaining 42% were female (Table 5.2). However, more than 90% of the farmers report owning their macadamia orchards in partnership with their spouses, emphasizing the importance of family relationships. In terms of age, the majority of the sampled farmers (62%) are more than 50 years old, implying an aging population and highlighting the need to encourage younger generations to engage in macadamia production.

5.3.2. Education and marital status

About 53% of the sampled farmers report having attained the Malawi Primary School Certificate of Education, and 32% have completed secondary or university education.

Chikwatula and Neno cooperatives have the highest proportion of farmers with secondary and university education. However, 15% of the farmers have not received any formal education. Of the 144 participants, approximately 80% are married, while the remaining are single (3.5%), divorced (2.8%), or widowed (13.2%).

5.3.3. Occupation

The majority of the participants (90%) in this study consider farming their main occupation, implying that agriculture is the main source of income among these farmers. In-depth interviews with the participants revealed that farming is essential for their livelihoods in terms of income generation and plays a crucial role in ensuring food security. Nevertheless, about 6% of the farmers are engaged in alternative ventures, such as operating motorbike taxis, while the remainder is either retired or involved in non-agricultural jobs. The farmers emphasized that the motorbike taxi business is particularly profitable in the study areas due to poor access roads to the district centres, serving as an additional source of household income.

Table 5.2: Socio-demographic characteristics by cooperative.

Variable	Chikwatula (n = 20)	Malomo (n = 19)	Mphaza (n = 20)	Tithandizane (n = 24)	Mwanza (n = 24)	Nachisaka (n = 18)	Neno (n = 24)	Overall (N = 144)
Gender (%)								
Female	6.3	4.9	6.3	2.1	10.4	2.8	9.0	41.7
Male	7.6	8.3	7.6	13.9	6.3	9.7	4.9	58.3
Age (%)								
18–30	0.7	0.0	0.7	0.7	1.4	0.0	1.4	4.9
31–40	0.7	0.7	1.4	0.0	0.7	0.7	2.8	6.9
41–50	2.8	3.5	3.5	4.2	6.9	4.1	1.4	26.4
51–60	4.9	2.8	4.2	6.3	2.8	3.5	2.8	27.1
61–70	3.5	2.8	2.8	2.8	2.1	2.1	3.5	19.4
≥ 70	1.4	3.5	1.4	2.1	2.8	2.1	2.1	15.3
Marital status (%)								
Single	0.7	0.0	0.7	0.0	0.7	0.0	1.4	3.5
Married living with spouse	9.7	13.2	10.4	14.6	12.5	11.8	7.6	79.9
Married living without spouse	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.7
Divorced	0.0	0.0	1.4	0.0	0.7	0.0	0.7	2.8
Widowed	3.5	0.0	1.4	1.4	2.8	0.0	4.2	13.2
Education (%)								
No formal education	1.4	2.1	2.8	4.2	3.5	0.7	0.7	15.3
Primary education (1 – 8)	6.3	6.9	8.3	9.7	8.3	6.9	6.3	52.8
Secondary	2.8	4.2	2.8	2.1	4.2	4.9	6.3	27.1
Tertiary (College & University)	3.5	0.0	0.0	0.0	0.7	0.0	0.7	4.9
Occupation (%)								
Agriculture self-employed	12.5	12.5	13.2	14.6	13.2	11.1	11.8	88.9
Informal unskilled labour	0.7	0.0	0.0	0.0	1.4	0.0	0.0	2.1
Domestic worker	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.7
Pensioner	0.7	0.0	0.0	0.0	0.0	0.7	0.7	2.1
SME owner	0.0	0.7	0.7	1.4	1.4	0.7	1.4	6.3

5.3.4. Household sizes

On average, the family sizes range from 3.2 to 5.7. Farmers in Mwanza, Chikwatula, and Mphaza cooperatives have the highest average household sizes of 5.7 and 4.7, respectively, whereas Malomo and Nachisaka have the smallest average family sizes of 3.3 and 3.2, respectively (Figure 5.2). The remaining cooperatives, i.e., Neno and Tithandizane, have average family sizes of 4.6 and 4.0, respectively. According to the farmers, these large family sizes stem from the necessity of having family members involved in agricultural activities. Moreover, within their communities, having more children is considered a symbol of wealth, further underscoring the cultural significance placed on family size among these farmers.

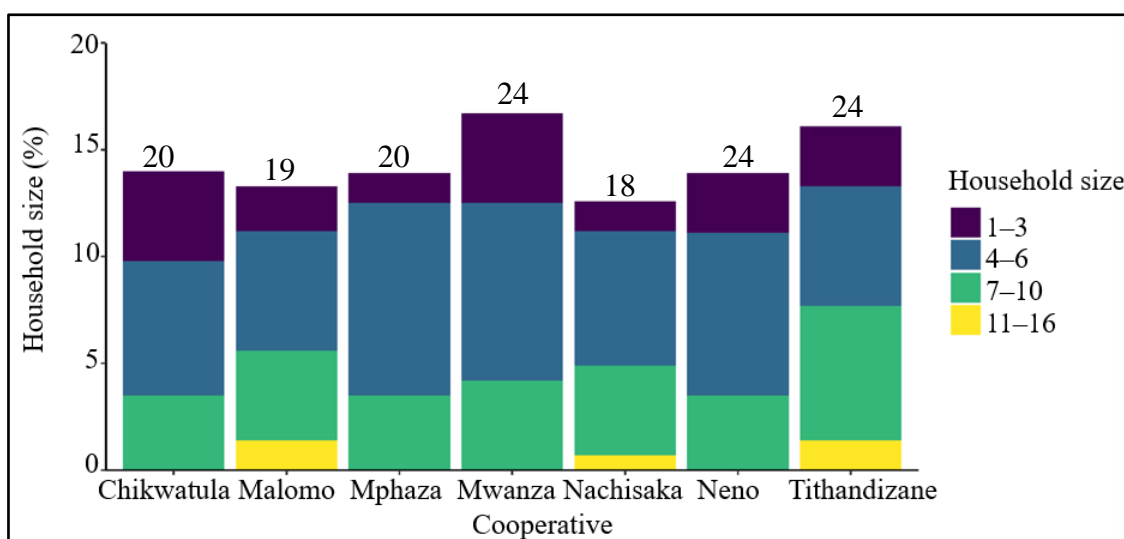


Figure 5.2: Size of smallholder macadamia farming household (N = 144).

5.3.5. Land acquisition

Land is a critical and irreplaceable factor for agricultural production. The Malawi integrated household survey (2020) identifies seven key modes of land acquisition used by farmers in Malawi: land allocation by a family member, inheritance, short-term rent, land grants from local leaders, land gifts from non-family members, private purchases, and borrowing. Most participants in this study acquire land through inheritance (89%) and purchase (14%). Only 4% of the participants report renting land for agriculture. The farmers highlighted using personal land for cash crops and rented land for staples.

5.3.6. Landholding sizes and allocation to macadamia

The average landholding size for smallholder macadamia farmers in Malawi is 1.23 hectares. The largest landholdings are in Mphaza (1.70 ha, Table 5.3) and Chikwatula (1.33 ha) cooperatives. However, land ownership does not imply macadamia production, and to better understand this, farmers were asked to provide information on the total land allocated for macadamia production. Of the seven cooperatives, Chikwatula and Tithandizane have the largest land allocated to macadamia, averaging 1.04 and 0.94 ha, respectively. On the other hand, Neno (0.36 ha) and Mwanza (0.35 ha) cooperatives have the smallest land sizes allocated to macadamia, mainly due to the land allocation for citrus production, especially tangerines.

Table 5.3: Average total land and macadamia land sizes at the cooperative level.

Cooperative	Total land in hectares	Land allocated to macadamia (ha)
Chikwatula	1.33	1.04
Malomo	1.20	0.80
Mphaza	1.70	0.73
Tithandizane	1.30	0.94
Mwanza	0.80	0.35
Nachisaka	1.30	0.71
Neno	1.00	0.36

5.3.7. Crops grown

Smallholder macadamia farmers in Malawi cultivate multiple crops, including maize, macadamia, soybeans, common beans, groundnuts, tobacco, and vegetables (Figure 5.3). They also grow bananas, cassava, pigeon peas, and sweet potatoes on a smaller scale. The majority of the study participants report that macadamia is their main crop (after maize), with soybeans, common beans, and groundnuts as secondary crops. Farmers highlighted that the cultivation of multiple crops is driven by the need to enhance resilience against frequent climatic shocks like dry spells and flooding and diversify their sources of income. Additionally, the farmers report that including legume intercrops helps them improve the soil for the crops, while also giving them a source of relish.

However, the cultivation of each crop varies in intensity and complexity. For example, tobacco and vegetables require more intensive cultivation than maize and macadamia. The analysis of tobacco production reveals interesting trends: Neno and Mwanza cooperatives do not engage in tobacco production, while its production is declining in Chikwatula and Tithandizane cooperatives. Farmers in Chikwatula and Tithandizane cooperatives report a reduced interest in tobacco production compared to previous decades, attributing it to high production costs, fluctuating prices, and high rejections levels at the auction holdings. On the other hand, farmers in Malomo and Mphaza cooperatives continue to show a high interest in growing tobacco. Farmers in these cooperatives mentioned that tobacco estates facilitate access to production inputs and markets, contributing to their continued interest in growing the crop.

"Despite the reduction in tobacco hectarage allowed by buying companies, I continue to grow the crop. I allocate a smaller portion of land for tobacco to meet their requirements. This decision is driven by the proximity of my residence to tobacco commercial estates, which grants me access to inputs, extension services, and markets."
(EJZ_02).

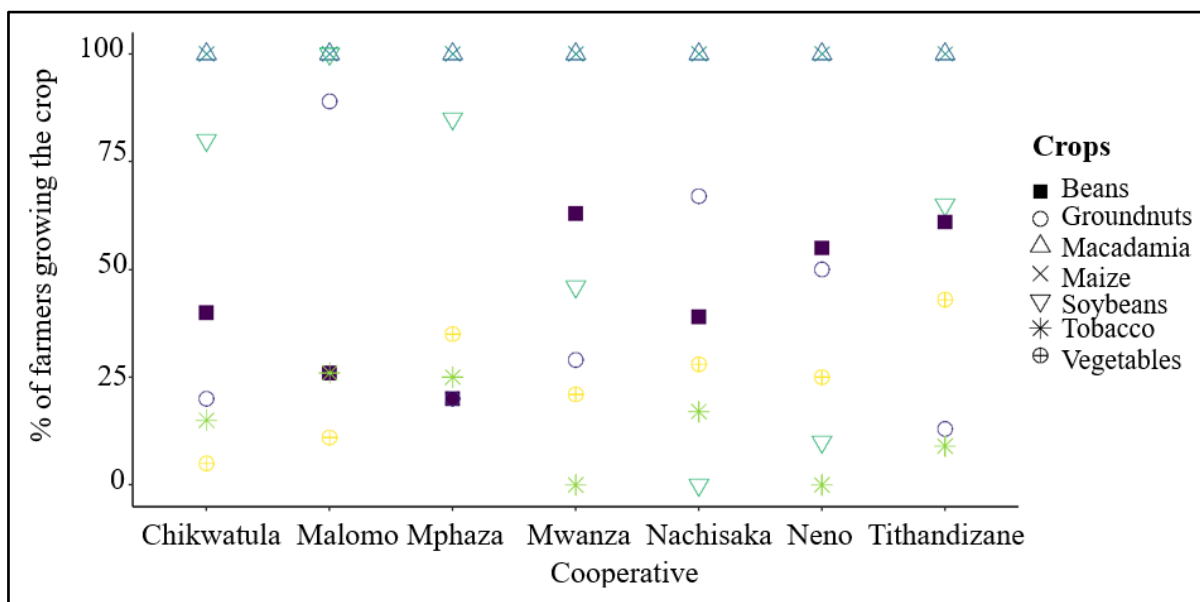


Figure 5.3. Common crops grown by smallholder macadamia farmers.

5.3.8. Cropping system characteristics

Smallholder macadamia farmers use a mixture of cropping systems, including agroforestry, intercrops, and monocultures. Most farmers (98%) indicate that they practice agroforestry. This is followed by intercrops (50%). About 57% also use sole cropping, especially for tobacco and cotton production. The intercropping systems comprise combinations of cereal and legume crops, such as maize with soybeans, or doubled-up intercrops consisting of pigeon peas with grain legumes like groundnut and soybean. On the other hand, agroforestry systems mainly consist of macadamia trees intercropped with either fruit trees (e.g., citrus, bananas, mangoes) or fertiliser trees, along with understory crops. The farmers reported different reasons for such diverse cropping systems, such as improving soil fertility, increasing yield, diversifying income sources, and resilience to climatic shocks.

"One of the advantages of macadamia agroforestry is the year-round crop harvest. I am preparing to harvest the cabbages, and I already had my first macadamia nut harvest last December. Moreover, I find the prices for macadamia to be highly competitive compared to other cash crops like groundnuts and soybeans. Additionally, I have a reliable market through HIMACUL." (EJZ_03).

5.3.9. Macadamia utilisation

The study findings indicate that smallholder farmers primarily use macadamia nuts for income generation (100%) and personal consumption (47%) while also diversifying their crop production (6%). Additionally, the dried husks and shells of macadamia nuts serve as a versatile fuel source (5%). Farmers report that the fire from macadamia shells burns longer than wood charcoal, which helps reduce deforestation caused by charcoal production and the use of firewood. Furthermore, farmers consider macadamia production as a means to adapt to and build resilience against climate change (10%, Table 5.4). These results demonstrate the potential of macadamia nut production to enhance smallholder farmers' dietary and economic diversity in Malawi while also serving as a climate change adaptation strategy. Some of the focus group participants reported these:

"Despite the flooding that destroyed my maize field, I can still depend on my macadamia trees during these difficult times. I already harvested the first batch of macadamia nuts, keeping some for consumption and selling the surplus for income while I wait for the second and third harvests. This means I have an additional crop that provides both food and income for my family." (EJZ_04).

"When I initially began growing macadamia with the MSDP project, it was merely an experimental venture. However, I now view macadamia as my retirement crop. In addition to being a source of food and income, I receive incentive payments for the carbon sequestration my macadamia trees accomplish. This is one of the motivating factors that drive me to continue cultivating macadamia and to pass on the knowledge to my children." (EJZ_05).

Table 5.4: Utilisation of macadamia trees, nuts, and by-products.

Method of utilisation	Frequency (N = 144)	Percentage (%)
Source of income	144	100
Consumption	67	46.5
Climate change adaptation	15	10.4
Broad crop diversification	9	6.3
Source of fuelwood	7	4.9

5.3.10. Reasons for macadamia nut consumption and methods of consumption

The study findings indicate several reasons why smallholder farmers consume macadamia nuts. Of the 144 participants, about 61% consume macadamia nuts because of the perceived nutritional benefits, with easy access to the nuts (28%) and supplementing diets (7%) being additional factors for farmers' consumption of the nuts (Figure 5.4). Moreover, 4% of the sampled farmers have other reasons they consume macadamia nuts.

The study participants use multiple ways to incorporate macadamia nuts into their diets (Appendix 6). Approximately 21% of the farmers mill the macadamia nuts together with maize

to produce flour. This flour is then used to make the local staple "nsima," porridge, or as a flavouring additive in relishes, thereby enhancing the nutritional value of the dishes. Consequently, macadamia flour is a beneficial supplement to maize among the smallholder farmers. About 42% of the farmers prefer to consume nuts as raw snacks, while 36% enjoy dry pan-fried nuts. Furthermore, the farmers report that they have access to a small oil press provided by HIMACUL, which enables them to extract oil from their macadamia nuts. This oil serves as a healthy cooking base, further diversifying their culinary applications, some of which are described below based on focus group discussions:

"I consume macadamia nuts because they have many medicinal benefits, including lowering blood pressure." (EJZ_06).

"One common dish I love to prepare is boiling pumpkin leaves in combination with a half cup of macadamia flour and a touch of salt, which is eaten with nsima or potatoes and red beans." (EJZ_07).

"The cake, which is the residue from macadamia oil extraction process, is mixed with maize flour to make traditional Malawian bread ("chigumu") for the household." (EJZ_08).

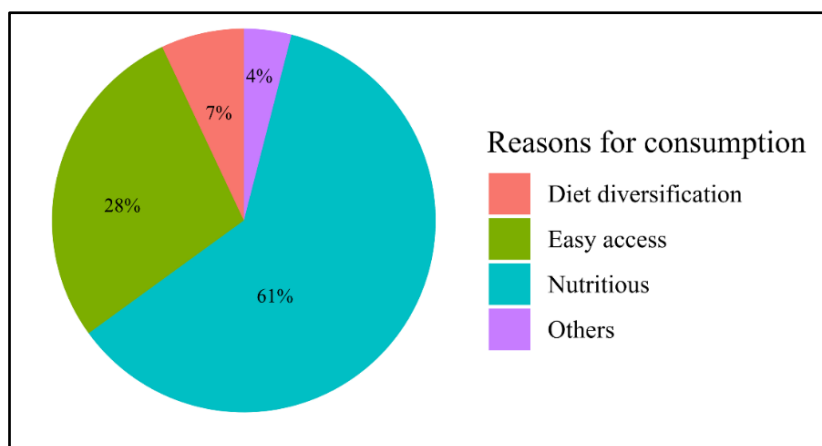


Figure 5.4: Reasons for the consumption of macadamia nuts.

5.3.11. Source of macadamia tree seedlings

Fifty-six percent of the participants acquire their macadamia tree seedlings from HIMACUL nurseries, with 28% obtaining them from commercial estate nurseries. Farmers also report that they graft their own materials (13%) and exchange tree seedlings with each other (3%). Through discussions with the farmers, it is evident that they perceive the prices of tree seedlings, especially from commercial estate nurseries, as expensive. In contrast, the farmers report that HIMACUL provides subsidies for tree seedlings. However, as the demand for tree seedlings continues to rise, farmers express the need to increase nursery capacity to meet their requirements.

5.3.12. Sources of agricultural extension services

Access to agricultural extension services plays a crucial role in maximising crop productivity. Farmers rely on access to agricultural information to adapt, adopt new technologies, modify their practices, access inputs, achieve agricultural outputs, add value to their products, and effectively market their produce. Within the study areas, HIMACUL is the main provider of macadamia extension and training services (Table 5.5). The secondary providers of macadamia extension services are fellow farmers (13%), NGOs (6%), and the government (5%). HIMACUL's prominent position is attributed to its collaborations with NMT and proximity to farmers, facilitating effective knowledge transfer and support.

Table 5.5: Macadamia information sources.

Source	Frequency (N = 144)	Percentage (%)
HIMACUL	110	76
Fellow farmers	15	13
Malawi government	9	5
NGOs	10	6

5.3.13. Macadamia cultivars grown

Smallholder macadamia farmers in Malawi commonly cultivate a diverse range of 18 macadamia cultivars (Figure 5.5). Among these cultivars, HAES 660 is the most commonly grown cultivar, accounting for 49% of the total, followed by HAES 800 (26%), 791 (19%), 333 (13%), and 246 (12%). On average, these farmers cultivate a combination of seven to eight cultivars in their orchards. Interestingly, the study also reveals that some farmers have adopted some of the new generation cultivars, including HAES 772 (12%), 816 (11%), and 741 (11%). However, smallholders have not yet widely adopted some of the newer cultivars introduced by commercial estate producers in 2010, such as Beaumont, Daddow, and MCT1.

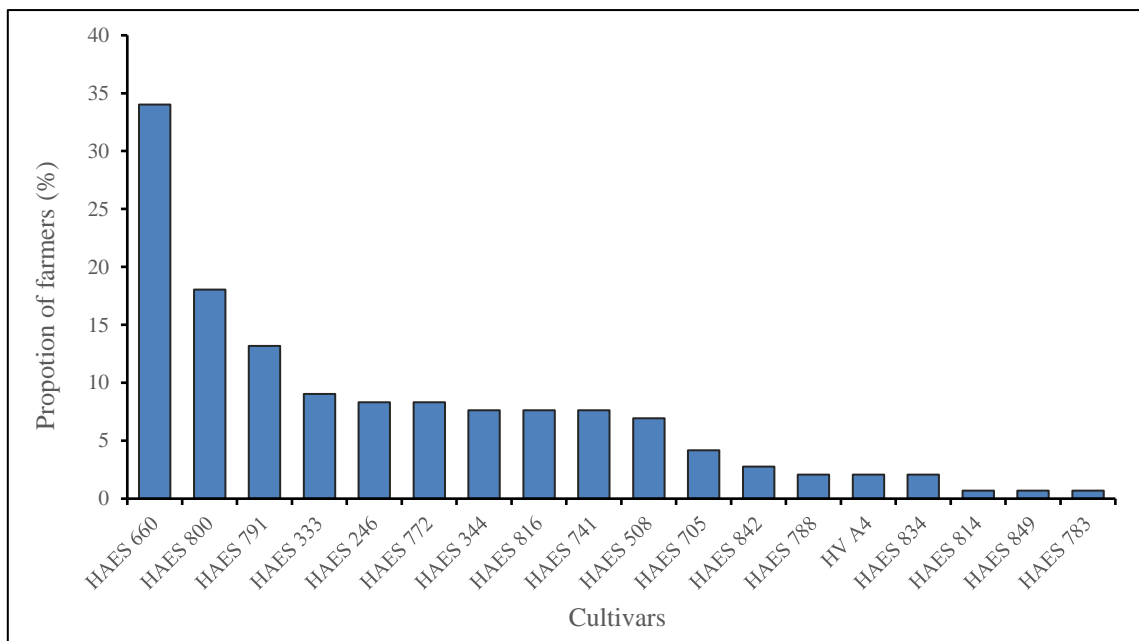


Figure 5.5: Macadamia cultivars common among smallholder farmers in the study areas.

5.3.14. Drivers of macadamia cultivar preference

Farmer perceptions are a key factor in determining the overall acceptability of macadamia cultivars. Figure 5.6 shows that smallholder macadamia farmers use a combination of similar criteria to select desirable attributes for preference of macadamia cultivars. The most important attributes that influence farmer choices for a macadamia cultivar are high yielding potential (38%), nut quality (29%), and extended flowering period (15%). However, for the HAES 660 cultivar, rootstock and price benefits are the most important considerations for farmers.

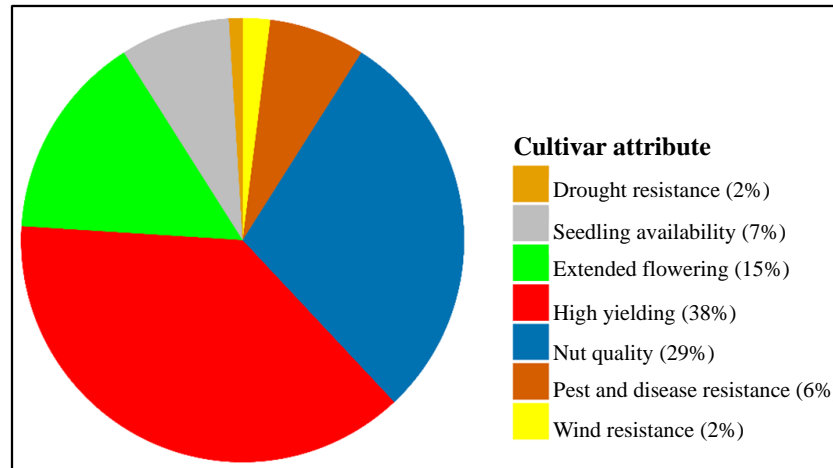


Figure 5.6: Proportion of smallholder farmers stating a preference for a given macadamia cultivar attribute.

Table 5.6 presents the attributes influencing smallholder farmer preference for macadamia cultivars based on the model developed for this study. It is observed that high yield ($p = 0.032$) and nut quality ($p = 0.014$) have significant influences on cultivar preferences among the sampled farmers. The greatest preference for high yielding cultivars is observed in Chikwatula (60%) and Neno (55%) cooperatives. In contrast, farmers in the Malomo (36.8%), Neno (30%), and Tithandizane (34.8%) cooperatives prioritise cultivars that have higher nut quality in terms of weight and size. Though not statistically different, the current study shows that the geographical location of the cooperatives plays a role in determining cultivar preferences. For instance, farmers in Chikwatula (31%), Mphaza (31%), and Mwanza (20%) cooperatives prefer cultivars that are resistant to wind due to their specific location. Farmers in these cooperatives report experiencing heavy seasonal winds, which lead to significant flower and nut drops. Additionally, the farmers suggest that, apart from temperature and precipitation, wind plays a crucial role in determining the climate suitability of macadamia cultivation in these areas.

Table 5.6: Proportion of farmers perceiving the importance of cultivar attributes.

Cultivar attribute	Chikwatula	Malomo	Mphaza	Mwanza	Nachisaka	Neno	Tithandizane	Prob > F
High yield	0.600 (0.503)	0.263 (0.452)	0.300 (0.470)	0.167 (0.381)	0.389 (0.502)	0.550 (0.510)	0.478 (0.511)	0.032**
Nut quality (weight & size)	0.600 (0.503)	0.368 (0.496)	0.100 (0.308)	0.167 (0.381)	0.222 (0.428)	0.300 (0.470)	0.348 (0.487)	0.014***
Flowers all year round	0.250 (0.444)	0.105 (0.315)	0.100 (0.308)	0.125 (0.338)	0.167 (0.383)	0.250 (0.444)	0.130 (0.344)	NS
Seedling availability	0.150 (0.366)	0.053 (0.229)	0.050 (0.224)	0.042 (0.204)	0.167 (0.383)	0.250 (0.444)	0.000 (0.000)	0.081*
Pest & disease resistance	0.100 (0.308)	0.105 (0.315)	0.050 (0.224)	0.000 (0.000)	0.111 (0.323)	0.100 (0.308)	0.130 (0.344)	NS
Drought resistant	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.042 (0.204)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	NS
Wind resistant	0.100 (0.308)	0.000 (0.000)	0.100 (0.308)	0.042 (0.204)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	NS

Notes: Standard deviations are in parentheses.

*** Significant at $P \leq 0.001$, ** Significant at $P \leq 0.05$, * Significant at $P \leq 0.1$ and NS = Not significant.

5.3.15. Macadamia cultivar preference

The majority (18%) of the sampled farmers prefer the HAES 660 cultivar over other available cultivars. The new generation cultivars HAES 800 (10%) and 791 (9%) are currently ranked as the second and third preferred cultivars, respectively (Figure 5.7). The least preferred cultivars include HAES 783, 788, 834, and 849.

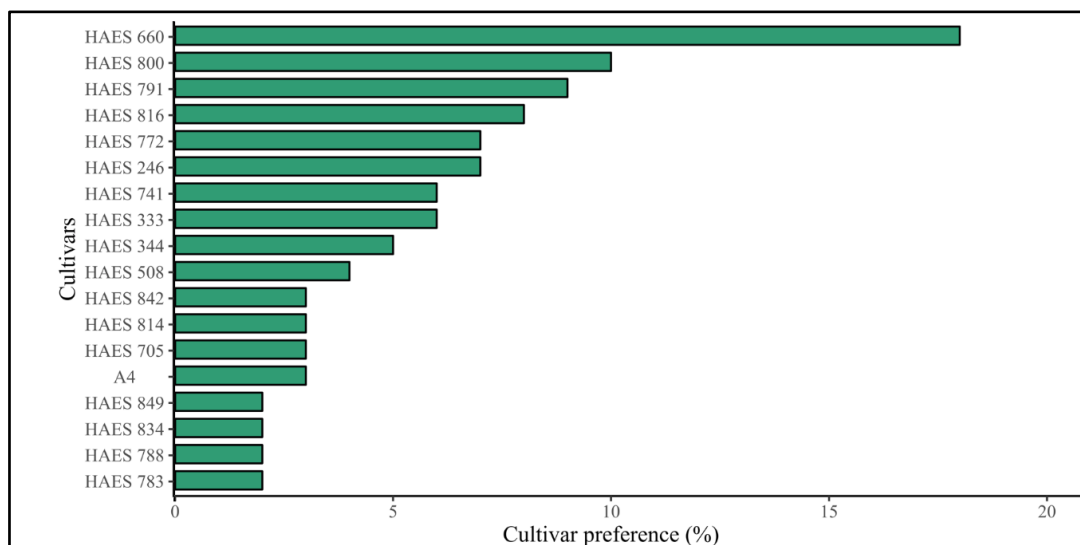


Figure 5.7: Preference for macadamia cultivars among smallholder farmers in the study areas.

