PROJECTED FUTURE HABITAT SUITABILITY OF SELECTED MEDICINAL PLANTS IN EASTERN UGANDA UNDER CLIMATE CHANGE: A MAXENT MODELLING APPROACH

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DECLARATION

This thesis is my original work and has not been presented for award of a degree at any other university.

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Title of the work---------- PROJECTED FUTURE HABITAT SUITABILITY OF SELECTED MEDICINAL PLANTS IN EASTERN UGANDA UNDER CLIMATE CHANGE: A MAXENT MODELLING APPROACH

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DEDICATION

To my family Rev. Patrick Wanzala and Mrs. Eseza Wanzala, Robert, Mary and Emma for their relentless support both financially and emotionally during the entire journey of the work.

Also, to Mrs. Allen Wademba who supported me with the laptop that I used during the preparation of the work.

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LIST OF ABBREVIATIONS

AUC	area under curve
Evs	environmental variables
IUCN	International union for conservation of nature
MAP	mean annual precipitation
MAT	mean annual temperature
MaxEnt	maximum entropy
MPs	medicinal plants
SDMs	species distribution models
SD	Standard deviation
GBIF	Global biodiversity information facility
NFA	National forestry authority
NEMA	National environmental management authority
TMK	Traditional medicinal knowledge
HM	Herbal medicine
SMs	Secondary metabolites
TMPs	Traditional medicine practitioners
DM	Diabetes mellitus
OIs	Opportunistic infections
MUH	Makerere University Herbarium
GPS	Global positioning system
PLHIV	People living with HIV
ROC curve	Receiver operating characteristic curve

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ABSTRACT

The selected medicinal plants are a source of primary health care for both poor communities and those in developing countries. They are an alternative for synthetic drugs in places with limited health facilities, and in some areas, they are resorted to for their safety and low toxicity. However, accurate prediction of the future distribution of these MPs under changing environmental conditions has, until now, not been available, limiting the conservation strategies that could be planned in advance of anticipated habitat change.

The area of study was selected using purposive sampling from information sources such as the Global Biodiversity Information Facility (GBIF) and the Makerere University Herbarium (MUH), supplemented by field-collected GPS occurrence and elevation data. The changes in five environmental variables (land use, slope, precipitation, temperature, and soil factors) were projected using MaxEnt software, and the future distribution was mapped for two horizons, 2040 and 2060, alongside a current-conditions baseline for comparison.

The projections show that most of the nine focal species are expected to retain broadly stable habitat suitability surfaces through 2040 and 2060, with the most spatially restricted species *Warburgia ugandaensis* and *Croton macrostachyus* projected to remain confined to their current narrow southern range with no new refugia emerging elsewhere in the country. *Tephrosia linearis* is the exception, with its currently even distribution projected to fragment into a mosaic of high- and low-suitability patches in north-eastern Uganda by 2060. The environmental variables of mean annual temperature, elevation, precipitation, and land use/cover were identified as the primary drivers of the projected future distribution.

Key words: *Zanthoxylum chalybeum, Albizia coriaria, Gymnosporia senegalensis, Warburgia ugandaensis, Croton macrostachyus, Rhoicissus tridentata, Mondia whitei, Kigelia africana,* and *Tephrosia linearis,* MaxEnt, habitat suitability projection, climate change, Karamoja, Katakwi, Mbale, Tororo, Busia, Kaliro, Busitema University

CHAPTER ONE INTRODUCTION

1.1 Background

Herbal medicines serve as the primary health care resource (Tabuti et al., 2023) for approximately 80% of the global population, as reported by Mollel et al., (2024), Appau et al., (2024) and Applequist et al., (2020) in treatment of many ailments with malaria inclusive. This increased proportion of use of medicinal plants (MPs) has been attributed to many factors that can be economy in developing countries (Mguni et al., 2023; Appau et al., 2024), and also preference arising from concerns that they have low side effects compared to the synthetic drugs (Imphat et al., 2021; Mollel et al., 2024; Teixidor, 2017; Choudhury Barua et al., 2018). In Africa, MPs extracts have been widely used in both livestock and human health management and it ranks at 80 %. In the Sub-Saharan Africa, the prevalence of diseases such as malaria, and together with the low-income standards of the population, the use of medicinal plants is so high. Uganda has since been considered the pearl of Africa due to its diverse biodiversity (Ofcansky, 2018; Ssenku et al., 2022). However, it has been rampantly hit by very many epidemic diseases simply due to poor medical facilities (Ssenku et al., 2022). As a result, the use of herbal medicine (HM) has been reported to be high between 60-85% specifically supporting the rural communities (Ssenku et al., 2022; Nakibuuka & Mugabi, 2022). They have been tried in various studies and found to reduce the disease burden greatly; for example, Zanthoxylum chalybeum has shown 80 % anti-plasmodial activity, and Maytenus senegalensis is 50 % activity (Tajbakhsh et al., 2021) especially in developing countries where the medicines are readily available. They have been and are still of importance because of their anti-microbial activities (Baral et al., 2024; Dewatisari & Nuryandani, 2024; Mguni et al., 2023; Nayaka et al., 2020; Schultz et al., 2021; Taibi et al., 2023; Soussi et al., 2023), antimalarial (Ajayi et al., 2020; Olalubi et al., 2021; Tabuti et al., 2023), antifungal (Alam et al., 2020; Mukasa et al., 2023), anti-diabetic (Mguni et al., 2