Individual cooperatives exhibit unique preferences for specific macadamia cultivars. Among the farmers of Chikwatula cooperative, HAES 246 (46%) is currently the most preferred cultivar, while HAES 772 (5%) is the least preferred cultivar (Figure 5.8). In Malomo cooperative, HAES 791 (35%) is the most favoured, whereas HAES 741 is the least popular. Mphaza farmers show a greater preference for HAES 741 (19%), while cultivars HAES 333 (4%) is the least preferred cultivar in the cooperative. Mwanza cooperative farmers exhibit the greatest preference for cultivars HAES 800 and 741. Among the farmers of Nachisaka cooperative, HAES 791 (30%) is the most preferred cultivar. The majority of farmers in Neno cooperative prefer HAES 660 (70%), with HAES 772 being the least favoured. In Tithandizane cooperative, the most preferred cultivar is HAES 333 (24%), and the least preferred cultivar is HAES 842.

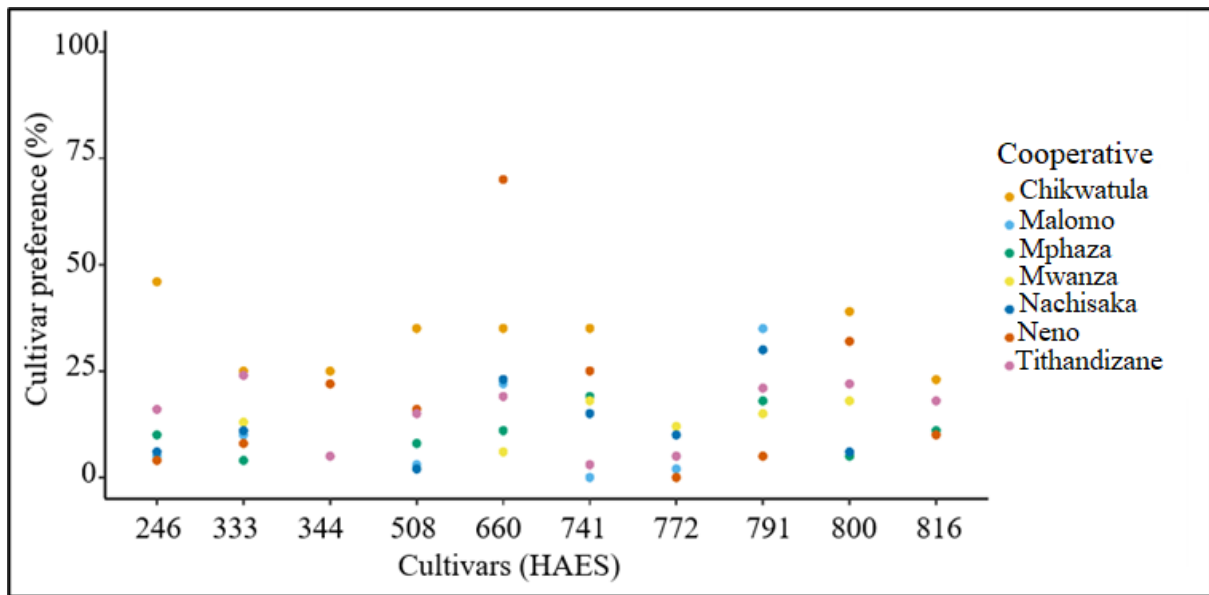


Figure 5.8: Macadamia preference at the cooperative level.

5.3.16. Econometric findings for HAES 660

This section uses the model described in Section 5.2.9 to evaluate farmer preference for the HAES 660 cultivar. Cooperative membership's influence on preference for the cultivar is analysed, with Chikwatula as the reference group. The findings indicate that cooperative membership significantly impacts the preference for HAES 660. Farmers from Malomo and Neno cooperatives are 35% and 50% more likely to prefer HAES 660 than other cultivars (Table 5.7). However, the relationship between Mwanza cooperative membership and preference for HAES 660 was not estimable due to the smaller sample size.

The results indicate that male farmers have a higher probability (22.5%) of preferring HAES 660 than female farmers. This could be attributed to the fact that HAES 660 is used as a rootstock for grafting, leading to greater interest among male farmers in establishing nurseries to sell tree seedlings and earn additional income. Furthermore, the higher prices offered by HIMACUL for HAES 660 nuts may also serve as an added incentive for male farmers to prefer this cultivar.

The level of education among the sampled farmers negatively impacts their preference for the HAES 660 cultivar. Farmers with secondary and tertiary education have 31.3% and 28.9% less preference for the HAES 660, respectively, compared to farmers with lower levels of education. This indicates that farmers with higher levels of education opt for cultivars with greater resistance to pests and diseases, unlike HAES 660, which is susceptible to such damage. Consequently, the level of education directly impacts the cultivar choice of some farmers.

The analysis of landholding size reveals that farmers with smaller land sizes are less likely to prefer HAES 660. Farmers who own less than 0.5 hectares of land have a 41% lower probability of preferring HAES 660. However, no significant differences in the preference for HAES 660 are found between farmers who own one hectare and those with more than ten hectares of land. These findings show that landholding size is a key factor when attempting to increase the adoption of the HAES 660 cultivar among smallholder farmers in Malawi.

Except for nut size, this study shows no significant differences in the probability of selecting the HAES 660 cultivar based on other cultivar characteristics. However, the findings indicate a significant negative correlation between preference for larger nut cultivars over HAES 660. Specifically, farmers who prefer cultivars with bigger nuts are 41% less likely to select HAES 660. This suggests that the smaller nut size of the HAES 660 cultivar is seen as a disadvantage, likely due to marketing considerations.

Table 5.7: Probit model estimates summarizing factors affecting smallholder macadamia farmer preference for HAES 660 cultivar.

Variable	Coefficient	Marginal effects
Cooperative		
Malomo	2.842	0.345*
Mphaza	-0.131	-0.0129
Mwanza	-	-
Nachisaka	1.332	0.157
Neno	3.906*	0.501***
Tithandizane	0.411	0.0451
Sex		
Male	1.647	0.225**
Education		
Primary	-0.156	-0.0229
Secondary	-2.940	-0.313**
Tertiary	-2.627	-0.289
Family size		
< 4	-	-
4-6	-1.263	
7-10	-1.141	
< 4	-	-
>16	-	-
Land Size (ha)		
< 0.5	-2.883**	-0.411***
1.5	-	-
2-4	-1.938	-0.305*
5-10	-	-
> 10	-0.723	-0.124
Cultivar attributes		
High yielding in total	0.275	0.0465
Big nuts	-2.370**	-0.412**
Flowers all year round	-1.376	-0.239
Resistant to pests & diseases	-0.203	-0.0353
Drought resistant	-	-
Easy to find seedlings	1.023	0.178
Wind resistant	-	-

*** Significant at $P \leq 0.001$, ** Significant at $P \leq 0.01$, *Significant at $P \leq 0.05$

5.3.17. Macadamia production challenges.

Farmers were asked to rank the major constraints affecting macadamia production. Responses are categorised into technical, socioeconomic, biophysical, natural, and cultural factors. The most widespread challenges among the farmers are insect pests (81%), diseases (34%), and market availability (33%, Table 5.8). Interestingly, the sampled farmers do not consider land availability a major challenge limiting macadamia production. They explained that they have access to larger landholding sizes, which diminishes the impact of land availability on their agricultural activities.

Table 5.8: Macadamia production constraints.

Constraint	Category	Frequency	Percentage (%)	Rank
Insect pests	Agronomic	117	81	1
Diseases	Agronomic	49	34	2
Market availability	Socioeconomic, policy	47	33	3
Wind	Natural	37	25	4
Lack of agricultural advisory services	Technical, policy	24	17	5
Shortage of seedlings	Socioeconomic, policy	22	15	6
Droughts	Natural	17	12	7
Lack of labour	Socioeconomic, household	11	8	8
Poor transportation	Socioeconomic, policy, household	10	7	9
Poor soil fertility	Biophysical, natural, socioeconomic	9	6	10
Climate change	Natural	7	4	11
Limited land	Socioeconomic	2	1	12

5.4. Discussion

5.4.1. Major socioeconomic characteristics

The current study shows that the majority (58%) of the sampled smallholder macadamia farmers are male and 42% female. This aligns with previous studies that suggest that male farmers have more control over cash crop management, as females have limited access to key agricultural resources such as land, inputs, and income (Bjornlund et al., 2019; Oyesigye et al., 2021). In terms of the average age of the participants (50), the study highlights that macadamia farmers are not in their active farming years. This affirms early assertions that macadamia farming in Malawi is considered a retirement crop (Evans, 2008). However, as farmers age, they become less innovative, which may impact their ability to learn and willingness to adopt new agricultural technologies (Matchaya, 2010; Feyisa, 2020).

The results also show that young farmers aged between 18 and 30 constitute approximately 5% of the sampled population. This is an interesting finding as it indicates an emerging interest among young farmers in macadamia cultivation, potentially leading to the expansion of their parents' farms. Research conducted in Malawi has shown that the majority of young farmers, especially those in rural areas, are primarily interested in growing annual crops and are reluctant to invest in high-value perennial crops such as macadamia and tea (Chinsinga & Chasukwa, 2012; Mapila, 2014; Tsisi et al., 2020). This is mainly attributed to limited access to arable land, credit, markets, and high initial investments for perennial crops (Kamchama, 2012; Kimaro et al., 2015). However, young farmers' attraction toward macadamia farming may be driven by the high market prices of macadamia nuts and the declining popularity of tobacco. Since young farmers are key to the future of agriculture in Malawi, their participation in the macadamia subsector is an encouraging sign of the country's progress toward sustainable and efficient agriculture (Zidana et al., 2020; Government of Malawi, 2022). Hence, it is important to consider providing young macadamia farmers with access to agricultural resources, training, and networks, as these lead to increased productivity.

"I planted Magede (a vernacular name for macadamia) because it is my pension and for my children and grandchildren. Once the tree has matured, it will, with little attention to pests and diseases and perhaps some livestock manure, continue growing bigger and giving more nuts yearly". (EJZ_10).

Education plays a vital role in improving economic and agricultural productivity (Nsapato, 2019). Educated farmers can better access and utilise agricultural advisory services and are willing to experiment with modern farming technologies (Tchale, 2009). This study reveals that over half of the respondents have completed primary school education. It can therefore be assumed that they possess the capability to understand and implement good agricultural practices if properly trained. Furthermore, about 5% of the farmers are secondary and university graduates actively involved in macadamia orchard management. Subsequently, the involvement of educated macadamia farmers is important because it can facilitate the adoption of improved agricultural practices that can lead to increased productivity.

The size of a household can have significant impact on agricultural production. The sampled farmers' households are larger than the average of 4.4 reported by the Malawi Population and Housing Census (NSO, 2020). Field-based evidence reveals that the large household sizes result from the need for family labour for agricultural activities. Moreover, farmers reported that smaller household sizes are associated with low agricultural production and food insecurity. This shows that the larger the household size, the greater the labour force available. These findings are concurrent with Tchale (2009), who reported that smaller households in Malawi are usually disadvantaged in agricultural production. Komarek & Msangi (2019) also argue that households with fewer adults and dependent children struggle to mobilise enough farm labour and are likely to have lower agricultural production.

Land is an important determinant of household food security in agrarian economies such as Malawi (Burke et al., 2022). Land scarcity can lead to extreme poverty and, in some cases, destitution. The current study shows that the average landholding size among smallholder

macadamia farmers is 1.23 ha, higher than the national average reported (0.53 ha, NSO, 2020). Nevertheless, interactions with the farmers suggest growing pressure and scarcity of land among the survey participants. This is attributed to larger family sizes and rapid urbanisation. Therefore, CSA practices like agroforestry and intercropping are key to reducing pressure on the land and ensuring land intensification.

The study also found that the average total cultivated area by males is larger (both for general agriculture and macadamia) compared to females. This validates and, more importantly, expands the findings of Chinyamunyamu (2014), who revealed that females have lesser land sizes than males, attributed to inheritance and the willingness of males to buy land. Despite these findings, in Mwanza and Neno cooperatives, females have more landholding sizes than males due to the matrilineal marriage system. According to the matrilineal system, after marriage, a husband moves to the wife's village and cultivates her land, implying that a husband has no decision-making power over the transfer of a wife's land rights. In contrast, a patrilineal marriage system is followed in Dowa and Ntchisi districts, with a wife living in her husband's village after marriage.

5.4.2. Crops grown and farming systems

Smallholder macadamia farmers grow a diversity of crops, with macadamia identified as the most important crop after maize. Legumes such as soybeans and groundnuts are the common secondary crops cultivated. However, many farmers reported not producing enough maize to meet their household's needs for an entire year, especially during the lean period (January and February). Additionally, more female respondents reported producing insufficient quantities of maize than male respondents. This could be attributed to the lack of access to inputs, especially improved seed and inorganic fertilisers.

Interestingly, the study findings indicate that only 12.5% of the sampled farmers grow tobacco. The declined interest in tobacco production is attributed to the negative market trend of the crop and better prices offered for macadamia nuts. This is in line with Wineman et al. (2022),

who observed a decline in the number and share of farmers growing tobacco in Malawi, especially in Dowa and Ntchisi districts. This demonstrates that farmers in the country are diversifying their cash crop portfolio, as also evidenced by the quote below:

"I have completely stopped growing tobacco. The reason is that the cost of producing tobacco is too high, and I end up in more debt when I grow the crop. Instead of taking me out of poverty, I feel tobacco production makes me poorer". (EJZ_11).

5.4.3. Macadamia nut utilisation

Macadamia nuts serve multiple purposes for smallholder producers. The majority of the study participants consider macadamia nuts are a good source of income and a supplement to their maize-based diets. The farmers emphasize that the crop is harvested during the lean period when annual staple crops are not matured, and, thus, it is an essential resource for improving food security, both as a source of food when other food is in short supply and expensive and as a cash crop. Furthermore, farmers regard macadamia production as a climate change resilience and adaptation strategy. They believe macadamia trees are well-suited for reducing deforestation, as the shells are used for fuelwood. Moreover, the farmers highlight that macadamia shells provide a longer-lasting and more efficient fire than traditional firewood and charcoal. Thus, macadamia production is helping reduce pressure on natural forests for firewood and, consequently, reducing deforestation.

"Despite the poor performance of annual crops this year, particularly maize (2019), due to cyclone Idai, I still have my macadamia trees to fall back on. I have harvested the first batch of nuts, kept some for consumption, and sold the excess for income. I spent the money on extra maize and fertilizer." (EJZ_12).

5.4.4. Source of macadamia tree seedlings

Access to high-quality macadamia tree seedlings is a major factor affecting macadamia production in Malawi. The results show that HIMACUL and commercial estate nurseries are

Malawi's main source of macadamia tree seedlings. Most farmers prefer tree seedlings from HIMACUL nurseries, as they are sold at a discounted rate to members. Nonetheless, some farmers indicate that the cost of macadamia tree seedlings, both from HIMACUL and commercial estate nurseries, is prohibitively expensive, and instead, they graft their seedlings or buy from friends. Nyoka et al. (2018) found that the majority of the self-grafted materials in Malawi are often of poor quality, negatively impacting crop productivity in the long term. Therefore, to sustain Malawi's smallholder macadamia productivity, high-quality planting materials must be accessible to all farmers. This can be achieved through subsidies and increased training on improved grafting techniques, which can be provided by the Government of Malawi and the World Agroforestry Centre (ICRAF). This can also lead to the adoption of recommended cultivars for each growing area.

"Macadamia tree seedlings are very expensive and one of the limitations for orchard expansion. For this reason, I requested a friend to train me how to graft the trees."
(EJZ_40).

5.4.5. Sources of agriculture extension services

Access to agricultural extension services and training can greatly benefit agricultural production as these can help to increase productivity (Phiri et al., 2019). Various strategies are used to disseminate information and raise awareness among Malawian farmers. Of these methods, training is the most significant. HIMACUL and farmer clubs are the primary providers of macadamia good agricultural practice trainings in the study areas. The study reveals limited involvement of the government and NGOs in providing macadamia agricultural extension services. Moreover, despite their expertise in technology generation, academic and research institutions in Malawi play a minimal role in the smallholder macadamia subsector. The minimal role of government extension and research services in the macadamia sector is mainly attributed to the lack of funding for various activities. Thus, it is essential to consider the study findings when creating future extension services for the smallholder macadamia subsector and concentrate on improving the provision of training through farmer-led initiatives.

"More extension officers are needed to teach good agricultural practices for healthy and productive macadamia trees. During the MSDP project, we used to have weekly macadamia trainings with Malawi government extension officers. However, extension officers currently focus on other crops, and only HIMACUL conducts the weekly trainings. We need more extension officers focussing on macadamia production as we have many things to learn." (EJZ_13).

5.4.6. Drivers of macadamia cultivar preferences

Farmers' adoption of new agricultural technologies, such as crop cultivars, results from a dynamic interaction between evaluations of the value of improved cultivars and confidence in their quality (Derwisch & Kopainsky, 2011). The study finds that smallholder macadamia farmers in Malawi prefer cultivars with multiple desirable attributes, especially yield potential, grain quality (weight and size), and flowering patterns.

Yield potential is a key factor in determining the profitability of macadamia nuts. Farmers cited that yield and weight of the nuts are important marketing aspects for their crop. The results of this study show that even though HAES 800 produces smaller kernels (23–25 mm), it is high yielding (45 kg tree⁻¹ year⁻¹) compared to HAES 246, which produces big seeded kernels (28 mm) but low yielding (25 kg tree⁻¹ year⁻¹). Despite the low-yielding nature of HAES 246, the cultivar is one of the most preferred among HIMACUL farmers. This is because of its high demand by the macadamia processors in the country who target confectionery macadamia export markets due to its size. This highlights that macadamia cultivar preference by farmers may also be influenced by the buyer's demands.

Regarding flowering patterns, farmers prefer cultivars with an extended flowering period, such as HAES 791 and HV A4. The preference is likely because an extended flowering period leads to longer harvesting and higher yields (Vock et al., 1998). This phenomenon is particularly common in high-altitude areas (Chikwatula, Nachisaka, and Tithandizane), where temperatures are cooler, and precipitation is evenly distributed throughout the year, thus promoting more shoot growth and, as a result, more flowering. In contrast, farmers' experiences in low-altitude

areas (Malomo, Mwanza, and Neno) show that cultivars tend to flower for no more than three months, affecting total nut yields. This helps to explain the variations in macadamia nut yields between higher and lower altitude areas in Malawi, especially between Malomo and Tithandizane cooperatives.

Table 5.9: Characteristics of macadamia cultivars cultivated in Malawi.

Cultivar	Origin	OG	NG	Tree shape	Kernel nut size	Kernel weight (g)	Recovery (%)	Harvesting	Husk thickness	Susceptibility to TNB	Susceptibility to SGSB	Close planting
HV A4	Australia		✓	Spreading	Large	2.8–3.2	40–45	Mid	Thin	High	High	Yes
HAES 246	Hawai'i	✓		Spreading	Large	2.0–3.0	35–37	Mid-late	Variable	Intermediate	Intermediate	No
HAES 333	Hawai'i	✓		Round	Small	1.8–2.4	30–40	Mid-late	Thick	Low	Low	No
HAES 344	Hawai'i		✓	Upright	Medium	2.0–2.5	32–35	Early	Variable	Intermediate	Intermediate	Yes
HAES 508	Hawai'i	✓		Spreading	Medium	2.0–2.5	40–45	Very late	Variable	Intermediate	Intermediate	No
HAES 660	Hawai'i	✓		Upright	Small	1.8–2.3	33–39	Very late	Thin	High	High	Yes
HAES 705	Hawai'i		✓	Spreading	Large	2.3–2.8	34–35	Very late	Thick	Low	Low	No
HAES 741	Hawai'i	✓		Upright	Medium	2.0–2.5	32–37	Early	Thin	High	Intermediate	Yes
HAES 772	Hawai'i	✓		Spreading	Medium	2.0–2.8	26–29	All year	Variable	Intermediate	Intermediate	Yes
HAES 781	Hawai'i		✓	Upright	Large	2.6–3.0	34–38	Very late	Thin	Intermediate	High	No
HAES 783	Hawai'i		✓	Spreading	Medium	2.2–2.4	38–40	Very late	Thick	Low	Low	No
HAES 788	Hawai'i	✓		Spreading	Medium	2.2–2.4	38–40	All year	Thin	High	Intermediate	No
HAES 791	Hawai'i		✓	Upright	Medium	2.0–2.5	34–35	All year	Variable	Intermediate	High	Yes
HAES 800	Hawai'i		✓	Spreading	Large	2.0–3.0	35–40	All year	Thick	Low	Low	Yes
HAES 814	Hawai'i		✓	Upright	Small	1.8–2.4	37–39	Mid-late	Thin	High	High	Yes
HAES 816	Hawai'i		✓	Upright	Large	2.0–2.5	42–45	Early	Thin	High	High	Yes
HAES 842	Hawai'i		✓	Upright	Medium	2.0–2.5	35–39	Early	Variable	Intermediate	Intermediate	Yes
HAES 849	Hawai'i		✓	Spreading	Small	1.8–2.3	35–40	Mid-late	Thin	High	High	No
Beaumont	Australia		✓	Spreading	Medium	2.0–2.5	33–39	Mid	Thick	Low	Low	Yes
Daddow	Australia		✓	Spreading	Medium	2.0–2.4	37–40	Mid-late	Thin	High	High	No
MCT1	Australia		✓	Spreading	Large	2.0–3.0	38–40	Mid-late	Variable	Intermediate	Intermediate	Yes

Note: OG – Old generation cultivars and NG – New Generation cultivars.

: HV A – Hidden Valley Australia cultivars and HAES - Hawai'i Agricultural Experimental Station cultivars (Bell et al., 1996).

The availability of cultivar tree seedlings is another significant factor influencing farmer preference and, consequently, the adoption of a macadamia cultivar in Malawi. Farmers expressed concerns that most new generation cultivars are scarce (rootstock) among HIMACUL nurseries and expensive when available. Because of these factors, farmers are discouraged and continue to plant old generation cultivars that are readily available. These findings confirm and, importantly, extend work by Evans (2021), who reported that scion availability of most new generation cultivars is scarce among smallholder macadamia farmers in Malawi, leading to low adoption levels of the cultivars. Thus, having a nursery system that can better provide the needed tree seedlings is key to increasing smallholder farmer adoption of recommended cultivars.

Despite farmers suffering higher yield losses annually due to insect pests (≥ 388 MT of nut in shell) and diseases, the study shows that only 6% of the smallholders consider cultivar resistance to pests and diseases to be an essential factor influencing their preference for a cultivar. This could be due to higher nut yields from the cultivars that compensate for the losses caused by pest and disease damage. For example, Ching'oma et al. (2001) found that some cultivars, such as HAES 246, 660, 741, and 788, are tolerant or resistant to pests and disease damage. The study also found that farmers in Chikwatula, Mphaza, and Mwanza consider wind resistance an additional trait they prefer in their cultivars.

5.4.7. Macadamia cultivar preference

Farmers have specific criteria when selecting crop cultivars, which vary among communities (Bucheyeki et al., 2008). This study shows that HAES 660, 800, 791, 816, and 246 are the most preferred macadamia cultivars among HIMACUL farmers. These cultivars represent the "core" of established cultivars in Malawi. The cultivars HAES 246 and 660 have historical significance, as they were recommended in the past, while cultivars HAES 800, 791, and 816 are more recent recommendations from the Malawi Smallholder Development Project.

The cultivar HAES 660 is the most preferred due to its superior rootstock characteristics and a high percentage of grade A kernels. Furthermore, the preference for HAES 660 is driven by HIMACUL, which pays more for this cultivar than others. HIMACUL can also use this strategy to encourage the adoption of other cultivars they recommend to farmers. However, HAES 660 cultivar is susceptible to damage from nut borers and stink bugs (Knight, 2007). The second most preferred cultivar is HAES 800. Farmers reported that the cultivar is high yielding and resistant to stink bug damage due to its thick shell. However, the smaller nut size of the cultivar is a big turn-off among the farmers. These findings align with Ngondo (2002), who observed a higher percentage of small nuts from HAES 800 than HAES 660.

Farmers cited multiple flowering throughout the growing season as one of the reasons for their preference for HAES 791, along with quick maturity (begins nut production after four years) and high yield potential. Nevertheless, farmers expressed concern that the cultivar has a high soil nutritional demand and that its yields decrease earlier than other cultivars. This concern suggests that the cultivar is best suited for farmers who are dedicated to managing their soil nutrition. Additionally, preference for cultivars HAES 816 and 246 is attributed to larger nut size (28 mm) and prolonged flowering periods.

The second tier of cultivars consisting of HAES 333, 344, 772, 741, and 508 appeared less frequently but regularly preferred by the respondents. This list presents two generations of cultivars: HAES 772 and 741 represent the new generation, while HAES 333, 344, and 508 represent the old generation. However, HAES 333, 741, and 508 are cultivars most preferred by smallholders in the low-altitude areas of Mphaza, Mwanza, and Neno cooperatives. Despite farmers' preference for HAES 344, Evans (2021) has reported that the cultivar is not widely grown by smallholders and is unavailable at HIMACUL nurseries. This indicates that farmers are getting this cultivar from sources other than HIMACUL. In terms of the HAES 772 cultivar, the study shows that it is popular among farmers in the highland areas of Chikwatula and Tithandizane cooperatives. Preference for this cultivar is attributed to its quick maturity and extended flowering periods, which result in higher yields.

Results from individual cooperatives show a wide variability among preferred cultivars, with five of the 18 being most preferred or least preferred by at least one respondent. These variations may be attributable to farmers' demographics, cultivar characteristics, and orchard location (lowlands and highlands). Respondents' demographics have been used in other studies to explain some of the variability in farmer preferences. For example, Simtowe et al. (2010) found that groundnut varietal preference in Malawi was positively influenced by age, gender, education, and membership in a social grouping. Abadi et al. (2015) found that adult literacy, family size, and livestock wealth were predictors of maize varietal preferences in Ethiopia. However, this study shows a lack of significance in the association between any demographic factor and cultivar preferences except for the cultivar HAES 660, which is attributed to the sample size as it is insufficient to demonstrate statistical differences. This finding is concurrent with Santos et al. (2022), who reported insignificant cultivar trait preference among macadamia farmers in Australia due to an insufficient sample size. Therefore, this highlights the need for more sampling to have in-depth statistical analyses. However, because smallholder macadamia production is still new, this will be important for future research activities.

5.4.8. Macadamia production constraints

Table 5.8 presents the challenges faced by smallholder macadamia producers in Malawi. Insect pests have been identified as the most prominent limitation affecting smallholder macadamia productivity. This is consistent with Evans (2021), who reported that stink bugs and nut borers are the principal economic pests that suppress nut in shell yields and volumes of sellable kernel, resulting in a 5% loss of NIS yield (388 MT or \$1.6 million) and 8% of the kernel (188 MT or \$2.9 million) in the country. Taylor et al. (2013) found that stink bugs and nut borers can cause economic losses of 40–70%, with farmers in the present study reporting similar economic losses. Despite a lack of pest management training, farmers report implementing various pest control measures such as field sanitation (weeding) and organic pesticides (such as Neem and Nkhadze leaves) to mitigate pest damage.

Diseases are the second major constraint affecting smallholder macadamia production. According to interviews with farmers, soil nutrient deficiency-related diseases are the most common. However, some farmers also report observing root rots and stem cankers on their trees, albeit with less severe effects.

Limited market access is the third important limitation that smallholder farmers face. Commercial processors determine nut prices without government involvement, leaving farmers with no bargaining power and no alternative buyers. These findings concur with Toit et al. (2017), who reported a monopoly in macadamia nut pricing by a small number of large commercial processors in Malawi. However, the establishment of the Malawi Macadamia Association and the integration of a smallholder farmer position is expected to increase collaborations between smallholder farmers and processors.

Wind represents another significant challenge to macadamia production in some study areas. Farmers from Chikwatula, Mphaza, Mwanza, and Tithandizane cooperatives report that strong winds, especially Chiperoni winds experienced between May and July, damage their macadamia trees annually. Strong and persistent winds negatively impact the growth and development of young macadamia trees, as well as their flowering and fruiting (Keeler & Fukunaga, 1968; Queensland Government, 2003; Bernard, 2005). As such, the creation of windbreaks specific to areas prone to strong winds is critical to ensuring orchard health.

Inadequate provision of agricultural extension services also hampers the production of smallholder farmers. Empirical evidence has shown that extension contact influences farm households' adoption of production enhancing techniques (Gebermedin & Tolera, 2015). The current study reveals that HIMACUL and GIZ are the only organizations providing agricultural extension services for macadamia production, management, and marketing. Consequently, a limited number of farmers have access to training and information on macadamia production,

leading to low productivity and farmers abandoning their trees due to a lack of assistance on technical issues.

Other constraints farmers face include a shortage of quality tree seedlings, droughts, poor transportation, poor soil fertility, and climate change, all of which negatively impact macadamia productivity.

5.5. Conclusions

This chapter empirically analyses the socioeconomic characteristics of smallholder macadamia farmers in Malawi, including their cropping systems, cultivar preferences, and constraints to macadamia production. The results indicate that most macadamia farmers are more than 50 years old and rely on farming as their primary source of livelihood. Furthermore, these farmers consider macadamia the second most valuable crop after maize.

The results reveal that HIMACUL smallholder farmers cultivate 18 macadamia cultivars, with a multifaceted mix of perceptions and criteria influencing their decision-making process. High-yielding potential, nut quality, and flowering patterns are the most critical factors driving their cultivar preferences. The top five preferred cultivars are HAES 660, 800, 791, 816, and 246, while the second tier includes HAES 333, 344, 772, 741, and 508. It is, therefore, essential to consider farmer preferences during cultivar introductions and breeding to increase adoption and promote sustainable smallholder macadamia productivity.

Malawi's smallholder macadamia farmers face several production constraints, including insect pests and diseases, poor market access, wind damage, and inadequate agricultural extension services. To address these challenges, improving the provision of quality agricultural extension services is crucial. Hence, the government should invest in and provide specialised services for farmers to enhance their knowledge of macadamia, good agricultural practices, and pest and disease management.

In conclusion, this study provides valuable insights into the socioeconomic characteristics and constraints of smallholder macadamia farmers in Malawi. By considering farmer preferences and providing quality agricultural extension services, policymakers can enhance productivity and promote sustainable smallholder macadamia farming in the country. For this to be successful, there will be a need for multi-stakeholder partnerships, including farmer groups, cooperatives, the private sector, and the government.

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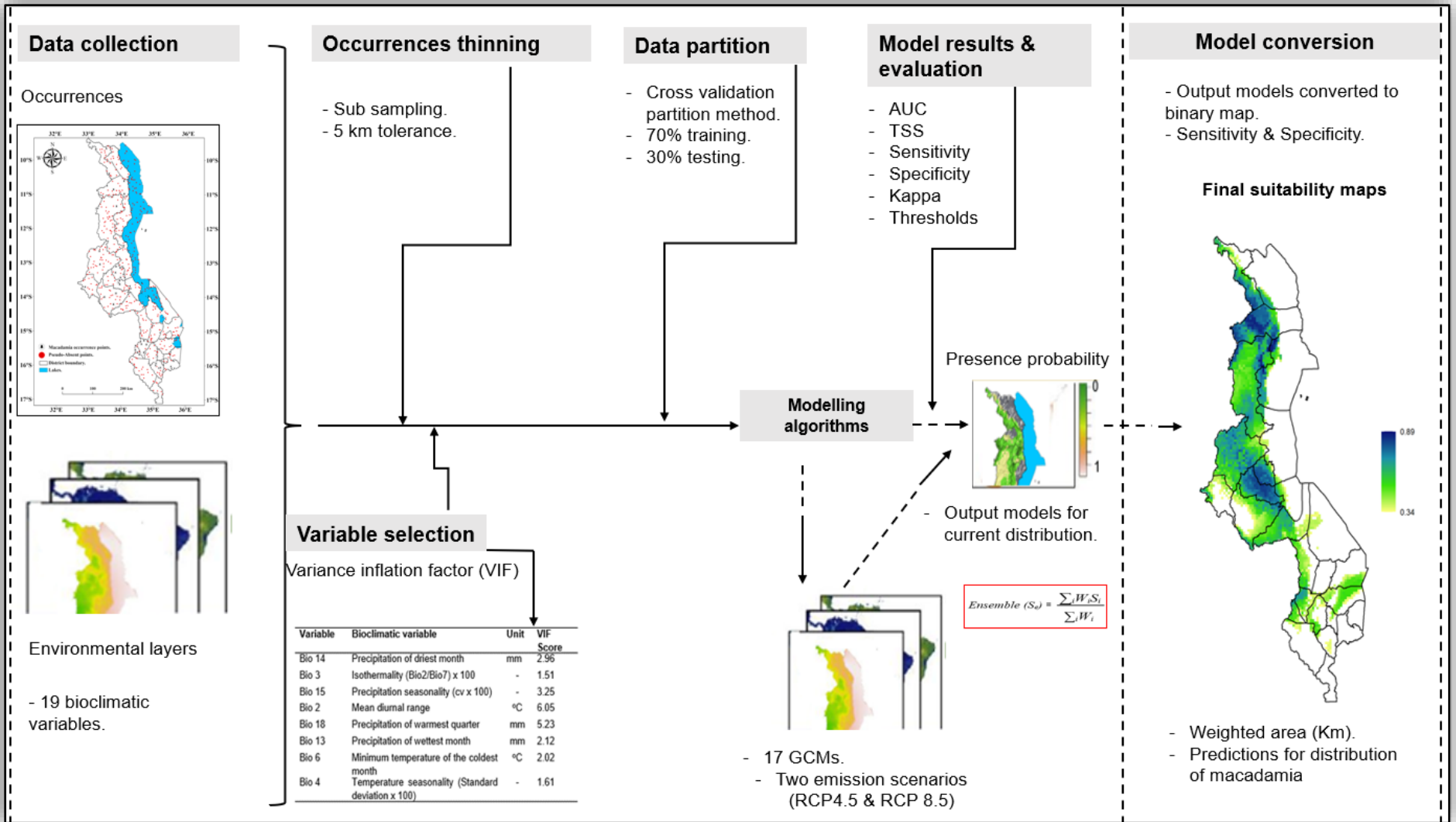
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Graphical Abstract



CHAPTER SIX: CLIMATE SUITABILITY PREDICTIONS FOR THE CULTIVATION OF MACADAMIA IN MALAWI

Abstract

Climate change is having significant effects on crop production areas, with adverse impacts on people who rely on these crops as sources of food and income. Macadamia is one of Malawi's most important and profitable crop species, but climate change threatens its production in current cultivation areas. Thus, this study aims to quantitatively examine the potential impacts of climate change on the agro-climate suitability for macadamia in Malawi. An ensemble model approach is utilised to predict macadamia's current and future (the 2050s) suitability under two representative concentration pathways (RCP 4.5 and RCP 8.5). The model achieves a good fit in determining suitability classes for macadamia (AUC = 0.9). The results show that precipitation of the driest month (29.1%) and isothermality (17.3%) are the climatic variables strongly influencing macadamia's climatic suitability in Malawi. Under current climatic conditions, 57% (53,925 km²) of Malawi is suitable for macadamia. Future projections suggest that climate change will reduce the suitable areas for macadamia by 18% (17,015 km²) and 21.6% (20,414 km²) based on RCP 4.5 and RCP 8.5, respectively, with the distribution of suitability shifting northwards in the 2050s. The southern and central regions of the country will suffer the greatest losses ($\geq 8\%$), while the northern region will be the least impacted (4%). In conclusion, this study provides critical evidence that climate change will reduce the suitable areas for macadamia production in Malawi, depending on climate drivers. Therefore area-specific adaptation strategies are required to build resilience among producers.

6.1. Introduction

Ecosystems, human health, livelihoods, food security, water supply, and economic growth are all impacted by global climate change (Xu et al., 2020; IPCC, 2023). The severity of these effects are predicted to increase in direct proportion to the degree of global warming. By the

2050s, it is estimated that a 2°C increase in warming will increase the number of people exposed to climate related risks and poverty by several hundred million (Xu et al., 2020). This warming poses significant threats to many parts of Africa's current agricultural production systems, particularly smallholder farming families with limited adaptive potential (Sultan et al., 2019; Woetzel et al., 2020).

Sub-Saharan Africa is one of the most vulnerable regions to climate change, attributed to decreased amount and distribution of precipitation and increased temperatures (Jennings et al., 2022; IPCC, 2023). Malawi is particularly vulnerable to climate change because of its high poverty levels, limited cash flow, and low technological infrastructure (Mataya et al., 2019; Simmance et al., 2022). Moreover, the country's heavy reliance on the rainfed agricultural sector for food security and economic development increases this risk (Warnatzsch & Reay, 2020; Eviness et al., 2022; Li et al., 2022).

Agriculture is the backbone of Malawi's economy and society, as approximately four-fifths of the population relies on agriculture (van Vagt, 2018; Tufa et al., 2023). However, the country's growing food demand will pose a significant challenge in the coming decades as already stressed agricultural systems are threatened by population growth and rising incomes (Goodman et al., 2020; Nindi et al., 2023). In this context, knowledge of how climate change may alter crop production patterns and their suitability is critical for effective agricultural adaptation in the country.

Multiple studies have already indicated the dire consequences of climate change on crop production in Malawi. For instance, Bunn et al. (2017) and Dougill et al. (2020) have predicted the loss of suitable areas for tea production, particularly in the low-lying areas of southern Malawi, including Thyolo and Mulanje districts. Maize yields are also expected to decline by at least 50% (Warnatzsch & Reay, 2020; Jennings et al., 2022), while tobacco yields may

decline by at least 45% (Drope et al., 2016). Tobacco is the mainstay of the rural economy in Malawi, contributing to almost 60% of the country's export earnings, valued at \$660 million (Government of Malawi, 2022). Given the current downturn in tobacco market trends, macadamia has been identified as a suitable alternative that can significantly contribute to Malawi's economy and livelihoods (Zuza et al., 2021a). Nonetheless, this can only be achieved if suitable areas for macadamia cultivation are identified and mapped under current and future climate conditions.

Macadamia is a perennial crop native to Australia (Alam et al., 2019). Due to its origin, the crop is susceptible to climate influences, including sudden temperature shifts and precipitation variations that deviate from the current and historical growing conditions in its native habitat. Economic macadamia production is, therefore, only possible within certain geographical and climatic ranges (Barrueto et al., 2018c). Optimum diurnal and seasonal temperatures for macadamia are within 30°C by day and 14°C by night. Prolonged exposure to temperatures outside this range can adversely affect growth, yield, and quality (Nagao, 2011; Chandler, 2018).

Regarding precipitation, macadamia thrives in areas with well-distributed precipitation, totalling an average of 1500 mm per year (Britz, 2015; Shabalala et al., 2022). Water stress during nut maturity negatively impacts the yield and quality of macadamia (Stephenson et al., 2003). To stimulate flowering and nut set, macadamias require strong temperature contrasts and mild water stress for up to four months (Stephenson & Gallagher, 1986; Stephenson et al., 2003). This demonstrates how much macadamia production is influenced by climate, while geographical parameters such as altitude, aspect, and slope are only considered important in terms of affecting temperature and water requirements (Powell, 2009).

Understanding macadamia's current and future suitability is essential for developing adaptation and mitigation strategies for the projected negative impacts of climate change, particularly

among smallholder producers in Malawi. For these smallholders, the promotion of macadamia agroforestry remains a viable adaptation option. This is because the farmers can interplant their macadamia trees with annuals, enhancing their long-term resilience to climate change. Evidence indicates that climate change is already reducing macadamia suitable areas (Barrueto et al., 2018a), limiting yields (Nagao & Hirae, 1992; Pichakum et al., 2014; Britz, 2015), and increasing pest and disease incidences and severities globally (Evans, 2020). Though it is assumed that climate change is likely to reduce suitable areas for macadamia (Powell, 2009; Barrueto et al., 2018b), integrated spatially quantitative impact studies are still lacking.

This study aims to fill this gap. This analysis uses an ensemble modelling approach driven by 17 general circulation models under two emission scenarios (RCP4.5 and RCP8.5) for the 2050s. The study particularly focuses on identifying the key climate determinants of macadamia suitability in Malawi. Furthermore, this study examines the potential distribution of currently suitable areas of macadamia and assesses the crop's response to climate change. Such climate risk assessments on the macadamia sector are essential for generating scientific evidence on the impacts of climate change, particularly among smallholders. In addition to informing policy and trade, this assessment is a first step toward identifying and implementing adaptation measures tailored to macadamia within global boundaries. The study focuses on climate projections for the 2050s to align with the United Nations framework of global challenges in agriculture and food security.

6.2. Methodology

6.2.1. Study area

Malawi is a southern African country that falls within the longitudes 30 and 40 and the latitudes -17 and -10 . The country spans over $\sim 118,484$ km², with $94,449$ km² (80%) of land area and $24,035$ km² (20%) of water surface. The country is divided into three main regions; Central, Southern, and Northern, with 28 districts. Because of variations in topography (Figure 6.1),

parental materials, and management, soil nutritional status varies greatly across the country, particularly among smallholder farms (Li et al., 2017; Munthali et al., 2022).

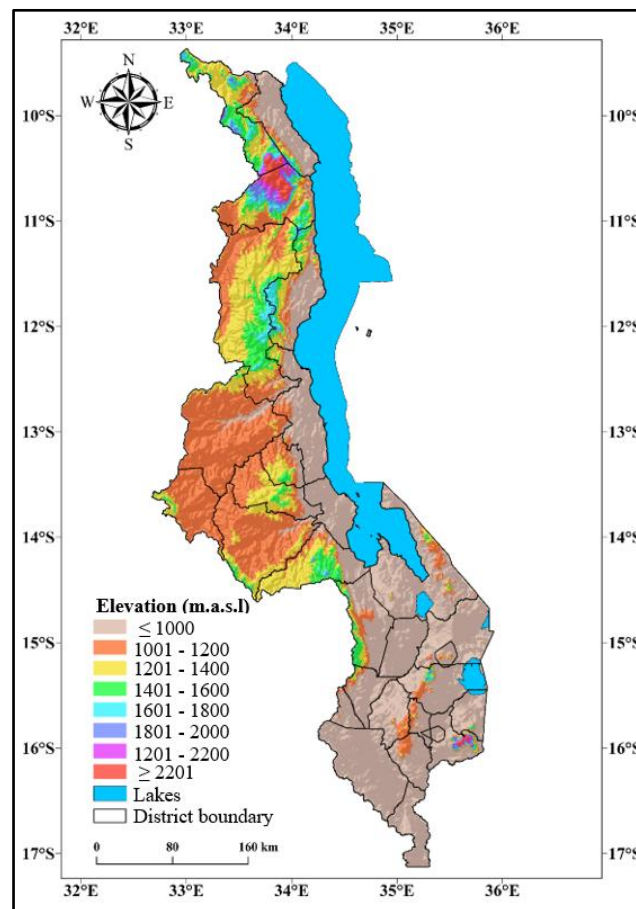


Figure 6.1: Malawi's geographic location and topography based on Shuttle Radar Topography Mission digital elevation model data.

Malawi has a subtropical climate with two distinct seasons: the rainy season (November to April), which accounts for 90–95% of the annual precipitation, and the pronounced dry season (May to October, Government of Malawi, 2020). The timing of the rainy season varies by region, with earlier onset in the southern region and less pronounced dry seasons in the north, especially at higher elevations. The country's topography and proximity to Lake Malawi and Shire Valley determine the geographical distribution of temperature and precipitation. Average annual precipitation ranges from 500 mm in low-lying marginal areas to over 3000 mm in high plateau areas (Benson et al., 2016). The average annual minimum and maximum temperatures

in the country are 12 and 32°C, respectively, with the coldest temperatures in June and July and the hottest in October or early November (Mutegi et al., 2015). Figure 6.2 presents the spatial pattern of average annual temperatures (a) and annual precipitation (b) in Malawi.

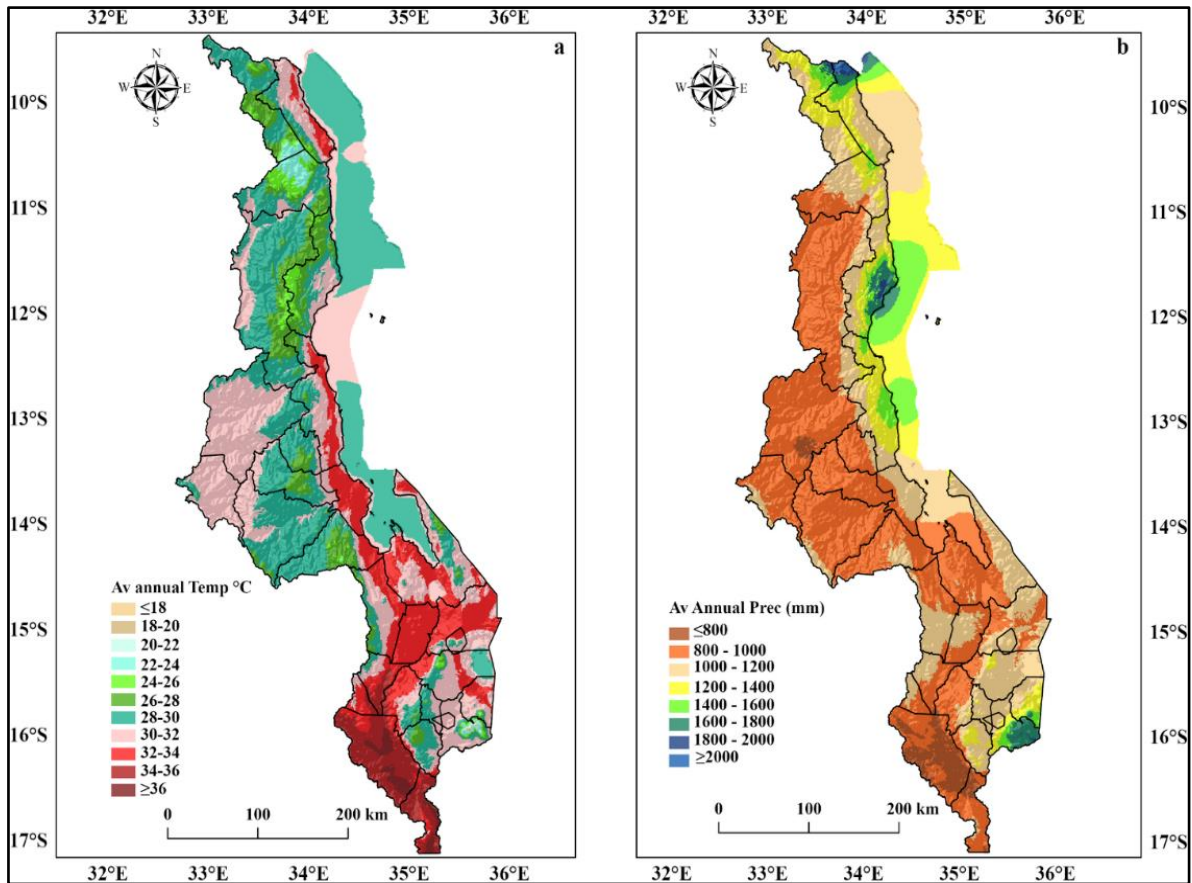


Figure 6.2: a) Average annual temperature (°C); and b) Precipitation (mm) of Malawi based on WorldClim-Global Climate Data.

6.2.2. Occurrence data

Data on macadamia tree species' occurrence was collected from smallholder macadamia farms in Malawi using a field survey. The sampling focused on successfully established ten-year-old macadamia orchards under smallholder rainfed conditions, as this stage is critical for peak productivity (Barrueto et al., 2018c). A total of 120 orchards were sampled throughout the country based on macadamia tree abundance, but only 84 of these locations are included in the study analysis. This is because the occurrence points were resampled to a tolerance of 5 km²,

ensuring that no two points were found in the same environmental layer at a resolution of 5 km² x 5 km². At each farm, the GPS coordinates and altitude were collected using a Garmin eTrex Vista[®] Cx device. Additionally, the study utilised the approach described by Barbet-Massin et al. 2012 to generate background pseudo-absence points (Figure 6.3). These points helped to account for any sampling biases in the study.

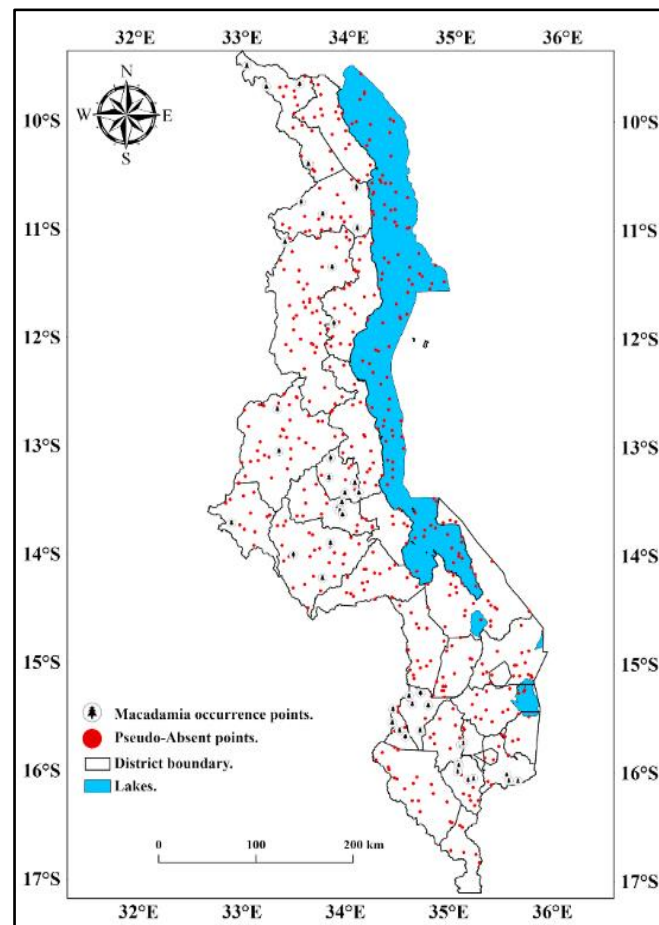


Figure 6.3: Map of Malawi showing macadamia occurrence points and pseudo-absent points.

6.2.3. Climate data

This study used bioclimatic predictors (~1970–2000) from WorldClim data set version 1.4 at a spatial resolution of ~5 km² x 5 km² to model the current areas suitable for macadamia in Malawi. Calculated from monthly temperature and precipitation climatologies, these bioclimatic variables describe spatial variations in annual means, seasonality, and

extreme/limiting conditions. The bioclimatic variables used in the future predictions were derived from 17 GCMs based on RCP 4.5 and 8.5 (van Vuuren et al., 2011).

RCP 4.5 is an intermediate scenario that considers an intermediate greenhouse gas concentration and predicts an average increase in temperature by 1.4°C (0.9–2.0°C), and RCP 8.5, is the most pessimistic scenario, which considers higher GHG emissions concentration with a 1.4–2.6°C projected increase in average global temperature by the 2050s (period 2040–2060).

The current study did not consider scenario 2.6 because it is the most efficient and effective mitigation scenario, i.e., keeping the temperature below 2°C by the 2050s. With current policy projections (expected temperature increase of 3.3–3.9°C), this scenario is currently not feasible unless there is effective policy adoption (de Sousa et al., 2017; UNEP, 2022). Furthermore, to achieve this scenario, emissions need to be 25% lower than in 2018 (UNEP, 2022).

Emission scenario 6.0 was also not considered for this analysis because its projections fall between RCP 4.5 and RCP 8.5 (UK Met Office, 2018). Further, RCP 6.0 contains only 42% of the GCM outputs, implying that the scenario contains fewer outputs than the other emission scenarios (Van Vuuren et al., 2007).

6.2.4. Variable selection

In species distribution models, multicollinearity among the bioclimatic predictors may result in overfitting or bias in the resulting suitability model (Mudereri et al., 2021; Sotomayor et al., 2023). In addition, multicollinearity may result in inflating standard errors that can lead to inaccurate estimates of the suitability model (Chemura et al., 2021; Alves et al., 2023). To avoid these challenges, variable quality evaluation criterion using a multicollinearity degree was employed through the variance inflation factor analysis (VIF). The VIF indicates the degree to which the standard errors have been inflated due to the levels of multicollinearity among the independent variables used in running the model (Lin, 2008; Zhang & Wang, 2023).

VIF was directly calculated from a linear regression model with the focal numeric variable as a response, as shown in the equation below.

$$VIF = \frac{1}{1 - R_i^2} \quad \text{Equation 6.1}$$

Where: R^2 is the regression coefficient of determination of the linear model.

In this study, the "*ensemble.test*" function inherent in the "*BiodiversityR*" package available in R (Kindt & Coe, 2005; Kindt, 2018) was used to eliminate correlated variables. Following the recommendation made by Ranjitkar et al. (2016), variables with a VIF of less than ten were retained (Table 6.1).

Table 6.1: Bioclimatic variables used in the final suitability model and VIF.

Variable name	Bioclimatic variable	Unit	VIF Score
Bio 14	Precipitation of the driest month	mm	2.96
Bio 3	Isothermality (Bio2/Bio7) x 100	-	1.51
Bio 15	Precipitation seasonality (cv x 100)	-	3.25
Bio 2	Mean diurnal range	°C	6.05
Bio 18	Precipitation of the warmest quarter	mm	5.23
Bio 13	Precipitation of the wettest month	mm	2.12
Bio 6	Minimum temperature of the coldest month	°C	2.02
Bio 4	Temperature seasonality (Standard deviation x 100)	-	1.61

6.2.5. Modelling approach

Macadamia's current and future distribution in Malawi was modelled based on an ensemble suitability method implemented by the R package "*BiodiversityR*" (Kindt, 2018). The ensemble modelling technique was used because it combines predictions from various algorithms and can provide better accuracy in predictions than relying on individual species distribution models (de Sousa & Solberg, 2020; Gábor et al., 2023). The procedure consisted of four steps.

In the first stage, the predictive accuracy of 18 SDM algorithms was assessed using cross-validation. The SDM algorithms used in this study are those that can distinguish between suitable and non-suitable areas without needing absence locations. To conduct this analysis, the occurrence data were randomly split into a 70% training dataset to fit the model, and the remaining 30% was used as test data to evaluate the model's predictive accuracy (Brotons et al., 2004; Thuiller et al., 2011). A five-fold (partition) cross-validation replicate was performed in each of the model algorithms to evaluate the stability of the prediction accuracy, as described by Rabara et al. (2020) and Mudereri et al. (2021). Each SDM algorithm's performance was evaluated from each partition separately after individual algorithms were assessed with data from the other four partitions. Cross-validation measures the performance of models and prevents overfitting, particularly in cases where the amount of data may be limited (Berrar, 2018; Mudereri et al., 2021).

The area under the curve (AUC) criterion computed by the R package "*PresenceAbsence*" (Shabani et al., 2018) was used to evaluate the performance of each algorithm. The AUC value is a specific measure of model performance that demonstrates the model's ability to locate a randomly chosen present observation in a cell with a higher probability than a randomly selected absence observation (de Sousa & Solberg, 2020; Rabara et al., 2020). Based on Kindt & Coe's (2005) recommendation, the AUC value of 0.77 was used as a threshold to select the best-performing algorithms for this study. SDM algorithms that did not meet this criterion were not used to calculate the final ensemble model's suitability. AUC values of 0.75 are considered reliable, 0.80 as good, and 0.9 to 1 as having excellent discriminating ability (Jorcin et al., 2019).

For this study, the presence-only approach was utilised, and this is because, for agricultural applications of niche models, it is inappropriate to treat areas without current production as entirely unsuitable (see Chapter Three, Section 3.4). Further, determining whether a species is absent in a specific location is difficult and rare, so absence data may not be a true

representation of naturally occurring phenomena (Chemura et al., 2016). As an alternative, 500 background pseudo-absence points were randomly generated for this analysis. A caveat to this approach is the recommendations of Barbet-Massin et al. (2012) regarding the use of lower pseudo-absences in some algorithms. These background pseudo-absence points were later combined with the 84 occurrence points "presence only" for the niche modelling of macadamia.

The second step consisted of retaining only the algorithms contributing at least 5% to the ensemble suitability (S_e) (Ranjitkar et al., 2016). This procedure generated AUC values for each and the parameters of the response functions (model training) to estimate the probability values of species occurrence based on the climate of each grid cell of the study areas. The results of all the models were later combined by calculating for each the weighted average (weighted by AUC for each model) of the probability values from each model to generate the ensemble suitability map. The AUC values obtained by each algorithm were weighted using the following equation:

$$Ensemble (S_e) = \frac{\sum_i W_i S_i}{\sum_i W_i} \quad \text{Equation 6.2}$$

Where: The ensemble suitability (S_e) is obtained as a weighted (W) average of suitabilities predicted by the contributing algorithm (S_i).

The predicted suitable areas for the probability of macadamia were calculated using threshold values, i.e., ≥ 0.34 for the suitable area, while < 0.34 was regarded as unsuitable. The researcher selected this threshold based on its indication of a higher probability of favourable climate conditions required for macadamia growth and production. Similar threshold-based approaches have been used in climate suitability studies for other crops in the region, such as tea (Bunn et al., 2017) and coffee (Mudereri et al., 2021; Chemura et al., 2022).

To generate the probability maps, the maximum sensitivity (true positive⁺) and maximum specificity (true negative⁻) approach was used (Liu et al., 2013), where the probability maps were reclassified to a binary raster image (suitable/unsuitable areas). Then, the predicted binary values for each pixel were extracted using the Malawi shapefile in R. Finally, the total number of pixels for each predicted class was used to estimate the total coverage of the predicted suitable areas against the unsuitable areas within Malawi. Following recommendations by Chemura et al. (2020), the two suitability classes (suitable/unsuitable) were reclassified into five classes (unsuitable, marginal, moderate, optimal, and highly suitable). The final visualisation maps for the suitability classes of macadamia were developed using [ArcGIS Pro](#) software version 2.5.

In the fourth stage, the derived baseline suitability model was applied to each of the 17 downscaled GCMs to predict the future distribution of suitable areas for macadamia by the 2050s in Malawi. The results of the 17 GCMs probability layers were integrated into a single layer, using the criterion of likelihood scale (Mastrandrea et al., 2010; de Sousa et al., 2019), which requires at least 66% of agreement among GCMs to keep the predicted presence or absence in a given grid cell. The final visualisation maps for the future suitability classes of macadamia were developed using [ArcGIS Pro](#) software version 2.5.

6.3. Results

6.3.1. Model performance evaluation

The results show that the performance of the ensemble model is satisfactory for predicting the potential distribution of macadamia in Malawi, as revealed by the AUC value of 0.90 (Figure 6.4). This higher AUC value indicates that modelling climate-suitable areas for macadamia in Malawi is based on model competence rather than chance. Importantly, it provides confidence to apply the ensemble model for examining the areas suitable for macadamia under future climatic scenarios.

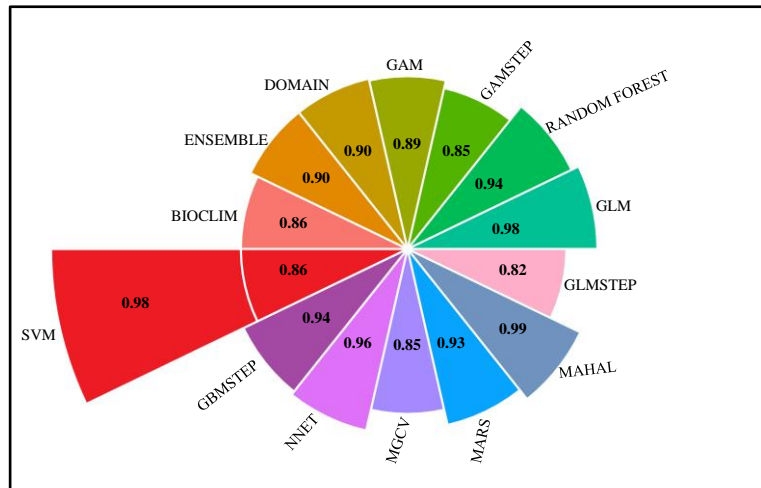


Figure 6.4: Performance of model algorithms and ensemble model based on AUC values.

6.3.2. Contribution of variables to the suitability of macadamia

Figure 6.5 presents the importance of climatic factors in determining the suitability of macadamia production in Malawi. Precipitation related variables explain 60.2% of the crop's suitability, while temperature based factors account for the remaining 39.8%. Precipitation of the driest month (May–October, Bio 14) is the variable with the greatest influence on macadamia suitability, contributing 29.1% to the model. This variable is nearly two times more important than the second most significant variable, which is temperature isothermality (Bio 3; 17.3%). The remaining two significant predictors are precipitation seasonality (Bio 15; 13.5%) and mean diurnal temperature range (Bio 2; 13.8%). Collectively, these four variables account for 73.7% of the model's contribution. Furthermore, precipitation seasonality is substantial as an individual factor, indicating that precipitation amount and distribution are important for defining the crop's range in the country. The remaining four variables each contributed no more than 11% to the model.

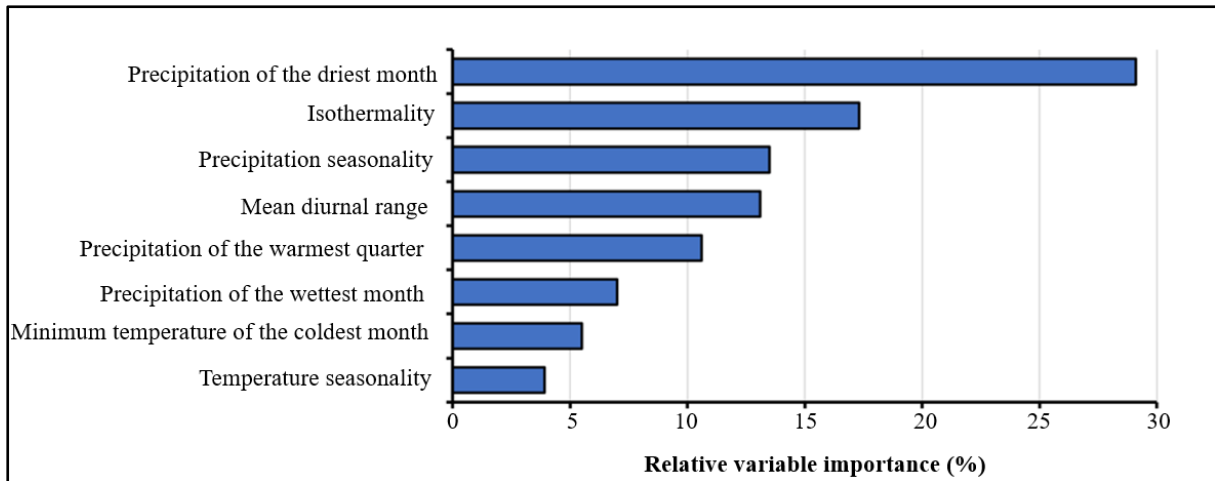


Figure 6.5: The relative importance of a variable in explaining macadamia suitability in Malawi.

6.3.3. Current suitability for macadamia in Malawi

Under the current climatic conditions, the ensemble model shows that 57% (53,925 km², Figure 6.6) of the land surface area in Malawi is suitable for macadamia production. This includes both cultivated land already being used for macadamia or other crops, as well as uncultivated land yet to be converted for agricultural purposes. The central region has the largest suitability (25.8%), which translates to 24,327 km², followed by the northern region, with 20.5% (19,341 km²) of suitable land. The southern region has the lowest suitability (10.7%), translating to 10,257 km² of suitable areas. Optimal suitability (26%, 24,565 km²) is observed in the country's highland areas with elevations ranging from 1000–1400 m.a.s.l. These areas are mainly in some parts of Dowa, Chitipa, Mulanje, Mwanza, Mzimba, Ntchisi, Nkhatabay, Rumphi, and Thyolo districts.

Moderate suitability, spanning 22.4% or 21,195 km², is projected in the mid-hill regions between 950–1000 m.a.s.l. in the districts of Blantyre, Chiradzulu, Dedza, Kasungu, Lilongwe, Mchinji, and Zomba. Marginally suitable areas are found in the country's lower elevation (\leq 900 m.a.s.l.). Because of the topography, the districts of Neno and Ntcheu have both optimal and marginally suitable areas for macadamia. It is noted that the model projections of the current distribution of suitable areas align closely with the crop's actual occurrence in the country.

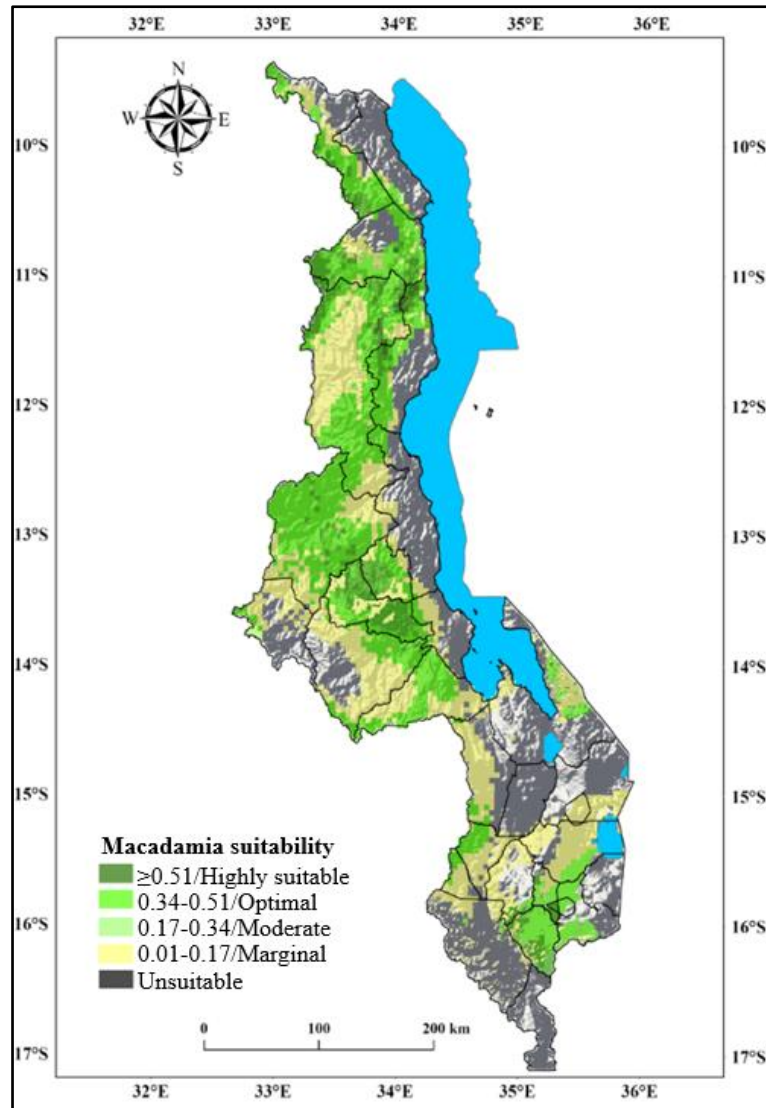


Figure 6.6: Current suitability for macadamia production in Malawi.

6.3.4. The impacts of climate change on macadamia in Malawi

The impacts of climate change on macadamia suitability in Malawi are depicted in Table 6.2 and Figure 6.7. The results highlight the potential repercussions, indicating a significant risk of losing suitable areas for macadamia production in the country by the 2050s. This vulnerability is consistent across the emission scenarios explored in this study. Projections indicate significant net losses of suitable areas, amounting to 18% under RCP 4.5 and 21.6% under RCP 8.5. This translates to 17,015 km² (RCP 4.5) and 20,414 km² (RCP 8.5) of Malawi's surface area.

Table 6.2: Simulated impacts of climate change on macadamia suitability in Malawi.

Region	Current		RCP 4.5		RCP 8.5	
	Area (km ²)	%	Area (km ²)	%	Area (km ²)	%
Central	24,327	25.8	6,784.1	7.2	7,950.1	8.4
Northern	19,341	20.5	1,850	2.0	3,730	3.9
Southern	10,257	10.7	8,380.9	8.9	8,733.9	9.2
Total	53,925	57	17,015	18	20,414	21.6

The study indicates that lower altitudes (0–900 m.a.s.l.) are particularly vulnerable to substantial declines in suitable production areas for macadamia due to the predicted increase in warming. Malawi's southern region is the most vulnerable and is estimated to lose 81.7% (RCP 4.5) and 85.2% (RCP 8.5) of all its current suitable areas due to projected drier and hotter conditions in the coming decades. Thyolo district, the largest and most productive macadamia growing area in the country, is projected to lose 100% (1228 km²) of its suitable areas for macadamia production due to the impacts of climate change. The study projections also show that the area suitable for macadamia in the country's central region will shrink by at least 7.2% (6784.1 km², RCP 4.5) and 8.4% (7950.1 km², RCP 8.5). For the northern region, the suitability for macadamia is predicted to decline by 2% (1,850 km²) and 4% (3,730 km²) under RCP 4.5 and RCP 8.5, respectively (Figure 6.7).

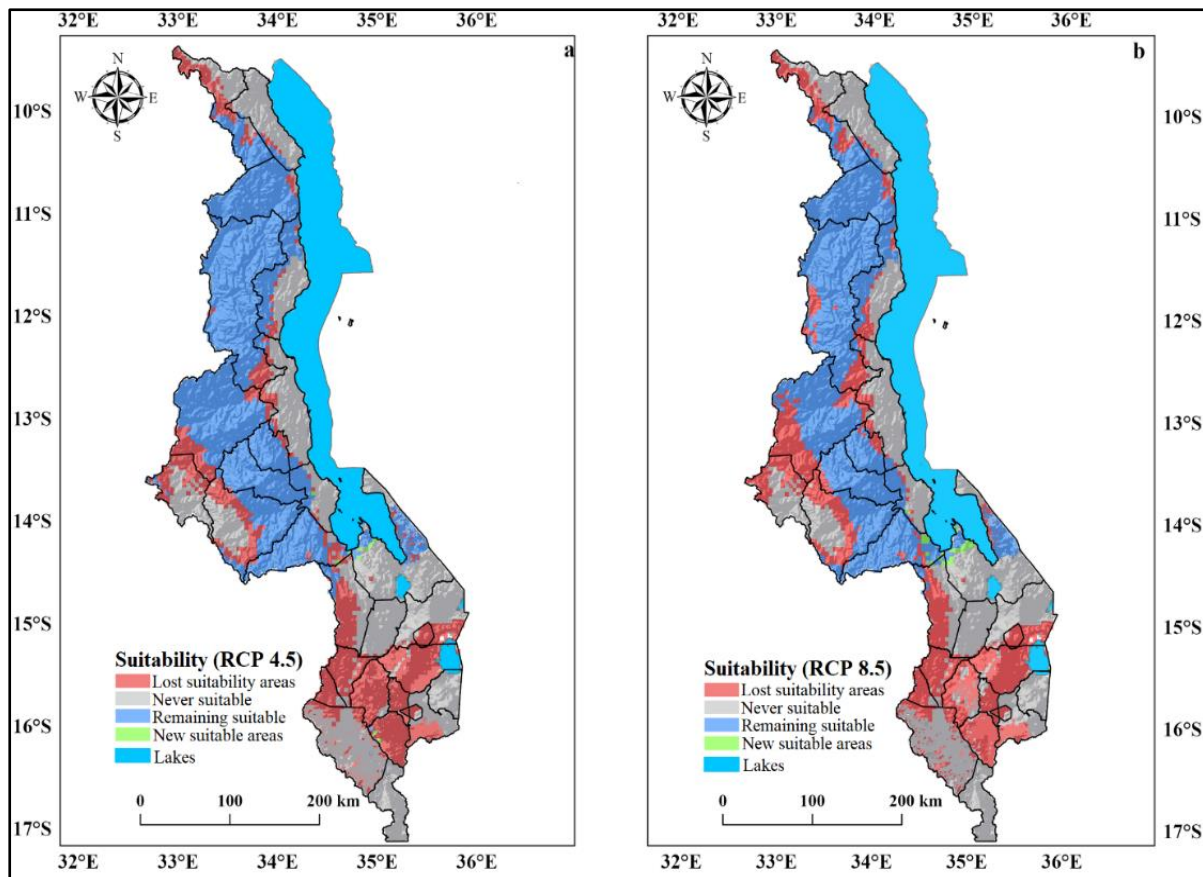


Figure 6.7: Shifts in macadamia suitability due to climate change by 2050 (a) RCP 4.5; (b) RCP 8.5.

Despite the projected losses in suitable macadamia growing areas, the current study indicates that 39.1% (36,910 km²) and 35.5% (33,511 km²) of Malawi's surface area will remain suitable for the crop under RCP 4.5 and RCP 8.5, respectively. The results from the intermediate scenario show that 18.6% (17,543 km²), 18.5% (17,491 km²), and 2% (1,876 km²) of Malawi's land surface areas will remain suitable for macadamia production in the 2050s in the central, northern, and southern regions, respectively (Figure 6.8).

The outcomes for the pessimistic scenario suggest that approximately 17.3% (16,377 km²), 16.5% (15,611 km²), and 1.6% (1,523 km²) of Malawi's land will remain suitable for macadamia in the central, northern, and southern regions, respectively. In addition, based on RCP 4.5 and RCP 8.5, the ensemble model predicts an average gain in suitable areas of +0.22% (207 km²) and +0.5% (476 km²) across Malawi. These newer areas are expected to occur in

Dedza (Mua and Chipansi), Mangochi (Namwera and Chaponda), Salima (Kasamwala), and Thyolo (Thekerani) districts (Figure 6.7). However, these only apply to a small portion of the country and cannot compensate for the country's decreased suitability.

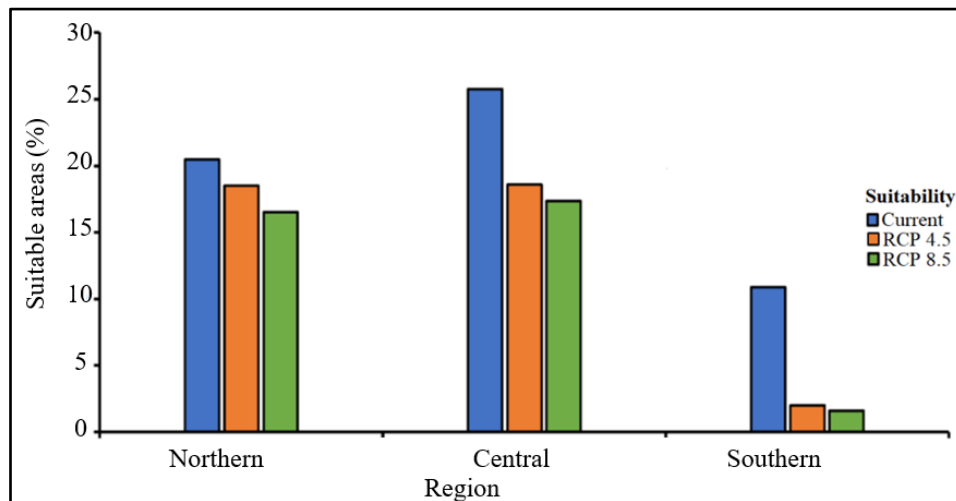


Figure 6.8: Percentage of predicted suitable areas for macadamia production using current and two future climate scenarios.

6.4. Discussion

This study uses an ensemble suitability model to determine key climatic variables that influence rainfed macadamia production and to evaluate the effects of climate change on macadamia cultivation in Malawi for the 2050s. By identifying areas with the highest potential for macadamia, the study provides a valuable resource for improving the crop's productivity that can facilitate enhancing food security and livelihoods of the producers. Furthermore, the study identifies areas that are vulnerable to losing their suitability due to the impacts of climate change and therefore highlights the need to develop adaptation measures for the crop in these hotspots and provides important information that can be used for land use planning.

6.4.1. Contribution of variables to the suitability of macadamia

The study findings reveal that macadamia production in Malawi is heavily influenced by specific environmental factors present in certain areas. The results indicate that macadamia suitability in the country is influenced by the seasonal fluctuations of precipitation and

temperature rather than annual averages, confirming findings by Evans (2008). However, the climatic variables identified in this study differ from global climate indicators for macadamia (Nagao et al., 1994). Conversely, in Australia, Hawaii, and Nepal, temperature based factors were identified as the primary determinants of macadamia suitability (Barrueto et al., 2018a). Chemura et al. (2021) argue that such variations are explained by differences in scale and geography, implying that local and regional factors can influence macadamia potential. This explains the current study findings, which show that precipitation based factors are more relevant in predicting macadamia suitability than temperature based factors, collaborating with the assertions that moisture stress adversely affects macadamia suitability in Malawi (Chandler, 2018).

According to the results, precipitation of the driest month and precipitation seasonality are the two most essential precipitation variables affecting macadamia's suitability in the country. These two factors represent precipitation amount and distribution, thus, are associated with crop water use and evaporative losses. Furthermore, the study findings reveal that Malawi's dry season (May–October) coincides with the most critical stages of macadamia development, including flowering, nut growth, and oil accumulation. Interviews with HIMACUL farmers, as shown in the quote below, also support these modelling results, revealing the link between water scarcity during the dry season and the occurrence of critical phenological stages of the crop.

"Irrigating my macadamia trees during the dry season is necessary because flowering coincides with this period, and if the trees do not have moisture, they lose many flowers." (EJZ_21).

However, moisture stress is detrimental to macadamia growth and development. Studies have shown that moisture stress inhibits and delays flower development (Mayer et al., 2006), as well as causing premature nut drop, leading to reduced nut yields and quality (Stephenson et al., 2003). In Australia, Nagao & Hirae found that water deficits from prolonged drought periods

caused macadamia flower loss and tree mortality. Consequently, projections that climate change will decrease the number of rainy days and months (Mittal et al., 2017; Chandler, 2018; Chemura et al., 2022), thus reducing moisture availability to macadamia trees during the dry season will drive many areas out of macadamia production (Figure 6.7). These findings confirm and, more importantly, extend the work by Jennings et al. (2022), who predicted that climate change will reduce the amount and distribution of precipitation throughout Malawi, particularly the southern region, altering the suitability of important crops such as tea, coffee, and sugarcane. Below is a quote highlighting the impacts of higher temperatures as perceived by smallholder farmers.

"During the flowering time, which coincides with the dry season, I have noticed that many macadamia flowers die when less water is available in the soil. This is why I irrigate my plants during this time of year. Without the additional irrigation water, I believe my yields can be very low " (EJZ_14).

In order to increase resilience to the negative impacts of moisture stress on macadamia yields and quality, it is recommended that farmers are encouraged to adopt moisture conservation measures such as mulching, rainwater harvesting, box ridging, and basins. Furthermore, farmers are encouraged to consider developing sustainable irrigation systems (solar or wind powered) to ensure that their macadamia trees receive sufficient water throughout the year, especially during the drier months. These measures can assist in supporting the healthy growth and development of macadamia trees and minimise the impact of moisture stress on crop productivity.

Temperature isothermality and the mean diurnal range are other important factors influencing macadamia suitability in Malawi. The findings of this study suggest that large fluctuations in day and night temperatures and increased warming ($\geq 30^{\circ}\text{C}$) are responsible for the observed marginal suitability of macadamia in some parts of Malawi, particularly along the lakeshore and Shire Valley, confirming previous research (Pichakum et al., 2015; Barrueto et al., 2018c).

Higher day temperatures of more than 30°C have already been linked to excessive water loss from macadamia plants (Nagao et al., 1994). Such moisture losses result in a disproportional supply of nutrients within the macadamia nut, limiting oil build up and affecting the nut quality (Britz, 2015). As a result, predictions that climate change will increase the number of days (30.5 days per year) with temperatures above 30°C and hot nights (40 days per year) with temperatures above 14°C in Malawi (World Bank, 2019) will undoubtedly have dual impacts on macadamia production by reducing suitable production areas and reducing nut yields and quality. Subsequently, irrigation will be crucial for long-term macadamia production, especially during the hotter, drier months, to compensate for water lost through evapotranspiration. Moreover, the government of Malawi is already advocating for irrigation farming as a climate change adaptation strategy to enhance crop productivity.

6.4.2. Impact of climate change on macadamia suitability in Malawi

Under the current climatic conditions, extensive areas in Malawi are suitable for macadamia production. Moreover, the study identifies potential suitable growing areas for macadamia in Malawi's south-eastern parts, including Luchenza, Katunga, and Nsabwe, outside the crop's current reported production areas. This is expected as suitability maps capture the potential production areas, some of which have not yet been translated into realised areas (Chemura et al., 2016). This also suggests the broad adaptability of some macadamia cultivars that can be grown in high-potential areas as well as marginal and low-input areas with several environmental constraints. Nonetheless, these areas are the most vulnerable to climate change due to their limited buffering capacity.

Macadamia production in Malawi is, however, already falling outside the recommended optimal temperature range of 14–30°C (Appendix 4), which is attributed to the increase in annual mean temperatures (~0.9°C) and overall drying recorded in the past five decades (McSweeney et al., 2008; Mittal, 2017; Jennings et al., 2022). Moreover, based on the current study, climate change is expected to reduce the suitable areas for macadamia production by the

2050s. The lowlands, predominantly those in the southern region, will be the most vulnerable to these losses ($\geq 85\%$), with suitability shifting to the country's central and northern regions.

The projected decreases in suitable areas will likely be attributed to increased warming, as well as increases in the intensity and frequency of heatwaves, droughts, and flooding linked to the El Niño Southern Oscillation (Mittal et al., 2017). Barrueto et al. (2018c) predicted losses in suitable areas for macadamia production in Nepal's lowlands due to warming conditions and reduced amounts of groundwater (due to lower precipitation or increased demand for other uses), which is concurrent with the current study results for Malawi. Chemura et al. (2021) projected declines in suitable areas for specialty coffee under climate change scenarios in Ethiopia, confirming the findings of this study that climate change may negatively impact the suitability of areas for macadamia in Malawi. Bunn et al. (2017) predicted losses in suitable areas for tea and sugarcane production in southern Malawi due to the impacts of climate change, which is also in line with the current study in the same region. Additionally, the number of days with average temperatures above 35°C is projected to increase in the country (Jennings et al., 2022). Subsequently, this will negatively impact macadamia phenological stages and may lead to flower abortion and premature nut fall, affecting yields.

The suitability for macadamia production in northern Malawi is expected to face minor losses ($\leq 4\%$). This is because a larger percentage of the region (75%) is located at higher elevations (≥ 1200 m.a.s.l.), making them less vulnerable to higher temperatures. However, some of the high-elevated areas (≥ 1400 m.a.s.l.) in central and northern Malawi will likely become unsuitable for macadamia due to predicted increased cloud cover (Mataya et al., 2019). This will reduce the amount of light reaching the trees, affecting net photosynthesis and, ultimately, nut yields. Furthermore, excessive cloud cover has been found to cause thick shells in macadamia and lowers the overall nut yields (Barrueto et al., 2018a).

Climate change is also projected to increase the prevalence and severity of crop pests and diseases in Malawi, particularly in the highland areas (Mutamiswa et al., 2022). Hence, without

effective agricultural policies, crop damage and yield losses are anticipated in the 2050s (Jennings et al., 2022). Moreover, the projected increases in the frequency of extreme weather events, such as the number of heatwaves, droughts, and flooding, are expected to increase the populations of insect pests (Liu et al., 2020). For instance, droughts are projected to decrease the abundance of natural enemies of insect pests and create mismatches between pests and enemies in space and time (Jennings et al., 2022), while flooding will lead to ideal breeding conditions for certain insect pests of crops and disease carrying insects like mosquitoes. Therefore, while macadamia suitability may shift to the central and northern highland areas, it is crucial to plan management strategies for the potential impacts of insect pests and diseases.

The study's findings demonstrate macadamia's sensitivity to variations in environmental conditions. Thus, farmers can continue planting macadamia trees in areas where no changes in suitability for the crop are expected. However, both research and field-based evidence from discussions with farmers show that climate-related changes are already occurring and affecting the suitability for macadamia in the country. Thus, farmers are strongly encouraged to take action and start implementing adaptation measures to ensure sustainable macadamia production. These measures can include using improved macadamia cultivars that are more resistant to pests and disease damage, increasing crop diversity through agroforestry and multiple cropping, practicing water conservation and irrigation, integrated pest and disease management, and integrated soil fertility management.

"Recently, I have started seeing the effects of climate change on my macadamia trees, the seed coats have changed their colour from dark green to brown, and as a result of very hot weather, there is increased falling and abortion of flowers, which later cause lower annual yields." (EJZ_15).

It is important to note that the changes in suitability are predicted to occur over the next 30 years, mainly affecting the next generation of macadamia farmers. While there is still time for adaptation, failure to act promptly could have serious implications for Malawian farmers,

communities, and consumers of macadamia. Firstly, and perhaps more importantly, the harvesting and consumption of macadamia in the country extend to the lean period when other common food crops such as maize, cassava, and rice are unavailable, and the decreases in its suitability increase risks of food insecurity.

Secondly, macadamia nuts are a high-value crop that fetch higher market prices than tobacco, legumes, and cereals, meaning that if farmers migrate to other crops, they may lose this potential income stream per unit land by moving to lower-value crops. Thirdly, macadamia provides supplementary nutrients that are essential in providing balanced diets. For example, they have higher monosaturated fat content than other nuts (Hu et al., 2022; Quinton et al., 2022), are richer in essential minerals (Mg, P, K, and Cu), and are highly recommended for diabetic patients and persons with heart and brain disorders and children due to their health benefits (Arab et al., 2015; Tindall et al., 2019).

Proper design and implementation of adaptation measures can maintain macadamia production and productivity in almost all the districts currently producing the crop, given that the decreases in suitability are not drastic. However, there is potential for macadamia production under agroforestry systems because such systems help to regulate microclimates, including the reduction of soil temperatures by 0.14°C (Middel et al., 2015), promotes water infiltration and soil fertility improvement if legumes are part of the crops in the system (Lott et al., 2009; Saputra et al., 2020). Such potential is particularly important because tree cover has declined in many farmlands in Malawi yet has complementary roles in nutrient cycling, carbon sequestration, and climate regulation and cushioning against climate extremes (Bhagwat et al., 2008; Gassner & Dobie, 2022).

Additionally, there is a need to identify the best-bet practices in macadamia production and use them for training agricultural extension staff. There is also a need for capacity building of farmers on macadamia production by including and mainstreaming it in extension packages for areas in which it can be cultivated. Water conservation systems, particularly irrigation, are

another potential climate change adaptation measure for macadamia, given that the projections indicate increases in the number of dry days and distribution of precipitation and temperature increases.

This research also emphasizes the importance of developing and selecting macadamia cultivars that are more heat tolerant and drought resistant, especially for the low-lying areas in southern Malawi. According to Carr (2013) and Shabalala et al. (2022), different macadamia cultivars have varying responses to heat and droughts, making it crucial to choose the appropriate cultivars for production under changing climate conditions. Previous research has identified drought-tolerant cultivars, including HAES 344, 660, 741, and A16 are drought tolerant (McConachie, 2009; Hardner et al., 2009). Therefore, it is recommended to use these cultivars as a source of rootstocks for grafting purposes.

6.5. Applicability and potential limitations of this study

Species distribution modelling is a powerful tool for predicting species occurrences and understanding the drivers of their distributions. While the results of this study are robust and reliable (AUC = 0.90), several issues should be considered when interpreting and applying the results. For example, the study identifies potentially suitable areas for macadamia production across Malawi. However, this may not directly translate to the availability of arable land on the ground. In addition, the analysis did not account for soil and socioeconomic factors typically considered in land suitability assessments for specific crops. Therefore, it is recommended that the interpretation of the current study's results be coupled with an understanding of soil fertility, social and cultural factors, and the potential impacts of climate change on other crops grown in each area.

It is also crucial to keep in mind that this study focuses on smallholder rainfed macadamia production. As such, areas that are predicted to lose their suitability in the future may still be able to support macadamia production under intensive management systems. Nonetheless, the

results of the study are important for future planning purposes. Thus, there is a need for a thorough evaluation of adaptation approaches suggested for smallholder macadamia farmers, as these may differ from those used by commercial growers.

Furthermore, at the time of writing this thesis, some parts of Malawi were experiencing higher average monthly temperatures ($\geq 32^{\circ}\text{C}$), affected by cyclone Freddy, severe power outages, and a fuel crisis, making irrigation an expensive option with significant cost implications. Subsequently, another valuable contribution of this study is predicting how the costs of macadamia production may shift due to climate change.

6.6. Conclusions

An ensemble model approach is used in this study to determine the current and future suitable geographical areas for macadamia production in Malawi. The study's findings led to four important conclusions. Firstly, precipitation-related variables are the most important determinant of macadamia suitability in Malawi. Secondly, the majority of the current and future macadamia production areas identified exist on agricultural land currently used to grow other crops. Thus, the study recommends the promotion of macadamia agroforestry as a climate change adaptation strategy and for land intensification. Thirdly, the study suggests that the predicted increases in warming will increase pests and disease incidences, especially in the country's highland areas, which may lead to reduced crop yields. Finally, the analysis predicts that the extent of suitable areas for macadamia production will decrease under both emission scenarios utilised, and the most vulnerable areas are in the southern region. In general, the macadamia sector in Malawi faces production risks due to the projected impacts of climate change. However, the study's findings offer opportunities for adaptation strategies to help build a more resilient sector. Specifically, promoting agroforestry as a climate change adaptation strategy may have great value in helping to promote government policy change and may assist in maintaining or expanding the country's production of macadamia.

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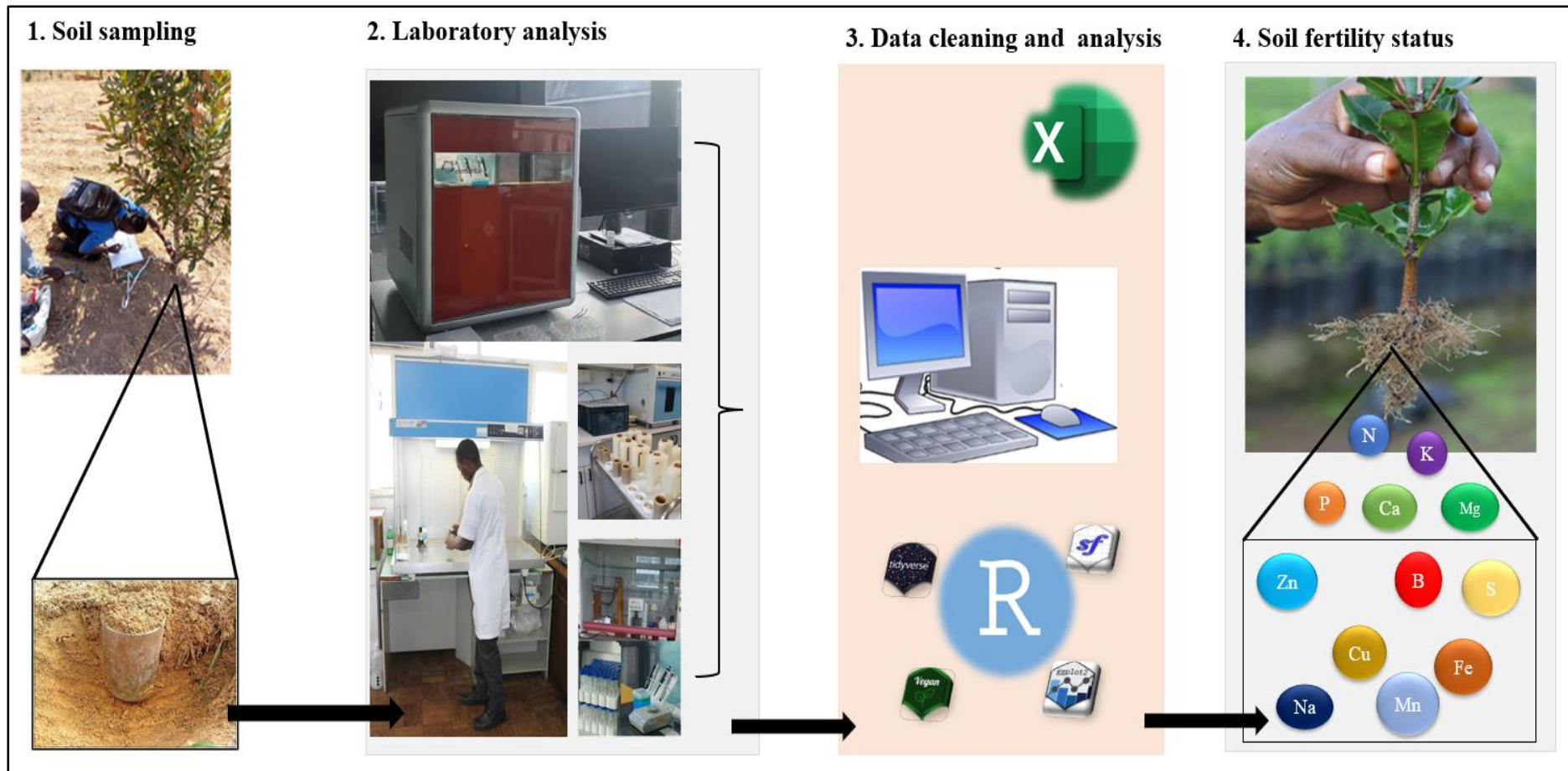
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Graphical Abstract



CHAPTER SEVEN: ASSESSING SOIL NUTRIENTS VARIABILITY AND ADEQUACY FOR THE CULTIVATION OF MACADAMIA IN MALAWI

Abstract

Declining soil fertility is a major factor that limits smallholder macadamia productivity in Malawi. To address this trend, applying both organic and inorganic fertilisers efficiently and effectively is crucial. However, current fertiliser recommendations for smallholder macadamia production in Malawi are not site-specific, resulting in nutrient imbalances, potential yield losses, unnecessary costs, and environmental issues. This study aims to establish an evidence base for promoting soil fertility restoration interventions for smallholder macadamia producers. A total of 189 soil samples were collected at a depth of 0–15 cm from smallholder macadamia farms belonging to HIMACUL members in central and southern Malawi. The results show different degrees of variability in soil physical and chemical properties in all the sampled farms. Overall, the majority of the soils are sandy loams (52%), strongly acidic (mean pH \leq 5.10), and generally deficient in essential nutrients required for the optimal growth of macadamia trees. Additionally, the cation exchange capacity of the soils is low (1.67 cmol (+) kg⁻¹) to support macadamia growth and development. More than half of the sampled soils have very low organic matter content (\leq 1%). Poor agronomic practices and inherent soil characteristics are responsible for this low soil fertility status. The study findings highlight the urgent need to implement land and nutrient management practices that address the observed low soil fertility, such as agroforestry, conservation agriculture, and cover crops.

7.1. Introduction

Soil fertility plays a crucial role in the agricultural industry, directly impacting crop yields and overall production (Asfaw et al., 2018). However, soil fertility is declining due to intense and mismanaged farming practices such as monocultures, lack of crop rotation, and over-application of inorganic fertilisers, pesticides, and herbicides, particularly in Africa. This has led to significant decreases in crop yields in Africa relative to other continents. According to

data from the [World Bank](#), the average yield of maize in southern Africa increased from 1.6 MT ha⁻¹ in 2016 to 2.0 MT ha⁻¹ in 2020, whereas in South America and Asia, yields increased from 3 to 4.5 MT ha⁻¹ during the same period. Moreover, besides limiting yields, low soil fertility further affects the nutritional composition of crops by altering their nutritional quality (Gashu et al., 2021).

In Malawi, declining soil fertility is a major challenge to crop productivity (Snapp, 1998; Ligowe et al., 2017; Gashu et al., 2021). Continuous cropping and lack of agricultural inputs have been identified as the country's common sources of soil fertility loss (Nájera et al., 2015; Asfaw et al., 2018). Studies have shown that long-term monoculture of annual crops, notably maize and tobacco, lead to the depletion of soil fertility (Ngwira et al., 2013; Stevens & Madani, 2016; Bouwman et al., 2021). Further, soil fertility loss has been linked to weathering, erosion, and blanket inorganic fertiliser applications (Asfaw et al., 2018; FAO, 2022). However, understanding the soil fertility status of previously cultivated arable lands where high-value perennials such as macadamia are currently or planned to be grown is essential for Malawi's long-term agricultural productivity.

Macadamia is a highly profitable export crop globally (Zuza et al., 2021a). The crop is native to the highly weathered acidic soils of north-eastern Australia but grows productively in subtropical climates (Moncur et al., 1985). More than forty countries are actively engaged in the cultivation of the crop, with a market value of more than \$1.14 trillion (INC, 2021). The crop is essential to the economies of producing countries as it contributes to income generation and revenue from foreign exports (Barrueto et al., 2018c; Zuza et al., 2021b). The growing public knowledge of the health benefits of consuming macadamia nuts, including improving artery health and lowering the risk of high blood pressure, has led to a 45% increase in macadamia nut production over the past decade compared to the previous decades (INC, 2022).

Because of this, international retail prices for first-grade macadamia nuts are higher than those for other nut crops ($\geq \$15 \text{ kg}^{-1}$, INC, 2021).

Macadamia nuts have high socioeconomic value among smallholder producers in rainfed agricultural economies, including Malawi. The country is the world's seventh-largest producer of macadamia nuts, accounting for 4% of global production (INC, 2022). The nuts are a high-value export crop with an estimated value of more than \$30 million. As a result, Malawi's macadamia industry is rapidly expanding. To further increase production and marketing of the crop, the Malawi government's Vision 2063 policy focuses on crop commercialisation and diversification to strategic crops like macadamia (NPC, 2022).

Macadamia production in Malawi is divided into two distinct subsectors: estate and smallholders, and a growing intermediate scale of growers between these two. Production is dominated by the estate subsector accounting for more than 90% of overall output (Zuza et al., 2021a). However, smallholder production has rapidly increased, particularly during the past decade, starting from a low base. This expansion has provided many smallholders with a unique option to support their livelihoods. In addition, with an estimated net carbon sequestration potential of three tonne $\text{CO}_2\text{e ha}^{-1} \text{ year}^{-1}$ (Murphy et al., 2012), macadamia is attractive for contributing to both economic development and decarbonisation.

Despite the expansion of the smallholder macadamia subsector in Malawi, smallholder crop yields are substantially lower than those of estate producers. The low input context of smallholder farmers on already nutrient-deficient soils has led to these massive yield reductions (Evans, 2021). On top of the general scarcity and suboptimal management of organic fertilisers, the lack of adequate replenishment of soil nutrients is one of the factors for the low macadamia yields among the smallholders (Zuza et al., 2021a).

The importance of soil fertility for macadamia productivity cannot be over-emphasized, as it impacts nut retention, quantity, and quality, all of which determine the yield and market value of the nuts produced (Bright, 2019). For optimal growth, macadamia trees require a soil pH between 5.5 and 6.5, adequate amounts of SOM, and essential nutrients, particularly during the sensitive phenological stages (Cull et al., 1986; Bright, 2018). For example, a study indicated that an insufficient supply of essential nutrients results in stunted growth and reduced nut production in macadamia trees (Aitken et al., 1990). Additionally, nutritional imbalance promotes floral abortion and contributes to macadamia yield losses (Stephenson et al., 1997). Previous research in Malawi reveals that most soils lack adequate amounts of organic matter and essential nutrients, especially micronutrients (Matabwa & Rowell, 1997; Njoloma et al., 2016; Gashu et al., 2021). Consequently, these nutritional deficiencies may limit the production potential of macadamia in Malawian soils.

Soil micronutrients are essential to the global functioning of ecosystems and food production (Jiménez et al., 2022). Among these micronutrients, B and Zn are particularly important for macadamia nut set, yields, and quality (Stephenson et al., 1986). Specifically, boron is required for the development of new tissues and nut set (Trueman, 2013). Zinc is essential for the fertility of the female parts of the macadamia flowers and for auxin metabolism, both of which contribute to fruit quality and disease resistance (Nagao & Hirae, 1992). Thus, a thorough understanding of soil limiting factors among Malawian smallholder macadamia farms is essential to creating site-specific soil fertility management strategies and fertiliser recommendations for the crop.

This is because applying inorganic fertilisers without determining their need may lead to excessive or insufficient levels of nutrients, ultimately affecting macadamia productivity. Furthermore, investing in expensive inorganic fertilisers in low pH soils can result in poor

returns on investment, as high levels of acidity can render nutrients unavailable to plants. It is also important to note that the inorganic fertilisers available in Malawi, typically high in N:P:K and lacking a proper mix of micronutrients, are commonly targeted for maize and tobacco production and may not be suitable for macadamia nutrition.

To date, soil fertility studies on smallholder macadamia farms in Malawi are still lacking. Because of this, smallholders still adhere to early recommendations provided in the 1990s for sustaining soil fertility on their macadamia farms. However, assessing the soil fertility status of these farms to identify underlying nutritional deficiencies is key to determining soil improvement recommendations. In addition, the lack of quantitative knowledge prevents smallholders from taking cost-effective corrective actions, thereby reducing the crop's potential yields. Realising the severity of these challenges, the present study was undertaken to better understand the soil fertility status among smallholder macadamia farms in Malawi and to identify nutrient variation and their adequacy for macadamia production. This should allow the first steps for effective nutrient management resulting in more efficient land use for sustainable smallholder macadamia production.

7.2. Materials and methods

7.2.1. Study sites

The study was conducted in Malawi, a country located in southern Africa. The country has a subtropical climate with two distinct seasons, the rainy season from November to April and the dry season from May to October. Soil samples were collected from beneath age uniform trees (10-year-old macadamia orchards) at 63 locations among HIMACUL members. These cooperatives include Nachisaka (NSA) in Dowa, Chikwatula (CTA), Malomo (MLM), Mphaza (MPA), and Tithandizane (TZE) in Ntchisi, Mwanza (MA) in Mwanza, and Neno (NN) in Neno districts (Figure 7.1). These cooperatives represent the country's primary smallholder macadamia production areas in terms of the number of growers and area under production (Zuza et al., 2021a).

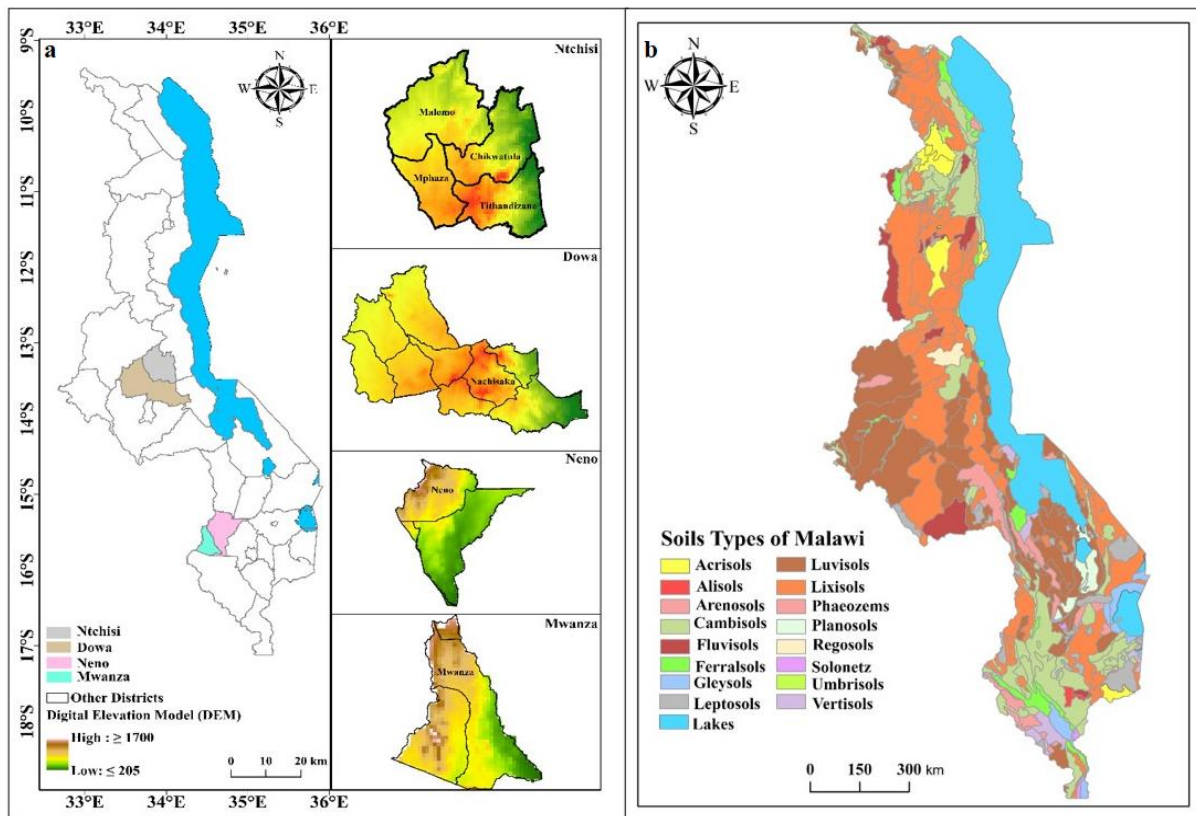


Figure 7.1: a) Map showing study sites b) Soil types.

7.2.2. Soil sampling

Soil samples were collected from all sample sites during the dry season in 2019 between August and September. The selection of the sampling sites involved identifying areas that have received less research interest. The researcher also ensured that the sites were representative of the altitudinal differences in the country. Within each cooperative, soil samples were obtained from 9 macadamia farms with a tree spacing of 8 m by 8 m. Three undisturbed soil cores (7 cm diameter x 7 cm height) were collected from the middle and two randomly selected locations at each farm. The soil cores were extracted at 0–15 cm depth to capture the desired profile. To create a composite sample representing the collective properties of the sampled farms, individual soil samples were mixed to achieve a 500g composite sample. The study only focused on the topsoil because macadamia has a shallow taproot and draws the majority of its nutrients through fibrous proteoid root systems near the soil's surface.

Soil cores were trimmed at both ends immediately after collection, covered with plastic caps, and transferred to the Lilongwe University of Agriculture and Natural Resources (LUANAR) Plant and Soil laboratory situated in Lilongwe city. After air-drying, the soil samples were sieved using 2 mm sieves to remove large particles, debris, and stones. A composite soil sample was generated by combining the three soil samples from each macadamia farm. Using soil standard preparation techniques outlined by Njoloma et al. (2016), 10 g of the composite soil sample was weighed and used for each analytical method.

7.2.3. Soil analysis

The soils were analysed for pH in a 1:2.5 soil to water slurry (McLean, 1982) using a calibrated electrode pH meter at room temperature (OrionVersaStar[®]), particle size distribution (texture) using the Bouyoucos hydrometer method as described by Bouyoucos (1962) at the LUANAR Plant and Soils laboratory. The cation exchange capacity (CEC) was determined by the ammonium acetate method (Metson, 1956), and available P was measured using the Olsen P method (Hodges & Sharpley, 2004) using the elemental analyser 146[®] at The Open University's, Ecosystems and Geobiology Laboratories (EGL).

Soil organic carbon (SOC) was analysed using the Elemental Vario EL Cube[®] analyser via wet digestion and colorimetric scale. Total nitrogen (TN) was extracted using the Kjeldahl method. Available potassium (K⁺) and other nutrients (B, Zn, S, Ca²⁺, and Mg²⁺) were extracted using acid digestion and analysed using the Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES)[®], Agilent 5110 at EGL. The soil's physical and chemical properties were analysed, with three replication runs for each element, and mean values were used for the statistical analyses.

7.3. Statistical analysis

The analysis of variance (ANOVA) and mean comparisons were carried out using the general linear model (GLM) procedure in R[®] Statistical Computing Software version 4.2.2 (R Core Team, 2022). The assumptions of the ANOVA were tested by ensuring that the residues were

random, homogeneous, and with normal distribution. Based on Bartlett's test, all soil properties exhibited a homogeneous variance. Shapiro's test revealed normal distributions for the soil's physical and chemical properties. When the *F-test* showed statistical significance at $p \leq 0.01$ or $p \leq 0.05$, the Tukey Honest Significant Difference (HSD) post hoc test was used to evaluate the significance of differences between pairs of group means (Tukey, 1949). Pearson's correlation coefficient matrix was further used to describe relationships among the soil properties.

7.4. Results

7.4.1. Soil texture

Using the USDA classification system, six distinct soil texture classifications are identified among the study sites (Table 7.1). The textural classes are principally sandy loams (52%) to sandy clay loams (15%), with some soil layers subtending clay loams (13%), loams (12%), and silty clay loams (5%). However, site-specific soil assessment reveals substantial variation both within and between the sampled farms. For example, some farms in Tithandizane cooperative (TZE) have silt contents of less than 2%, while others have silt contents of more than 25% (Figure 7.2c).

Table 7.1: Summary of soil texture classification results.

Textural class	Percentage of samples in class (%)	Soil class
Clay	3	Clay
Clay loam	13	
Loam	12	Loam
Sandy clay loam	15	
Sandy loam	52	
Silty clay loam	5	

Soils in Nachisaka cooperative (NSA) contain a high concentration of sand (57–81%), followed by clay (13–29%) and some low proportions of silt ranging from 2–14%. These soils have thus been categorised as sandy loams. Sandy clay loams (11.7%) are the most common type of soil

in Tithandizane cooperative (Figure 7.2b and 7.2c). Similar to Nachisaka, Malomo (MLM) and Mphaza (MPA) cooperatives have a majority of sandy loam soils (Figure 7.2d).

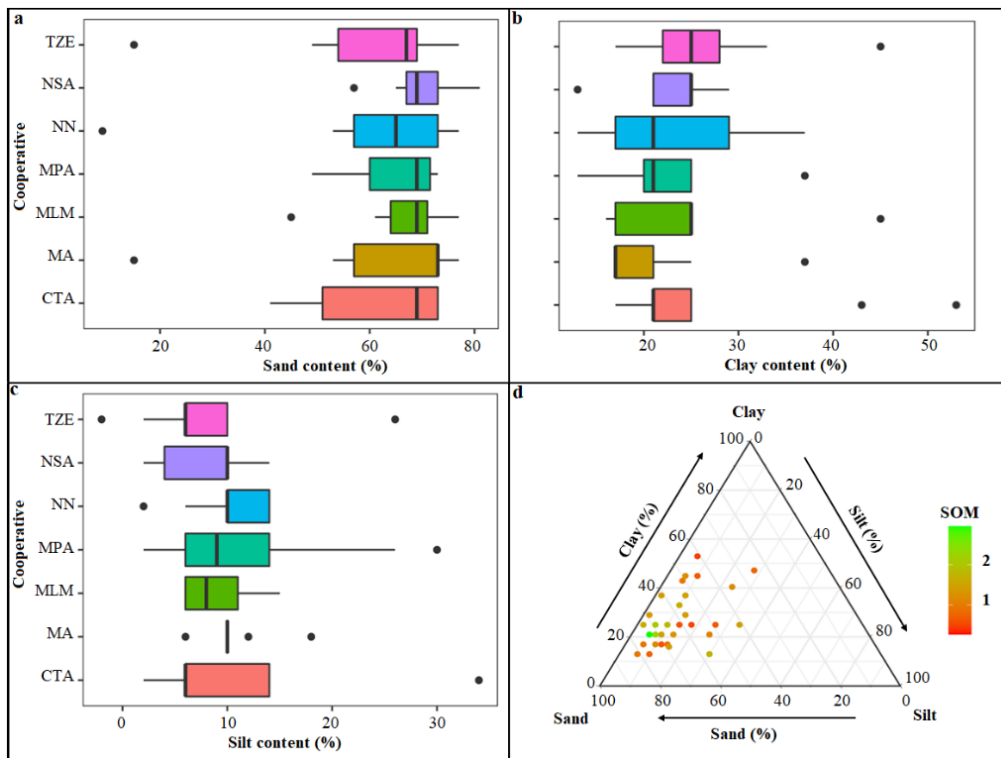


Figure 7.2: Percentages of a). Sand; b). Clay; c). Silt (Dots represent outliers and the boxes represent medians \pm IQRs); and d). Soil triangle for each sampled site (each of the dots represents the proportion of sand, clay, and silt and corresponding SOM content in %).

7.4.2. Soil pH

The study finds that soil pH levels among the sampled sites do not differ significantly ($p \geq 0.05$). However, the pH levels range from very strongly acidic (4.6) to moderately acidic (Figure 7.3). Furthermore, the results indicate that only 12.7% of the sampled farms have soil pH levels within the recommended range (≥ 5.5 – 6.5) for optimal macadamia growth, while more than a third (38.1%) have very low pH levels of 4.98 or less. Therefore, the study findings indicate significant variability in soil pH among the smallholder macadamia farms, ranging from suboptimal to ideal levels for macadamia growth.

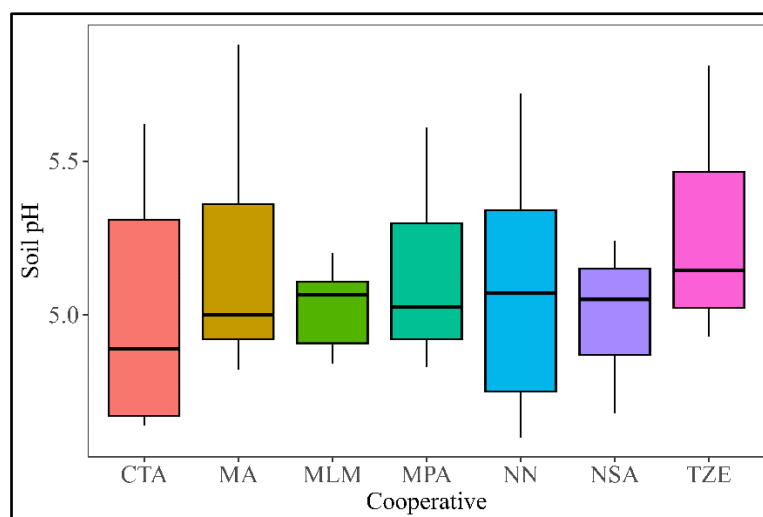


Figure 7.3: Distribution and variation of soil pH among study sites.

7.4.3. Soil macronutrients

The results of the present study show no significant differences in the levels of total nitrogen and available potassium across all the study sites. The TN levels are generally low, ranging from 0.065% to 0.102% (Figure 7.4a). Moreover, 70% of the sampled farms are deficient in TN, which is below the threshold of sufficiency ($\geq 0.1\%$) for many tropical crops (Landon, 2014).

Regarding available K^+ concentrations, the study reveals that farms in Malomo, Mphaza, Nachisaka, and Tithandizane cooperatives have adequate amounts of the nutrient relative to the reference range (200–300 $mg\ kg^{-1}$, Evans, 2021) required for a healthy macadamia crop, as shown in Figure 7.4b. Mwanza cooperative has the highest mean concentration of K^+ (237 $mg\ kg^{-1}$), whereas Chikwatula has the lowest mean concentration of K^+ (176 $mg\ kg^{-1}$).

Significant differences ($p \leq 0.01$) regarding available P are observed among the study sites. Mean comparisons show that Mphaza cooperative has the highest average available phosphorus (46.1 $mg\ kg^{-1}$), while Chikwatula has the lowest average levels of available P (9.82 $mg\ kg^{-1}$, Figure 7.4c). Nonetheless, only 17% of the sampled farms meet or exceed the recommended 30 $mg\ kg^{-1}$ (Nortjé, 2017), indicating a general deficiency in soil available phosphorus.

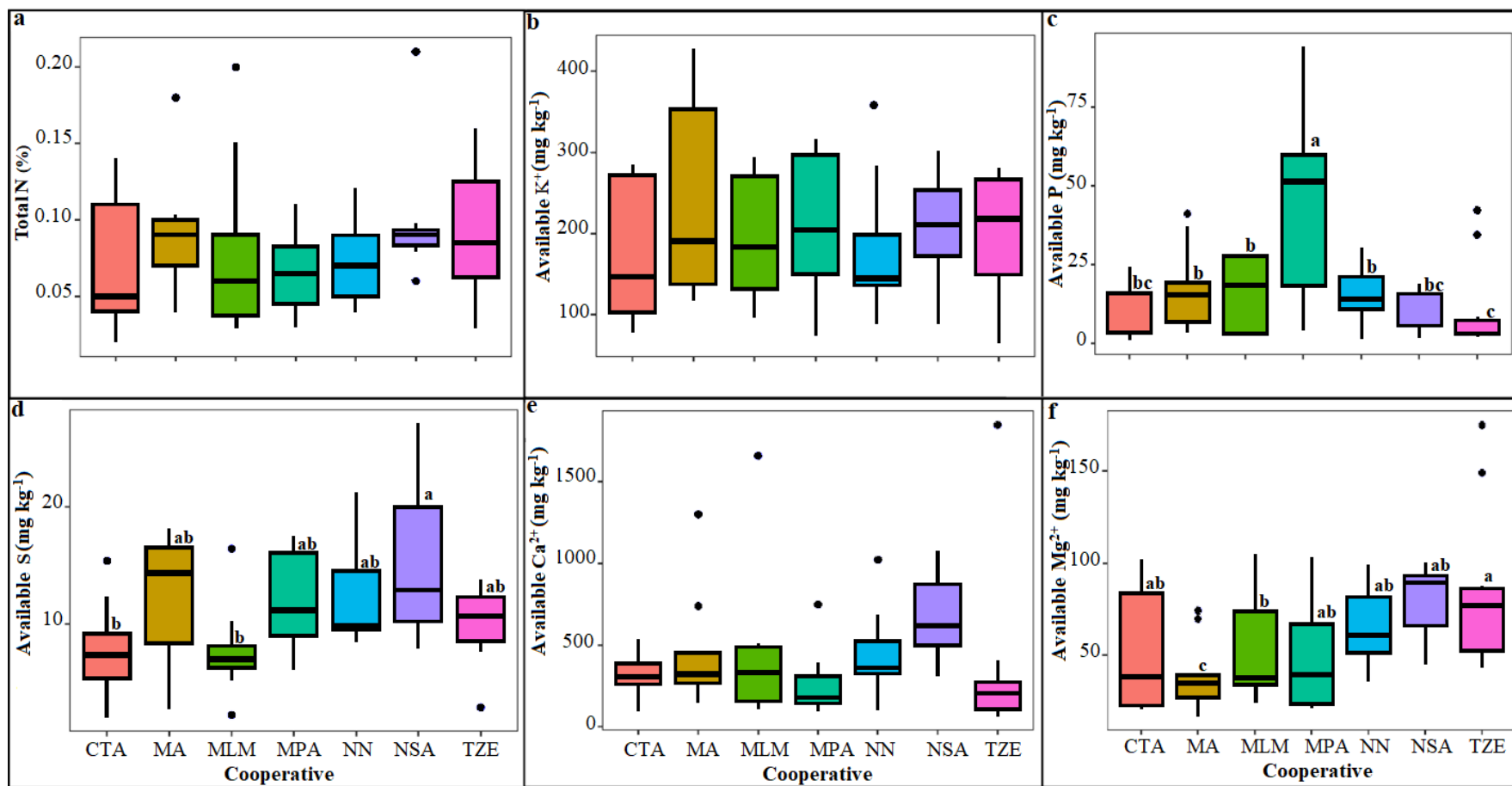


Figure 7.4: Status of soil macronutrients among smallholder macadamia farms in Malawi (medians followed by the same letters are statistically the same at $p \leq 0.05$).

Significant variations ($p \leq 0.02$) are observed in the concentrations of available sulphur among macadamia farms at the studied locations. The concentration of the nutrient ranges from 2.06 mg kg⁻¹ to 27.03 mg kg⁻¹, with an average of 10.9 mg kg⁻¹ (Figure 7.4d). On average, five of the seven cooperatives have available S concentrations within the recommended range (10–300 mg kg⁻¹) for the crop (Nortjé, 2017). Among the cooperatives, Nachisaka has the highest average concentration of available sulphur (15.4 mg kg⁻¹), followed by Malomo (12.2 mg kg⁻¹), Mphaza (12.0 mg kg⁻¹), Neno (12.0 mg kg⁻¹) and Tithandizane (10.1 mg kg⁻¹).

No significant differences ($p > 0.05$) are observed in the concentration of available Ca²⁺ among the sampled macadamia farms (Figure 7.4e). Nearly all sampled farms are deficient in Ca²⁺ concentrations. Further, the average calcium concentration of the soils examined (417.9 mg kg⁻¹) is threefold lower than the minimum optimal level for macadamia (Landon, 2014, ≥ 1200 mg kg⁻¹). Nevertheless, Nachisaka has the highest average concentration of available Ca²⁺ (677 mg kg⁻¹), while Mphaza has the lowest concentration of the nutrient (267 mg kg⁻¹).

Significant differences are observed in the concentrations of available magnesium among the sampled macadamia farms ($p \leq 0.024$). Tithandizane cooperative has the highest average of available Mg²⁺ (84.9 mg kg⁻¹). Mwanza, in contrast, has the lowest average of available Mg²⁺ (38.5 mg kg⁻¹). Despite these differences, available Mg²⁺ levels at all the study sites are deficient, with an average of 60.4 mg kg⁻¹ (Figure 7.4f) below the optimal level of 170 mg kg⁻¹ required for the healthy growth of macadamia (Nortjé, 2017).

7.4.4. Soil micronutrients

Compared to the recommended ranges for macadamia, 95% of the soil samples in this study are deficient in B, and 98% are below the threshold for Zn. Boron concentrations range from 0.02 to 0.29 mg kg⁻¹, with none exceeding the lower threshold concentration (≥ 1 mg kg⁻¹, Figure 7.5a) recommended for macadamia production (Stephenson & Cull, 1986). Zinc exhibits similar patterns as those of boron, with very low concentrations in all the study areas (≤ 0.4 mg

kg⁻¹, Figure 7.5b) than the optimal (≥ 3 mg kg⁻¹). This is not surprising as most soils in Malawi are deficient in these two nutrients attributed to the parental soil material (Evans, 2021).

The available copper (Cu²⁺) concentration of the majority (90%) of the soils across the study sites is below the recommended range (2–5 mg kg⁻¹) for macadamia cultivation (Porter, 2004). However, some soils in Chikwatula and Malomo cooperatives recorded higher concentrations (≥ 3 mg kg⁻¹, Figure 7.5c) of the nutrient. This is attributed to the use of copper fungicides (Copper Oxychloride 85WP) in tobacco production.

Soil sodium concentrations are highly heterogeneous among the study sites (Figure 7.5d). These range from 13.4 mg kg⁻¹ to 76.8 mg kg⁻¹, with an average of 38.8 mg kg⁻¹. Approximately 66.7% of the soil samples contain adequate amounts of Na⁺ for the healthy growth of a macadamia tree. This indicates that Na is not a limiting factor in the sampled soils.

Available Fe²⁺ in all the study sites falls within the optimal range for macadamia trees. However, these iron concentrations are on the lower side ranging from 9.88 – 75.02 mg kg⁻¹, necessitating annual additions via inorganic fertiliser application to ensure that the nutrient remains available to the crop. Figure 7.5e shows that Chikwatula cooperative has the lowest mean concentration of available Fe²⁺ (31.3 mg kg⁻¹), while Tithandizane and Mwanza cooperatives have the highest mean concentrations (45.7 mg kg⁻¹ and 45.5 mg kg⁻¹, respectively).

The available manganese concentration ranges from 2.18 mg kg⁻¹ to 23.2 mg kg⁻¹, with an average of 10.3 mg kg⁻¹ (Figure 7.5f). The distribution of the nutrient varies from low to optimum levels for macadamia requirements (Porter, 2004). Nevertheless, as macadamia trees age, annual Mn²⁺ applications will be required to replenish the soil reserves. This is because as the tree ages, the higher the requirements for the nutrient.

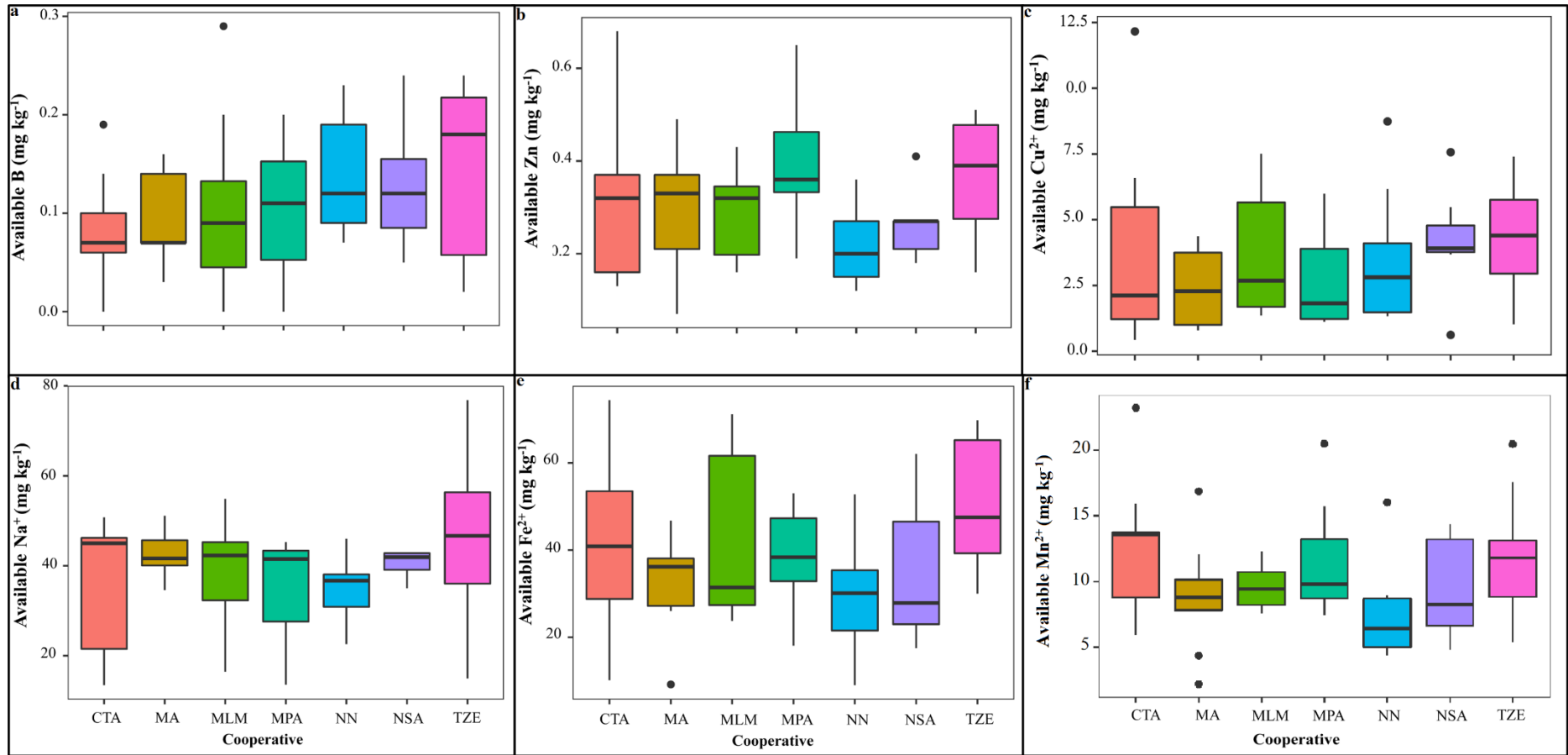


Figure 7.5: Soil micronutrient status among smallholder macadamia cooperatives (the lines represent medians \pm IQRs).

7.4.5. Cation exchange capacity

The cation exchange capacity (CEC) indicates the ability of soil to hold onto and exchange cations, including plant nutrients such as Ca^{2+} , Mg^{2+} , and K^+ . In this study, the average CEC did not differ significantly among the study areas. In general, the CEC is very low, ranging from $0.34 \text{ cmol (+) kg}^{-1}$ to $3.77 \text{ cmol (+) kg}^{-1}$, with an average of $1.67 \text{ cmol (+) kg}^{-1}$ (Figure 7.6a). These results indicate that the CEC of the sampled soils is below the global averages commonly reported for macadamia soils (Appendix 5), which typically fall within the range of $3\text{--}8 \text{ cmol (+) kg}^{-1}$. Figure 7.6b depicts the relationship between soil pH and CEC. It can be observed that the relationship between CEC as the dependent variable and soil pH as the explanatory variable is significant at $p \leq 0.001$ and that the adjusted R-square was 0.55. That is, soil pH explained 55% of the variation in CEC. This shows that the soil pH is a critical factor that significantly influences the CEC and hence the availability of nutrients in the soil. This shows the importance of managing soil pH to near neutral to enhance nutrient availability and proper functioning of the soil.

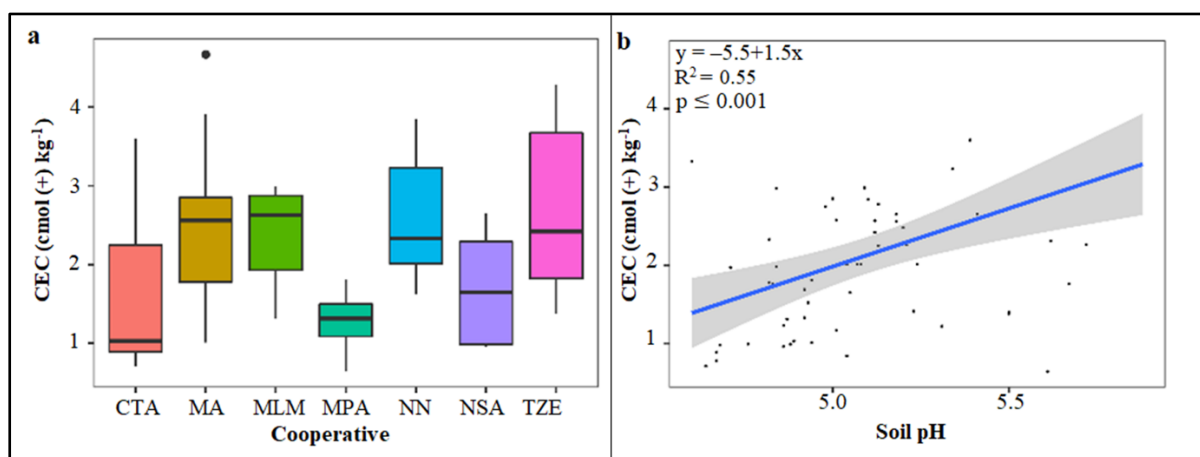


Figure 7.6: a) Cation exchange capacity (boxes represent medians \pm IQRs) b) Relationship between soil pH and CEC.

7.4.6. Soil organic matter (SOM)

Soil organic matter is a key indicator of soil fertility and is primarily composed of organic carbon. This study reveals that the SOM content among the sampled farms is lower than the

critical range of 2–5% required for optimal functioning of the soil. Across the sampled farms, the SOM content varies from 0.26 to 2.96%, with an average of 1.13% (Figure 7.7). Notably, more than half of the study sites have less than 1% SOM content, whereas 36.7% have less than 1.8% SOM content, and only 7.9% have SOM content greater than 2%. However, Chikwatula (1.31%) and Malomo (1.25%) cooperatives have the highest average SOM content, whereas Mwanza (0.87%) cooperative has the lowest average SOM content. These findings suggest that land management practices may be responsible for the SOM contents among the sampled farms. Interviews with farmers corroborate this notion, revealing a positive association between increased incorporation of crop residues and higher SOM contents in the Chikwatula and Malomo cooperatives. However, it is important to note that the perceived benefits of crop residues vary depending on the specific growing area. Farmers in the Mwanza and Neno cooperatives report burning the majority of their crop residues, as recommended by the Ministry of Agriculture, as a means of controlling cotton pests and diseases. Similarly, farmers in Mphaza also report similar recommendations to burn tobacco residues.

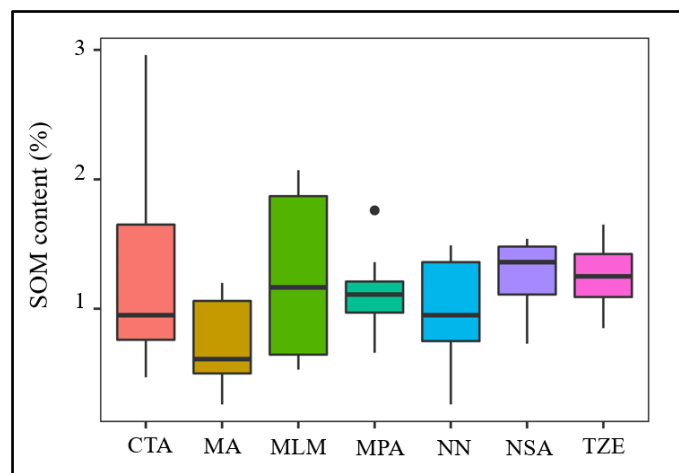


Figure 7.7: Distribution of soil organic matter content among macadamia cooperatives in Malawi.

7.4.7. Relationships among soil physical and chemical parameters

The study findings reveal significant negative relationships between sand content and soil nutrients, cation exchange capacity ($R^2 = -0.48$), and organic matter content ($R^2 = -0.33$, Figure

7.8). This shows that high sand concentrations impacted the availability of soil nutrients, as well as other chemical and microbial processes in the soil in the study sites. Correlations among soil nutrients are negatively significant for available sulphur versus available P and Ca^{2+} , indicating that these nutrients are affected by different factors. The study also indicates positive significant relationships between soil pH and available B, Ca^{2+} , K^+ , P, Zn, total N, and CEC. In contrast, a strong negative correlation ($R^2 = -0.48$) is found between available sulphur and soil pH. This indicates that the concentration of sulphur affects the soil pH. Furthermore, the study indicates significant inverse relationships between cation exchange capacity with sand ($R^2 = -0.48$), clay ($R^2 = -0.48$), and silt ($R^2 = -0.33$) concentrations. Suggesting that the composition of the soil has an impact on its ability to exchange cations.

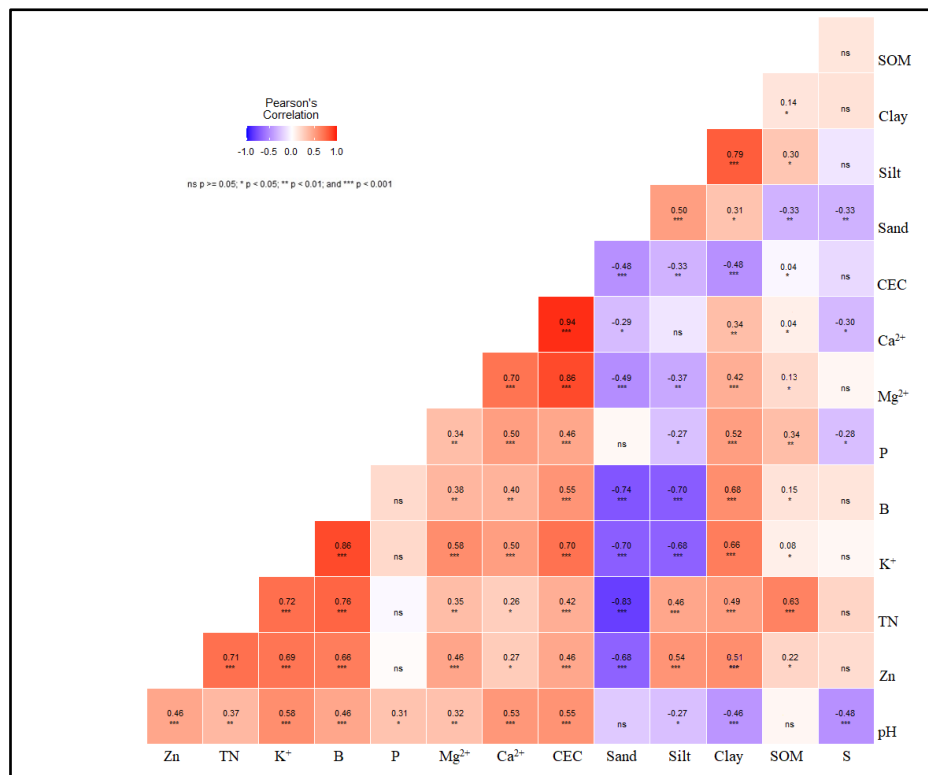


Figure 7.8: Correlations among soil nutrients, texture classes, soil pH, CEC, and SOM.

7.5. Discussion

Smallholder farmers in Malawi face significant challenges related to declining soil fertility, including reduced crop yields and quality (Kumssa et al., 2022; Longwe et al., 2023). In

particular, poor soil fertility is a major barrier to macadamia productivity. Existing studies and recommendations on soil fertility improvement in Malawi have predominantly focused on the commercial macadamia subsector, neglecting the smallholder subsector (World Bank, 1994; Evans, 2021). For this reason, it is challenging for smallholders to address nutrient deficiencies in their farms. Therefore, this study sought to determine the fertility status among some smallholder macadamia farms in the country and to provide recommendations for improving the fertility status to meet macadamia requirements. By focusing on the smallholders, this study seeks to provide practical and relevant solutions to improve macadamia productivity. The results indicate that soil characteristics within the sampled smallholder macadamia farms arise from inherent soil properties and management practices. For instance, the observed high sand content can be attributed to the parental material coupled with poor management practices such as monoculture, lack of application of organic materials, and soil erosion.

7.5.1. Current soil fertility status and macadamia needs

Soil texture and structure are important soil properties that determine the inherent capacity of soil and have profound implications on the soil's water holding capacity, drainage, nutrient retention, supply, and leaching (Nalivata et al., 2017; FAO, 2022). This study reveals that the majority of the sampled soils in Malawi are sandy (67%), with sandy loam (52%) and sandy clay loams (15%) being the most common types. Only 16% of the soils are classified as clays, specifically clay loam (13%) and clay (3%). These findings concur with descriptions of Malawi soils as generally sandy in texture (Li et al., 2017; Eze et al., 2020).

Soil textural classes vary among the sampled farms, particularly in hilly areas of Nachisaka, Neno, and Tithandizane cooperatives, which have greater sand content ($\geq 70\%$) than other cooperatives. In some areas of these cooperatives, soil erosion was evident and could be the major contributor to the high sand content. This was possibly enhanced by the previous sifting, as ridges are made for annual crops. Asfaw et al. (2018) found that, in contrast to wind and

water erosion, whose effects are often pronounced and easily identifiable in the landscape, the extent and severity of tillage erosion only become apparent after decades due to variations in soil properties. Amgain et al. (2020) found that the geological structure of hilly areas contributes to their higher content of sand, thus agreeing with the findings of this study. Contrarily, the proximity of some areas to Lake Malawi (Malomo and Nachisaka cooperative) and Shire Valley (Mwanza and Neno cooperatives) explain why some of the farms in these areas have a higher sand content. However, the higher clay content ($\geq 40\%$) on some of the sampled farms is attributed to their location in flood alluvial plains locally known as dambos.

Figure 7.8 reveals that the high sand content among the study sites negatively impacts the availability of essential soil nutrients and contributes to the lower CEC and SOM content levels. This outcome confirms earlier findings regarding the deficiency of essential nutrients in sandy soils (Nazif et al., 2006), attributed to their low organic matter content (Malla et al., 2020), low water retention capacity (Mungai et al., 2016), and low nutrient levels (Mloza-banda et al., 2016). These characteristics make sandy soils have poor soil fertility status, necessitating regular and increasing levels of soil organic matter addition and inorganic fertiliser applications to ensure the healthy growth of crops annually. However, this is becoming increasingly difficult for Malawi's smallholders to achieve and afford. Additionally, this has been made worse by the rapid increase in inorganic fertiliser costs (more than 130–160% higher than in 2020) and limited availability attributed to Russia's invasion of Ukraine, both of which are major global suppliers of inorganic fertilisers.

Soil pH is a crucial factor in determining soil fertility, as it affects the availability of all nutrients in the soil. In Malawi, soil acidity is prevalent, with 87% of the sampled soils having a very low pH (≤ 5.5), confirming previous studies conducted in the country (Njoloma et al., 2016; Munthali et al., 2021; Longwe et al., 2023). This low pH renders the soils unsuitable for growing macadamia and many tropical crops. However, the study shows that 13% of the sampled farms have soil pH levels within the optimum range for macadamia. This translates

to 5% of macadamia farms belonging to Tithandizane cooperative and 2% belonging to each of the four cooperatives (Chikwatula, Mwanza, Mphaza, and Neno). Discussions with HIMACUL staff revealed that some of the macadamia smallholders use agricultural lime to manage the pH of their soils.

Principal contributors to the soil's acidity among the study sites have been identified as poor agronomic practices, loss of major cations (leaching and soil erosion), and higher nutrient uptake by previously cultivated crops. Examples of agronomic practices include low input of organic materials, previous monoculture of annual crops, and use of higher rates of compound inorganic fertilisers, especially urea, and NPK, in an effort to achieve higher growth and production of crops. Over dependence on nitrogenous fertilisers is particularly prevalent among Malomo, Mphaza, and Tithandizane cooperatives, where tobacco remains the main cash crop. These results complement and, more importantly, extend the findings of Mutegi et al. (2015), who identified continuous monoculture and blanket inorganic fertiliser applications as Malawi's primary causes of soil acidification. Additionally, the traditional burning practices of cotton residues may be responsible for the lower soil pH in Mwanza and Neno cooperatives. Moreover, Dougill et al. (2002) found that the risk of soil acidification is exacerbated through the inorganic fertiliser only nutrition strategy used by smallholder farmers, thus confirming the current study findings.

Topography indirectly influences an area's temperature and precipitation (Xu et al., 2018). Cooler temperatures and intense precipitation characterise higher altitudes, whereas lower altitude areas are characterised by hotter temperatures and low amounts of precipitation (Pichakum et al., 2014). As such, the high soil acidity in some of the higher elevated areas (≥ 1400 m.a.s.l) of Chikwatula, Tithandizane, and Neno cooperatives can be partially attributed to the heavy precipitation amounts received in these areas (see Table 7.1), resulting in soil erosion and leaching, leading to soil acidification and transport of finer (clay) particles while coarser particles are left behind. This is concurrent with Munthali et al. (2021), who reported

that intense precipitation received in the higher altitude areas of Dedza district makes the soil vulnerable to acidification and nutrient losses due to soil erosion. Thus, for areas that receive intense precipitation, like Chikwatula, Tithandizane, and some parts of Neno cooperatives, water management technologies that control the speed of running water and promote infiltration are recommended. These may include construction of box, contour and tier ridges, mulching, intercropping and use of live cover plants such as vetiver grass.

The mineralogy of the soil and its formation also affects its pH. Subsequently, the observed acidity among the smallholder macadamia farms may be related to their high sand content because of the parental rock material. This finding is supported by the inverse relationship between soil pH and sand content (Figure 7.8). As macadamia trees require slightly acidic to neutral pH, increasing the soil pH in the study areas is essential.

CEC is an important soil property that influences soil structure stability, nutrient availability, pH, and the soil's response to fertilisers and other ameliorants (Hazelton & Murphy, 2016). According to the study findings, the average CEC of soils from all study sites barely exceeds the lower threshold of sandy soils ($5\text{--}10 \text{ cmol (+) kg}^{-1}$) (Van Ranst et al., 1999). The lower CEC levels in the study areas reflect the soil's high sand content, strong acidity, low organic matter, and clay type (kaolinite). Mloza-banda et al. (2016) reported that strong soil acidity lowers the CEC of soil. Furthermore, conventional tillage practices may have contributed to the lower levels of the cation exchange capacity.

Despite most of the sampled farms having low CEC levels, about 17.5% have CEC levels within the optimal range ($3\text{--}8 \text{ cmol (+) kg}^{-1}$) required to support the healthy growth of macadamia trees. Unfortunately, none of the farms in Neno meet this optimal range. In contrast, one farm in Mphaza and two farms in each of the remaining cooperatives have CEC levels equal to or above the recommended minimum threshold. A high CEC is favourable as it contributes to the capacity of soils to retain plant nutrient cations (Matter, 2009; Saidian et

al., 2016). Thus, farmers must be encouraged to adopt management practices that increase CEC levels to improve macadamia productivity.

The study's findings reveal a negative correlation ($R^2 = -0.48$) between cation exchange capacity and clay content, indicating that SOM fractions, rather than clay particles, are the primary contributor to CEC in the study sites. This aligns with Tudela et al.'s (2010) assertion that kaolinite clays, which are widespread in Malawi, including the study areas, do not significantly contribute to CEC. Moreover, Bortoluzzi et al. (2006) found that organic matter fractions contribute more than 50% of the negative charges in the soil compared to clay particles (31%), further supporting the findings of this study. Furthermore, the negative relationship between CEC and clay content observed in this study can also be attributed to the observed extensive weathered nature of the soils, leading to loss of surface charge in the soil clay particles and low CEC.

Soil organic matter is crucial to crop productivity and soil health (Omuto & Vargas, 2018; FAO, 2022a). SOM is a well-known source of nitrogen, phosphorus, and sulphur and regulates the physicochemical reactions that control the availability of micronutrients in agricultural soils (Dhaliwal et al., 2019; Malla et al., 2020). However, the majority of the sampled farms have very low levels of SOM ($\leq 1\%$), below the recommended threshold ($\geq 2\%$) for macadamia. This deficiency is partially attributed to previous conventional tillage practices, continuous cultivation, and harvesting of annual crops. Long-term research in Malawi has shown that 5 to 10 years of continuous cultivation can reduce soil organic matter by up to 40% (Maida & Chilima, 1976; Eze et al., 2020; Hermans et al., 2021). These findings are consistent with the present study's results, as macadamia trees are grown on land previously used for the cultivation of annual crops.

The low levels of SOM can also be attributed to the inherent nature of sandy soils, the smallholders' low incorporation of organic residues, and the overuse of acidifying fertilisers. According to Huang & Hartemink (2020), the large pore sizes of sandy soils result in higher

aeration, which causes rapid decomposition of SOM. Pang et al. (2021) found that long term use of acid forming fertilisers such as urea led to declines in SOM content, which is consistent with this study. Soil erosion and deforestation may have also contributed to the loss of organic matter among the study sites. It can therefore be concluded that the decline in organic matter among the sampled farms is primarily attributed to unsustainable farming practices by the smallholders. Hence, increasing the SOM levels among smallholder macadamia farms is important to improving the soil's capacity to support macadamia production.

While most of the sampled macadamia farms have very low SOM levels, 3% and 5% of the sampled farms in Chikwatula and Malomo have optimal soil organic matter levels for the crop. Field observations and farmer conversations revealed that the incorporation of farmyard manure (cattle and goat dung) and crop residues (groundnut, pigeon pea, and soybean) is responsible for the observed higher SOM content on their farms. These farmers report having easy access to farmyard manure due to ownership of considerable herds of cattle and goats (made possible by livestock pass on programmes in the areas) and crop residues from legumes. Thus, encouraging the incorporation of livestock manure and crop residues is a feasible option for increasing the SOM among smallholder macadamia producers in Malawi.

The current study shows variability in terms of essential nutrient concentrations among the smallholder macadamia farms. The study reveals deficient levels of total nitrogen with respect to the recommended levels for macadamia soils, likely due to poor agronomic practices, low SOM content, and a higher mineralisation rate of the nutrient due to the nature of sandy soils. In terms of potassium concentrations, the study reveals that only 44.4% of the sampled farms have adequate levels of the nutrient. The average potassium levels of Chikwatula, Malomo, and Neno cooperatives are lower than what is recommended for macadamia. These results indicate that soil potassium reserves on some of the sampled macadamia farms are becoming inadequate for macadamia's needs. It is recommended, therefore, to replenish nitrogen and potassium soil reserves in such farms by applying foliar inorganic fertilisers in the form of potassium nitrate, which is readily available in Malawi.

Regarding soil available phosphorus, the current study indicates that the majority (83%) of the soils have deficient levels of the nutrient, which are below the critical threshold of 30 mg kg⁻¹ recommended for macadamia. However, five of the sampled macadamia farms in Mphaza cooperative have sufficient available P (≥ 50 mg kg⁻¹). This is attributed to previous monoculture tobacco production and the ongoing intercropping of tobacco in the rows of macadamia trees.

This study also indicates that the distribution of sulphur ranges from low to optimal concentrations. Average lower concentrations are only observed in Chikwatula (7.53 mg kg⁻¹) and Malomo (7.74 mg kg⁻¹) cooperatives. With regard to calcium and magnesium, nearly all of the study sites are deficient in both nutrients. This is due to the inherent nature of sandy soil, strong soil acidity, and the observed low cation exchange capacity.

Boron and zinc are essential micronutrients required in small but critical amounts for macadamia's normal growth and development (Stephenson et al., 1986). The present study shows a deficiency in the B and Zn levels on smallholder macadamia farms in Malawi which are below the minimum reference levels for healthy macadamia trees (Evans, 2021). This may be due to the coarse texture of sandy soils and the low amounts of organic matter. These findings align with the research by Jiménez et al. (2022), which showed that tropical ecosystems with low soil clay content experience accelerated decomposition of SOM, resulting in reduced concentrations of soil micronutrients. Furthermore, interviews with farmers indicate a lack of access to inorganic fertilisers containing the required micronutrients to support macadamia growth and development. Therefore, the government of Malawi and other stakeholders must support smallholders by providing them access to inorganic fertilisers that meet the specific nutrient requirements of macadamia trees.

In addition, B and Zn are naturally deficient in Malawian soils, necessitating additions annually (Evans, 2020). The absent utilisation of boron and zinc fertilisers may also be the reason for the low levels of these nutrients in the study areas, as the nutrients are taken up and not replenished. Evans (2021) found that commercial estate producers in the country have

increased their B and Zn levels through routine foliar applications. In light of this, B and Zn fertilisers should be made available to smallholder farmers.

The present study also shows deficiencies in copper and magnesium concentrations among the study areas. This is mainly attributed to previous monocultures of tobacco. Additionally, it suggests that the nutrients are not mobile and available for uptake. In contrast, wide variations are observed in the concentrations of iron, manganese, and sodium, which range from low to optimum. The study's findings suggest that the macadamia trees in the study areas are not receiving adequate levels of these micronutrients due to the identified deficiencies. Addressing these issues through appropriate soil management practices such as building soil organic matter, conservation agriculture, and fertilisation is therefore important.

7.5.2. Implications of the study and recommendations for management

Effective nutrient management is crucial for maximising the success of macadamia crops. Based on the study's findings, it can be concluded that nutritional imbalances and deficiencies, especially of B, Cu^{2+} , Ca^{2+} , Mg^{2+} , P, TN, and Zn, are among the factors affecting macadamia's productivity under smallholder farmer management in Malawi. This is because a limited supply of one of the essential nutrients can limit crop yields ("Law of Minimum," Figure 7.9). As such, the identified deficiencies and imbalances in the study areas will need to be addressed simultaneously to improve their soil fertility status in a reasonable amount of time.

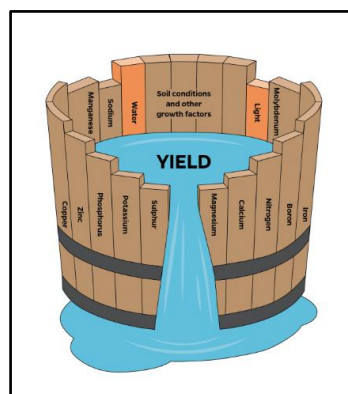


Figure 7.9: Illustration of the "Law of Minimum" (Stewart, 2007).

Contrasted with what was reported in the 1990s (World Bank, 1994), the findings of this study show that the current soil fertility status of smallholder macadamia growing areas in Malawi is very different and in a poor state. Early recommendations to smallholder farmers focused on using manure to maintain and replenish soil fertility without needing inorganic fertiliser applications. However, the current findings reveal that there is no "one size fits all" or "silver bullet" solution for maintaining and replenishing soil fertility loss in smallholder macadamia farms. Thus, a combination of soil organic matter and inorganic fertiliser application is essential for sustainable macadamia productivity.

In order to apply inorganic fertilisers precisely, providing smallholders with local-scale information about the soil fertility status of their macadamia orchards is crucial. This can be achieved through the annual low-cost testing of soil properties by trained agricultural officers or lead farmers (LUANAR and CIMMYT already use this technology in some parts of Malawi). Such testing can help monitor soil pH, major nutrients, and the critical balance between pH, Ca^{2+} , Mg^{2+} , and K^+ to ensure they are maintained within optimal ranges to support macadamia production. Nevertheless, further research is needed to develop recommended application rates of proposed blended (mixture of macro and micronutrients) inorganic fertilisers and to understand the trees' response to fertilisers and the long-term effects on soil health.

Soil acidity amelioration is a prerequisite for sustainable soil fertility management. By maintaining the correct soil pH level, plant nutrient availability is optimised, the solubility of toxic elements is minimised, and beneficial soil organisms are most active (Malla et al., 2020). Hence, raising the soil pH to near neutral is vital to improving smallholder macadamia productivity. To achieve this optimal pH range, this study recommends a combination of agricultural lime application and organic matter management. By adopting this approach, farmers can effectively raise the soil pH and improve the soil's physical and chemical properties.

Cover crops offer a range of benefits to agroecosystems, including protecting soil from erosion, improving water infiltration, controlling weeds, and building soil organic matter (Suci et al., 2021). To optimize these benefits, this study recommends that smallholder macadamia farmers grow annual crops, particularly legumes, between the rows of macadamia trees. This approach can increase the amount of high-quality organic residues and nitrogen. Maize-legume associations (cowpeas and pigeon peas) have been reported to enhance the amount of SOM and improve soil hydraulic properties (Eze et al., 2020; Hermans et al., 2021).

In addition to enhancing soil fertility, interplanting annual crops in the macadamia orchard can provide smallholders with an additional food source and income during the year. This practice can also enhance resilience in the face of crop failure. Figure 7.10 provides a summary of recommendations that smallholders can utilise to improve the soil fertility of their farms. Nonetheless, to ensure that farmers accept and continue using these recommendations, prioritising them according to the highest return on investment in each growing area is necessary.

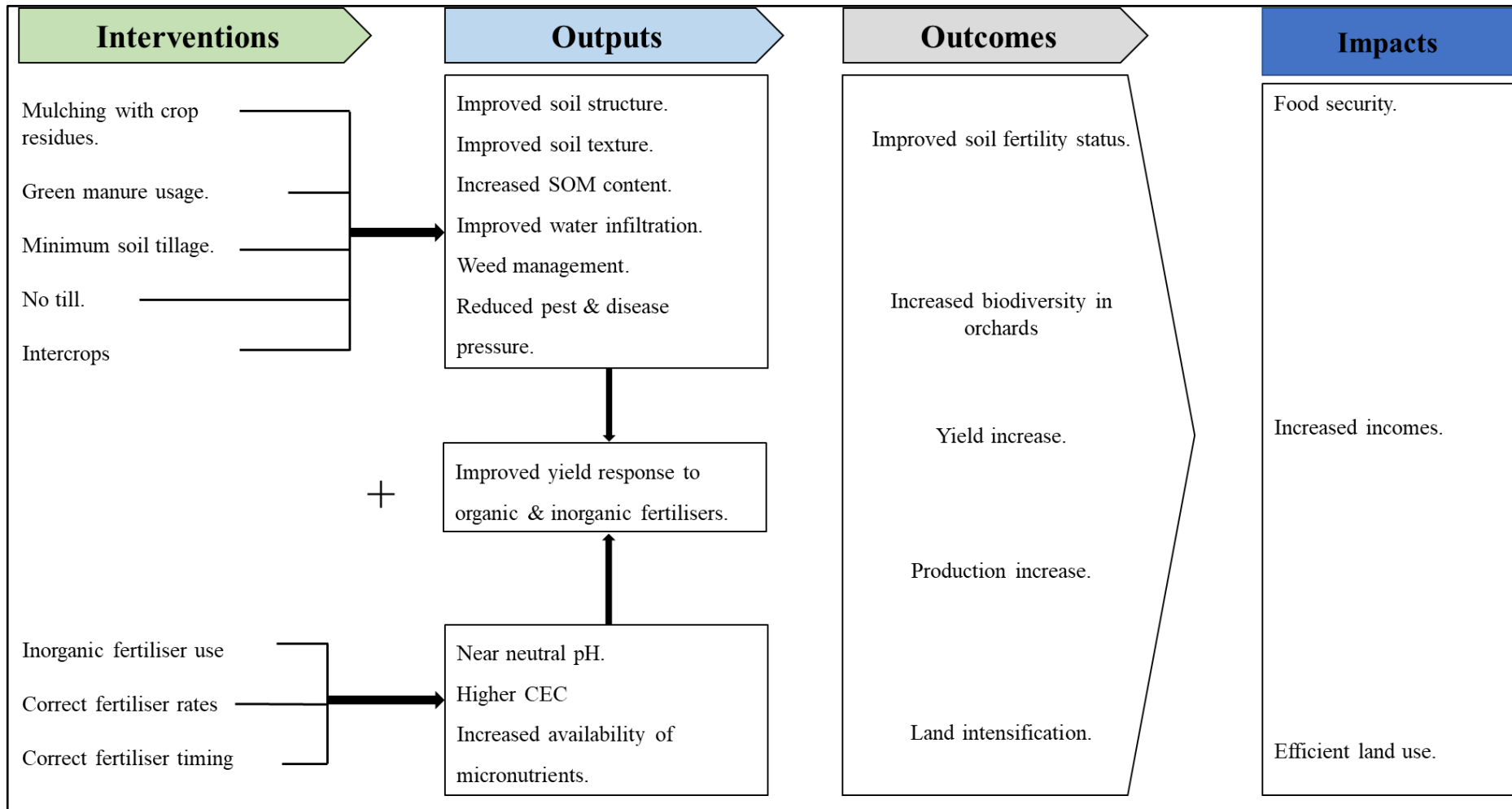


Figure 7.10: Recommended best-fit solutions for improving soil fertility for smallholder macadamia farmers in Malawi.

7.6. Conclusions

The results of this study indicate that the soil fertility status of the sampled macadamia farms is very low for macadamia production, which may be true for all smallholder macadamia production areas in Malawi. The findings highlight that the inherent soil properties and poor agronomic practices have resulted in highly acidic, nutrient-deficient, and low organic matter content soils with limited cation exchange capacity. A combination of management practices, specifically those that promote the build-up of organic matter and protect the soil, are recommended to address these issues. This should be coupled with the application of blended inorganic fertilisers containing essential macro and micronutrients. Moreover, tailored solutions with the highest return on investment are necessary to address the specific nutrient deficiencies in each growing area.

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CHAPTER EIGHT: SYNTHESIS

8.1. Introduction

This thesis has investigated the interdependent relationship between socioeconomic and environmental factors impacting smallholder macadamia production in Malawi. Macadamia is a high-value crop identified by the Malawian government as a suitable candidate for crop diversification among smallholder farmers in the country. However, the smallholder macadamia subsector has received limited research compared to other crops. This is one of the reasons macadamia yields among smallholders are considerably lower compared to commercial producers (Zuza et al., 2021a).

Evidence shows that biotic and abiotic factors pose challenges for farmers in producing sufficient quantities of macadamia nuts to meet the global demand (Gitonga et al., 2012; Barrueto et al., 2018b; Quiroz et al., 2019). Furthermore, climate variability and change increasingly impact crop productivity, especially on smallholder farmers with limited adaptation options, leading to fluctuations in crop supplies, including macadamia (Stevens & Madani, 2016; Mittal et al., 2017; Djenontin et al., 2022; FAO, 2022a). Therefore, this research aimed to assess the influence of socioeconomic, climatic, and soil factors on smallholder macadamia production in Malawi. Specifically, the objectives of this study were:

1. To characterise smallholder macadamia farming systems and preferred macadamia cultivars and to identify constraints to nut production in Malawi.
 - a. To conduct a baseline survey of smallholder macadamia farmer demographics, farming systems, and motivations for cultivating macadamia.
 - b. To determine factors influencing smallholder farmer preference for various macadamia cultivars.
 - c. To examine challenges encountered by smallholder macadamia producers.

2. To examine climatic factors influencing smallholder macadamia production in Malawi and the potential impacts of climate change on the suitability of the crop.
 - a. To identify climatic factors that influence suitability for smallholder macadamia cultivation in Malawi.
 - b. To assess the present geographical distribution of climatically suitable growing areas for macadamia in Malawi.
 - c. To evaluate the potential impacts of climate change on the future geographical distribution of growing areas for macadamia in Malawi.
3. To determine the soil fertility status of smallholder macadamia farms in Malawi.
 - a. To assess the chemical and physical properties of soil among smallholder macadamia farms in Malawi.

8.2. Discussion

Given the importance and the longevity of macadamia, long-term agricultural planning that considers farmer socioeconomic factors, soil fertility conditions, and the expected impacts of climate change on the suitability of the crop in growing areas is essential. Hence, the following discussions provide a summary of how these three factors are interconnected in this study.

In Chapter Five, the results show that the average age of smallholder macadamia farmers in Malawi surpasses 50 years, underscoring the aging trend within the farming population in the study areas. However, it is worth noting that young farmers (≤ 30 years old) are beginning to grow macadamia. The active engagement of these young farmers within the macadamia subsector holds immense significance. Their involvement has the potential to nurture enhanced expertise in tree management, labour supply, and cooperative management, ultimately ensuring the long-term sustainability of the subsector. Thus, it is vital to increase access to training on soil management and resilience strategies for these young farmers to adapt to projected shifts in macadamia suitability. This is particularly important considering the limited availability of

extension services, sub-optimal soil fertility of the macadamia farms, and the vulnerability of certain areas to climate change impacts, as revealed in this study.

Regarding landholding sizes, it is evident that smallholder macadamia farmers in the study areas possess comparatively larger landholdings (1.23 ha) than the national average (0.53 ha). Although this is the case, land scarcity will become a huge challenge in the study areas in the next decades. As the population grows, urbanisation intensifies, and customary tenure persists, the land will likely be subdivided among family members, leading to further fragmentation and scarcity. Furthermore, examining the soil fertility status of the smallholder macadamia farms in Chapter Seven reveals that most of these soils are in a poor state to support macadamia production. Consequently, this will invariably lead to reduced macadamia yields and quality. Moreover, the analysis conducted in Chapter Six indicates that the projected impacts of climate change will further decrease the suitability of these regions for macadamia production.

To address the challenges of land scarcity and productivity, it is imperative to provide smallholder farmers with access to training that emphasizes the benefits associated with the adoption of CSA practices, such as agroforestry and CA. By adopting these practices, farmers can optimise their limited land resources, enhancing productivity and improving their livelihoods. Moreover, these practices offer the potential to concurrently mitigate soil fertility degradation, thereby ensuring the long-term sustainability of macadamia production in the study areas.

The results in Chapter Five also indicate that low productivity is a primary constraint among smallholder macadamia farmers in the study areas. It is revealed that the underlying causes are multifaceted, encompassing dependence on the rainy season, inadequate access to extension services, limited knowledge regarding factors influencing macadamia suitability, and poor soil fertility. However, Chapters Six and Seven provide valuable insights to address the issue of low productivity. The findings show that despite being located in climatically suitable zones, the study areas do not have the soil suitability to support optimal macadamia productivity. This

is because the soil fertility status of the study areas is in a poor state to support the healthy growth of macadamia. This underscores the crucial role of conducting land suitability assessments, which is important for land use planning. Thus, addressing the issue of soil fertility becomes imperative to enhance the land suitability for macadamia cultivation among the study sites, which can also be applied to other parts of the country where macadamia is grown or intended.

To tackle the challenge of soil fertility, a combination of short and long-term strategies with multiple benefits is necessary. One of the prominent strategies is the building of SOM content. Management practices like crop residue retention, mulching, manure or compost incorporation, and green manuring can help in building up SOM content in the macadamia fields. Additionally, intercropping macadamia with nitrogen-fixing crops like legumes (beans, groundnuts, pigeon peas, and soybeans) and perennial shrubs (*Sesbania sesban*, *Gliricidia sepium*, and *Tephrosia vogelii*) can further contribute to organic matter build-up, thereby improving the soil health. These practices also play an important role in regulating the microclimate within the macadamia farms, thereby not only improving soil fertility but also enhancing the climate suitability of the growing areas.

Furthermore, the judicious use of inorganic fertilizers tailored to the specific growing areas and nutrient requirements of macadamia is crucial. It is recommended that the government of Malawi should facilitate smallholder farmers' access to macadamia-specific inorganic fertilisers, particularly those rich in micronutrients. Collaborative efforts with estate producers to develop blended fertilisers suitable for macadamia production should also be encouraged. Additionally, applying agricultural lime for pH adjustment is vital among the study sites. However, the successful implementation of these practices centres on addressing the limited availability of extension services.

The availability of extension services can be addressed if the government of Malawi and NGOs can provide macadamia trainings to the extension officers already operating in the study areas.

In addition, it is necessary to provide financial support to cooperatives such as HIMACUL so that they can hire more extension staff. Additionally, based on this study, training more lead farmers in macadamia good agricultural practices is needed as farmers have more confidence in fellow farmers' experiences with agricultural technologies.

The results in Chapter Six also show that projected climate changes, including warming and shifts in precipitation patterns by the 2050s, will have detrimental effects on the current areas suitable for macadamia production, including the study areas. Informal interviews with farmers revealed a decline in macadamia suitability attributed to reduced precipitation and increased warming. While irrigation holds potential as a solution to increase resilience to the predicted losses in macadamia suitability, its implementation poses complexities for smallholder farmers. For example, due to limited research, determining the optimal timing and amount of irrigation required for the crop is challenging. This lack of research can result in inadequate irrigation practices, causing crop stress, waterlogging, root rot, and reduced yields. Furthermore, in Chapter Seven, it is established that the majority of soils in the study sites are sandy and low in SOM. Thus, even if irrigation is an option, building organic matter remains essential to improve soil texture, structure, water infiltration, biological activity, and nutrient availability, ultimately supporting plant growth and development in the future.

8.3. Future work

Although this thesis provides conclusive findings, it is essential to note that it represents a baseline foundation for further research in this area. Therefore, the following future research directions are recommended to expand on the findings of this study:

Firstly, the study's limitations, attributable to Covid-19 travel restrictions and time constraints, prevented the researcher from conducting field studies to assess the performance of macadamia cultivars and identify the same for the specific agroecological zones (cooperatives). Evidence presented in Chapter Five shows that smallholder farmers know the differences in macadamia cultivar performance across the AEZs, influencing their preferences. Thus, future research

should assess the performance of the preferred cultivars (Tier 1) in each specific AEZ, taking into account the kernel and whole kernel attributes. This may lead to recommendations of the best performing cultivars in each growing area.

Secondly, the availability of high quality macadamia tree seedlings is a significant constraint for smallholder macadamia farmers, leading many to prefer old generation cultivars over newer, improved ones. Future research should include demonstration plots of old and new generation cultivars to enable farmers to evaluate their characteristics and facilitate their adoption.

Thirdly, while the modelling exercise identified climatic factors responsible for macadamia suitability in Malawi, the study's results are limited due to a lack of data on the phenology of various macadamia cultivars grown in the country. The findings show that flowering time varies across each growing area. Differences in microclimates could be responsible for the variations in the duration, onset, and peak of macadamia flowering across the agroecological zones. In order to maximise profits from macadamia, it is essential to have a clear understanding of the crop's annual growth cycle at the microclimate level. Therefore, further research should be conducted to assess the flowering performance of macadamia cultivars in various agroecological zones in Malawi.

Fourthly, the study shows that the majority of HIMACUL cooperatives are climatically suitable for macadamia production. However, due to poor soil fertility, these areas risk losing their soil's suitability for growing macadamia. It is recommended that future research should investigate the influence of the combined use of organic and inorganic fertilisers and their rates on enhancing soil fertility and yields.

As a fifth recommendation, future research should investigate the influence of Growing Degree Days (GDD) on macadamia productivity. By examining this relationship, it will be possible

to identify patterns and understand the impact of heat accumulation on macadamia production, especially during the drier months of the year.

Finally, this thesis suggests that climate change will increase the suitability of macadamia in the central and northern parts of Malawi, particularly the highland areas. However, studies in Malawi have predicted that temperature increases will increase the prevalence and severity of crop pests and diseases, especially in the highland areas. Therefore, future research should focus on assessing the impacts of climate change on macadamia pests such as stink bugs and nut borers and the distribution of their natural enemies. Additionally, it should consider the role of important insects in spreading human and livestock diseases, such as mosquitoes, ticks, lice, and snails.

8.4. Policy and Practice Recommendations

The findings from this thesis are significant for enriching the extant literature as discussed above and shedding light on some policy recommendations. The following are the key policy recommendations from this research:

1. It is recommended for the government of Malawi, academia, and commercial estates conduct thorough research before introducing new cultivars for the smallholder growing areas. The research should be conducted to ensure that the cultivars are suitable for the local environment and meet the required quality standards and preferences of the smallholders. This can be achieved through participatory cultivar selection.
2. It is necessary to address the availability of quality macadamia tree seedlings by increasing the nursery capacity under smallholder management to meet the demand for planting materials. Therefore, a modest investment in infrastructure and an increase in the size of already existing nurseries is crucial. This should be supplemented with tree seedling supply from commercial estate nurseries at an affordable cost.

3. The Malawi government should develop a comprehensive macadamia extension service programme in collaboration with farmer organisations, cooperatives, and NGOs to provide smallholder farmers with the necessary knowledge and skills to successfully manage their crops. This should include training extension offices in macadamia good agricultural practices, pest and disease management, and post-harvest handling, as it is already done with other crops in the country. Additionally, farmer field schools should be established as living laboratories for hands-on training and technology dissemination.
4. A marketing system should also be established to ensure that smallholder macadamia farmers can access markets for their produce. This can be achieved through partnerships with cooperatives and other marketing organisations that can help smallholder farmers to sell their produce at a fair price. Additionally, cooperatives should be given access to loans so that they can be able to get certification for their produce, such as the Fair Trade Foundation platform.
5. There should also be increased investment by the government of Malawi in infrastructure, such as storage facilities and processing plants, to help smallholder macadamia farmers to access markets and process their crops efficiently.
6. There is a need to strengthen agricultural policies that promote agroforestry as a climate change strategy to support the expansion of macadamia production areas in Malawi. This should include incentives for farmers to adopt agroforestry practices, such as providing technical support and training, and financial incentives (payment for ecosystem services) to encourage planting macadamia trees as part of their cropping systems.
7. The Malawi government should strengthen research and extension services to support farmers in managing pests and diseases likely to increase due to climate change in the next decades. This should include developing pest and disease-resistant cultivars, training

farmers on integrated pest management practices, and providing access to relevant information and technologies.

8. Effective implementation of policies and programmes that help improve soil fertility management practices must be prioritised among smallholder farmers in Malawi. This should include providing farmers access to information, training, and technologies on soil management practices, such as agroforestry, crop rotation, cover cropping, and conservation agriculture.
9. The government of Malawi should also invest in ensuring the availability of inorganic fertilisers that meet macadamia nutrient requirements. This can be through importing and blending these inorganic fertilisers containing essential macro and micronutrients, especially those that address the specific nutrient deficiencies in each macadamia growing area. This can involve developing targeted extension services that provide farmers with access to soil testing services and tailored fertiliser recommendations.
10. Smallholder farmers must be encouraged to use organic inputs, such as compost and animal manure, to build up soil organic matter content and improve soil health. This should involve training farmers on composting and manure management practices.

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Appendices

Appendix 1: Human Research Ethics Approval

HREC/3306/Zuza: HREC Favourable Opinion

 Research-REC-Review
To:  Emmanuel.Zuza;  Research-REC-Review
Cc:  Yoseph.Araya;  Kadmiel.Maseyk;  Shonil.Bhagwat;  Andrew Emmott

 Reply  Reply All  Forward  

Fri 28/06/2019 10:02

This message confirms that the research protocol for the following research project, as submitted for ethics review, has been given a favourable opinion on behalf of The Open University Human Research Ethics Committee.

Project title: Understanding macadamia tree growth, constraints of nut production and future-climate projections for sustainability.


HREC approval date: 26/06/2019

As part of your favourable opinion, it is essential that you are aware of and comply with the following:

1. You are responsible for notifying the HREC immediately of any information received by you, or of which you become aware which would cast doubt on, or alter, information in your original application, in order to ensure your continued safety and the good conduct of the research.
2. It is essential that you contact the HREC with any proposed amendments to your research, for example - a change in location or participants. HREC agreement needs to be in place before any changes are implemented, except only in cases of emergency when the welfare of the participant or researcher is or may be affected.
3. Your HREC reference number has to be included in any publicity or correspondence related to your research, e.g. when seeking participants or advertising your research, so it is clear that it has been agreed by the HREC and adheres to OU ethics review processes.
4. Researchers should have discussed any project-related risks with their Line Manager and/or Supervisor, to ensure that all the relevant checks have been made and permissions are in place, prior to a project commencing, for example compliance with IT security and Data protection regulations.
5. Researchers need to have read and adhere to relevant OU policies and guidance, in particular the Ethics Principles for Research with Human Participants and the Code of Practice for Research - <http://www.open.ac.uk/research/ethics/>
6. The Open University's research ethics review procedures are fully compliant with the majority of research council, professional organisations and grant awarding bodies research ethics guidelines. Where required, this message is evidence of OU HREC support and can be included in an external research ethics review application. The HREC should be sent a copy of any external applications, and their outcome, so we have a full ethics review record.
7. At the end of your project you are required to assess your research for ethics related issues and/or any major changes. Where these have occurred you will need to provide the Committee with a HREC final report to reflect how these were dealt with using the template on the research ethics website - <http://www.open.ac.uk/research/ethics/human-research/full-review-process> (HREC Final Report form)


Sent on behalf of the Human Research Ethics Committee

Professor Louise Westmarland Chair	Dr Duncan Banks Deputy Chair	Dr Claire Hewson Deputy Chair
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Human Research Ethics Committee - Research, Enterprise and Scholarship (RES)
The Open University, Walton Hall, Milton Keynes, MK7 6AA

Email: research-rec-review@open.ac.uk Tel: 01908 654849
[http:// http://www.open.ac.uk/research/ethics/human-research](http://http://www.open.ac.uk/research/ethics/human-research)



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Appendix 2: Consent form



Human Research Ethics Committee

Consent form

Informed Consent for "Understanding Macadamia tree growth, constraints of nut production and future-climate projections for sustainability."

Emmanuel Junior Zuza, PhD Research Student, Environment, Earth and Ecosystem Sciences/ Science, Technology, Engineering and Mathematics.

Please tick the appropriate boxes Yes No

Taking part in the study

I have read and understood the study information dated [/ /2019], or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.

I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time up until 30th November 2019, without having to give a reason.

I understand that taking part in the study involves prompts that are related to macadamia production.

I agree to the photos being taken during the observation sessions.

I agree to the interview being audio-/ video-recorded.

Use of the information in the study

I understand that information I provide will be used for [reports, publications and website].

I understand that personal information collected about me that can identify me, such as my name or where I live, will not be shared beyond the study team.

I understand that my data will be stored in an electronic source for 4 years and will be destroyed in 2023.

I agree that my information can be quoted in research outputs.

Future use and reuse of the information by others

I give permission for the data that I provide to be deposited in a specialist data centre after it has been anonymised, so it can be used for future research and learning. This will include anonymised transcripts that will be coded by NMT and will have access restrictions will apply to the data in future.

Signatures

Name of participant [IN CAPITALS] Signature Date

For participants unable to sign their name, mark the box instead of signing

I have witnessed the accurate reading of the consent form with the potential participant and the individual has had the opportunity to ask questions. I confirm that the individual has given consent freely.

Name of participant [IN CAPITALS] Signature Date

This research project has been reviewed by, and received a favourable opinion, from the OU Human Research Ethics Committee - HREC reference number: **3306/Zuza**

<http://www.open.ac.uk/research/ethics/>

Appendix 3: Survey Questionnaire

SOCIAL - ECONOMIC ANALYSIS OF SMALLHOLDER MACADAMIA PRODUCTION AMONG HIGHLANDS MACADAMIA COOPERATIVE UNION LIMITED IN MALAWI

Enumerator's instructions

1. This questionnaire **MUST** be administered to a HIMACUL member who has been purposively selected in the enumeration area (these are the members that have been randomly selected from HIMACUL registers).
2. Please administer the questionnaire only with the consent of the respondent (use the consent form). If, for some reason, the respondent is not comfortable to be interviewed, politely end the interview and go to the alternative members.
3. Please record all the responses within the interview session. Reserve some few minutes at the end of the interview to crosscheck the responses you have not clearly understood/recorded.

SEEKING CONSENT OF THE RESPONDENT

My name is _____. I am an enumerator for The Open University based in the United Kingdom. We are currently conducting research with smallholder farmers on “Understanding smallholder macadamia tree growth, constraints of nut production and future-climate projections for sustainability”. I am part of that team and will ask you for information about macadamia production. When collected, this information is intended to be used by The Open University to know what is happening in macadamia production in this area. Any personal information collected will be treated with strict confidence and will only be used for this research. Please let me know if you have any questions regarding my visit. If not, allow me to proceed with the interview.

Name of Enumerator: _____ Date of Interview: ____/____/____

1. MODULE A: GENERAL INFORMATION

1.1. Name of respondent _____

1.2. District

Ntchisi Dowa Neno Mwanza

1.3. Cooperative

Chikwatula Tithandizane Malomo Mphaza Nachisaka Neno Mwanza

1.4. Are you the household head?

Yes No

1.5. Personal details of the respondent.

Age		M/F	Marital Status		Education level		Family size		Occupation	
< 30	<input type="checkbox"/>		Single	<input type="checkbox"/>	No formal education	<input type="checkbox"/>	< 4	<input type="checkbox"/>	Agriculture self-employed	<input type="checkbox"/>
31-40	<input type="checkbox"/>		Married	<input type="checkbox"/>	Primary education	<input type="checkbox"/>	4-6	<input type="checkbox"/>	Seasonal farm worker (estate).	<input type="checkbox"/>
41-50	<input type="checkbox"/>		Divorced	<input type="checkbox"/>	Secondary education	<input type="checkbox"/>	7-10	<input type="checkbox"/>	Non-agriculture self-employed.	<input type="checkbox"/>
51-60	<input type="checkbox"/>		Widowed	<input type="checkbox"/>	Tertiary education	<input type="checkbox"/>	11-15	<input type="checkbox"/>	Non-agriculture wage labour (ganyu).	<input type="checkbox"/>
61-70	<input type="checkbox"/>		Separated	<input type="checkbox"/>			> 16	<input type="checkbox"/>	SME owner	<input type="checkbox"/>
> 71	<input type="checkbox"/>	Employed (Gvt or NGO)							<input type="checkbox"/>	
									Pensioner	<input type="checkbox"/>

2. MODULE B: AGRICULTURAL PRODUCTION

Land size for agriculture		Land ownership (Multiple answers, prompt)		Crops grown (Multiple answers, do not prompt)		Crop Ranking based on importance (1 is very important, and 5 is the least importance).		Cropping systems (Do not prompt)	
< 0.5 ha	<input type="checkbox"/>	Inherited	<input type="checkbox"/>	Common beans	<input type="checkbox"/>	1.		Sole cropping	<input type="checkbox"/>
1 ha	<input type="checkbox"/>	Rented	<input type="checkbox"/>	Groundnuts	<input type="checkbox"/>	2.		Mixed cropping	<input type="checkbox"/>
1.5 ha	<input type="checkbox"/>	Leased	<input type="checkbox"/>	Macadamia nuts	<input type="checkbox"/>	3.		Agroforestry	<input type="checkbox"/>
2 – 4 ha	<input type="checkbox"/>	Bought	<input type="checkbox"/>	Maize	<input type="checkbox"/>	4.			
5 – 10 ha	<input type="checkbox"/>			Soybeans	<input type="checkbox"/>	5.			
> 10 ha	<input type="checkbox"/>			Sunflower	<input type="checkbox"/>	6.			
				Tobacco	<input type="checkbox"/>	7.			
				Vegetables	<input type="checkbox"/>	8.			

3. MODULE C: SMALLHOLDER MACADAMIA PRODUCTION IN MALAWI.

C1: General information on smallholder macadamia production in Malawi.

Why do you grow macadamia nuts? (Multiple responses, do not prompt)		Size of macadamia field. NB: 1 ha = 2.5 acres		Do you consume macadamia? Yes: 1 No: 0 Why do you consume macadamia nuts?		How do you consume macadamia? (Multiple answers, do not prompt).		Which system do you use for macadamia farming?		If you practice agroforestry, why do you do that? (multiple answers, do not prompt).		# of macadamia trees on farms.		# of total trees fruiting on farms.		
Source of food	<input type="checkbox"/>	< 0.5 acres	<input type="checkbox"/>	Nutritious	<input type="checkbox"/>	Raw nuts.	<input type="checkbox"/>	Sole cropping	<input type="checkbox"/>	Saves land for agricultural production.	<input type="checkbox"/>	<100	<input type="checkbox"/>	<100	<input type="checkbox"/>	
Source income	<input type="checkbox"/>	1 acre	<input type="checkbox"/>	Alternative to other crops.	<input type="checkbox"/>	Roasted nuts.	<input type="checkbox"/>	Agroforestry	<input type="checkbox"/>	Control of soil erosion.	<input type="checkbox"/>	101-300	<input type="checkbox"/>	101-300	<input type="checkbox"/>	
Source of firewood by using shells.	<input type="checkbox"/>	2 – 5 acres	<input type="checkbox"/>	Easily found from my farm	<input type="checkbox"/>	Grind to flower for porridge.	<input type="checkbox"/>			Resilience i.e. multiple crop yields per year	<input type="checkbox"/>	301-500	<input type="checkbox"/>	301-500	<input type="checkbox"/>	
Climate change mitigation through trees.	<input type="checkbox"/>	> 6 acres	<input type="checkbox"/>	Other specify:		Grind to flower and mixed with relish.	<input type="checkbox"/>			Effective water use (shading).	<input type="checkbox"/>	501-900	<input type="checkbox"/>	50-900	<input type="checkbox"/>	
Broad Crop diversification.	<input type="checkbox"/>					Others.				Use for macadamia shell for fuel or replacement for fuelwood/charcoal.	<input type="checkbox"/>	>1000	<input type="checkbox"/>	>1000	<input type="checkbox"/>	
Purifying water	<input type="checkbox"/>									Part of climate change mitigation	<input type="checkbox"/>					

C2: Source of seedlings, causes of death, and yields.

What is the main source of your macadamia seedlings (<i>Do not prompt</i>)		What is the cause of death of trees?		What was the yield of macadamia in 2020?		How much was sold to HIMACUL?		How much was sold to other buyers?		How much was consumed at home?	
Own	<input type="checkbox"/>	Termites	<input type="checkbox"/>	5 – 10 kgs	<input type="checkbox"/>	5 – 10 kgs	<input type="checkbox"/>	5 – 10 kgs	<input type="checkbox"/>	5 – 10 kgs	<input type="checkbox"/>
HIMACUL/Nesmac	<input type="checkbox"/>	Drought	<input type="checkbox"/>	11 – 25 kgs	<input type="checkbox"/>	11 – 25 kgs	<input type="checkbox"/>	11 – 25 kgs	<input type="checkbox"/>	11 – 25 kgs	<input type="checkbox"/>
Government	<input type="checkbox"/>	Wind	<input type="checkbox"/>	26 – 100 kgs	<input type="checkbox"/>	26 – 100 kgs	<input type="checkbox"/>	26 – 100 kgs	<input type="checkbox"/>	26 – 100 kgs	<input type="checkbox"/>
Middlemen	<input type="checkbox"/>	Livestock	<input type="checkbox"/>	101 – 500 kgs	<input type="checkbox"/>	101 – 500 kgs	<input type="checkbox"/>	101 – 500 kgs	<input type="checkbox"/>	101 – 500 kgs	<input type="checkbox"/>
Friends	<input type="checkbox"/>	Vandalism	<input type="checkbox"/>	≥ 501	<input type="checkbox"/>	≥ 501	<input type="checkbox"/>	≥ 501	<input type="checkbox"/>	≥ 501	<input type="checkbox"/>

C3: Extension advisory services and marketing

Who mainly provides agricultural advisory services on macadamia? (<i>Do not prompt</i>).		On average, how useful was the advice/information received from [source]?		Major market source of macadamia (<i>Multiple answers, do not prompt</i>).	
Government of Malawi (Alangizi)	<input type="checkbox"/>	Useless	<input type="checkbox"/>	HIMACUL/Nesmac	<input type="checkbox"/>
HIMACUL/Nesmac	<input type="checkbox"/>	Not very useful	<input type="checkbox"/>	Sable farming	<input type="checkbox"/>
Total Land Care	<input type="checkbox"/>	Useful	<input type="checkbox"/>	Thyolo nut factory	<input type="checkbox"/>
Nasfam	<input type="checkbox"/>	Very useful	<input type="checkbox"/>	Middlemen	<input type="checkbox"/>
GIZ	<input type="checkbox"/>			Local village markets	<input type="checkbox"/>
Others Specify:				Others specify	

C4: Macadamia cultivar preferences

Names of cultivars grown by farmer (<i>Multiple responses, do not prompt</i>)		Which of the cultivars Do you prefer as the best (<i>Rank from best to lower best</i>)?	
246 <input type="checkbox"/>	783 <input type="checkbox"/>	1.	
333 <input type="checkbox"/>	788 <input type="checkbox"/>	2.	
344 <input type="checkbox"/>	791 <input type="checkbox"/>	3.	
508 <input type="checkbox"/>	800 <input type="checkbox"/>	4.	
660 <input type="checkbox"/>	814 <input type="checkbox"/>	5.	
705 <input type="checkbox"/>	816 <input type="checkbox"/>		
741 <input type="checkbox"/>	834 <input type="checkbox"/>		
772 <input type="checkbox"/>	842 <input type="checkbox"/>		
A4 <input type="checkbox"/>	849 <input type="checkbox"/>		
Don't know <input type="checkbox"/>	Others specify		

5: Characteristics of the five preferred cultivars (*Multiple answers, do not prompt*)

Best preferred cultivar characteristics.		Second best cultivar characteristics.		Third best cultivar characteristics		Fourth best cultivar characteristics		Firth best cultivar characteristics	
High yielding (in total)	<input type="checkbox"/>	High yielding (in total)	<input type="checkbox"/>	High yielding (in total)	<input type="checkbox"/>	High yielding (in total)	<input type="checkbox"/>	High yielding (in total)	<input type="checkbox"/>
Big nuts	<input type="checkbox"/>	Big nuts	<input type="checkbox"/>	Big nuts	<input type="checkbox"/>	Big nuts	<input type="checkbox"/>	Big nuts	<input type="checkbox"/>
Flowers all year round	<input type="checkbox"/>	Flowers all year round	<input type="checkbox"/>	Flowers all year round	<input type="checkbox"/>	Flowers all year round	<input type="checkbox"/>	Flowers all year round	<input type="checkbox"/>
Resistant to pest & diseases	<input type="checkbox"/>	Resistant to pest & diseases	<input type="checkbox"/>	Resistant to pest & diseases	<input type="checkbox"/>	Resistant to pest & diseases	<input type="checkbox"/>	Resistant to pest & diseases	<input type="checkbox"/>
Drought resistant	<input type="checkbox"/>	Drought resistant	<input type="checkbox"/>	Drought resistant	<input type="checkbox"/>	Drought resistant	<input type="checkbox"/>	Drought resistant	<input type="checkbox"/>
Easy to find seedlings	<input type="checkbox"/>	Easy to find seedlings	<input type="checkbox"/>	Easy to find seedlings	<input type="checkbox"/>	Easy to find seedlings	<input type="checkbox"/>	Easy to find seedlings	<input type="checkbox"/>
Wind resistant	<input type="checkbox"/>	Wind resistant	<input type="checkbox"/>	Wind resistant	<input type="checkbox"/>	Wind resistant	<input type="checkbox"/>	Wind resistant	<input type="checkbox"/>
Others:		Others:		Others:		Others:		Others:	

C6: Constraints to macadamia production (*Multiple answers, do not prompt*)

Drought	<input type="checkbox"/>	Seedling availability	<input type="checkbox"/>	Transport	<input type="checkbox"/>
Poor soil fertility	<input type="checkbox"/>	Market availability	<input type="checkbox"/>	wind	<input type="checkbox"/>
Diseases	<input type="checkbox"/>	Limited land for macadamia trees	<input type="checkbox"/>	Climate change	<input type="checkbox"/>
Insect pests	<input type="checkbox"/>	Labour availability	<input type="checkbox"/>	Lack of agricultural advisory services	<input type="checkbox"/>

C7: Rank the macadamia production constraints (Score: 1 = Very important; 2 = Most important, 3 = Important and 4 = less important).

Constraint	Rank	Comment
Drought.		
Poor soil fertility.		
Diseases.		
Insect pests.		
Seed availability.		
Market availability.		
Labour availability.		
Transportation.		
Wind.		
Climate change		
Drought.		
Lack of extension staff.		

C8: Soil fertility improvement practices

What is the fertility status of your macadamia soils?		If your soil fertility is declining what do you so to make it better?		I you applied inorganic fertilizers what is its name?		If you applied manure what is its name/origin?	
Stable	<input type="checkbox"/>	Apply fertilizers	<input type="checkbox"/>	N:P:K	<input type="checkbox"/>	Livestock manure	<input type="checkbox"/>
Declining	<input type="checkbox"/>	Apply manure	<input type="checkbox"/>	Urea	<input type="checkbox"/>	Chitowe	<input type="checkbox"/>
Improving	<input type="checkbox"/>	Mulching	<input type="checkbox"/>	DAPP	<input type="checkbox"/>	Nkhuti	<input type="checkbox"/>
		Intercrop with legumes	<input type="checkbox"/>	Agriculture lime	<input type="checkbox"/>		
		Other specify		Gypsum	<input type="checkbox"/>		

C9: Irrigation and moisture conservation

What methods do you use for moisture conservation in mac fields?		Do you irrigate you macs?		What is your System of irrigation?		Sources of water		If No irrigation why?	
Mulching	<input type="checkbox"/>	Yes	<input type="checkbox"/>	Stream diversion	<input type="checkbox"/>	Well	<input type="checkbox"/>	Can't afford	<input type="checkbox"/>
Basins	<input type="checkbox"/>	No	<input type="checkbox"/>	Bucket/ water can	<input type="checkbox"/>	Borehole	<input type="checkbox"/>	Unreliable source	<input type="checkbox"/>
Cover crops	<input type="checkbox"/>			Hand pump	<input type="checkbox"/>	Lake	<input type="checkbox"/>	Broken down	<input type="checkbox"/>
Box ridging	<input type="checkbox"/>			Solar pump	<input type="checkbox"/>	River	<input type="checkbox"/>	Labour intensive	<input type="checkbox"/>
Other specify:				Others specify:		Other specify:		Other specify:	

4. MODULE D: INSECT PESTS AND DISEASES IDENTIFICATION

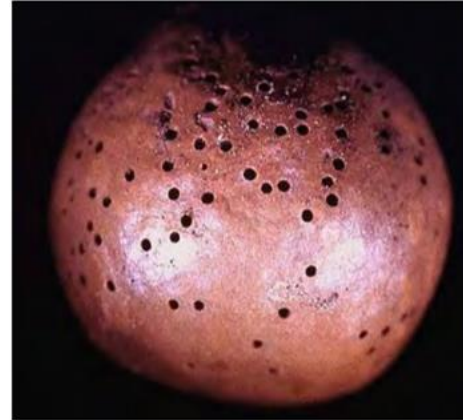
D1: What insects pests have you observed in your macadamia fields? (*Show the respondent the pictures*)



<p>Fruit borer (<i>Cryptophelebia Ombrodelta</i>)</p>	<input type="checkbox"/>			
<p>Fruit borer (<i>Banana spotting Bug</i>)</p>	<input type="checkbox"/>			





**Green vegetable
stink bug (*Nezara
viridula*)**



**Tropical Nut
Borer (*Hypothenemus
obscurus*)**



Termites	<input type="checkbox"/>	
Rats	<input type="checkbox"/>	
Mites	<input type="checkbox"/>	

<p>Husk disease spot</p>	<input type="checkbox"/>		
<p>Macadamia white scale</p>	<input type="checkbox"/>		

D2: Rank the pests and diseases based on severity (Score: 1 = Very severe; 9 = Less important).

Pest or disease	Rank
Fruit borer (<i>Cryptophelebia Ombrodelta</i>)	
Fruit borer (<i>Banana spotting Bug</i>)	
Green vegetable stink bug (<i>Nezara viridula</i>)	
Tropical Nut Borer (<i>Hypothenemus obscurus</i>)	
Termites	
Rats	
Mites	
Husk spot disease	
Macadamia white scale	

The End

Appendix 4: Suitable climatic conditions for macadamia production in Malawi (Evans, 2008).

Description	Category	Adverse	Moderate	Optimal
Minimum temperature of the coldest month.	T_{\min} [°C]	≤ 1	1–4	5–10
Annual mean temperature.	T_{mean} [°C]	≤ 9	10–15	16–30
Maximum temperature of the warmest month.	T_{\max} [°C]	≥ 36	31–35	25–30
Annual precipitation.	Prec[mm]	0–700 & ≥ 1750	900–1000 & 1300– 1750	1000–1250

Appendix 5: Optimum soil parameters for macadamia production in Malawi (Evans, 2021)

Parameter	Units	Below range	Optimal	Above Range
Soil pH	N/A	< 5.5	5.5 – 6.5	> 6.5
Electrical conductivity	$\mu\text{S cm}^{-1}$	< 13	13 – 190	> 190
Nitrogen	%	< 1	1 – 10	> 20
Calcium	Mg kg^{-1}	< 1200	1200 – 1800	> 1800
Potassium	Mg kg^{-1}	< 200	200 – 300	> 300
Magnesium	Mg kg^{-1}	< 180	180 – 250	> 250
Sodium	Mg kg^{-1}	<	< 45	> 45
Phosphorus	Mg kg^{-1}	< 30	30 – 75	> 75
Boron	Mg kg^{-1}	< 1	1 – 3	> 3
Copper	Mg kg^{-1}	< 2	2 – 5	> 5
Iron	Mg kg^{-1}	< 4	> 4	
Manganese	Mg kg^{-1}	< 2	2 – 40	> 75
Zinc	Mg kg^{-1}	< 3	3 – 10	> 40
Sulphur	Mg kg^{-1}	< 30	30 – 75	> 75
Cation Exchange Capacity	cmol (+) kg^{-1}	< 3	3 – 8	> 8
Soil organic matter	%	< 1	2 – 50	

Appendix 6: Methods of macadamia nut consumption

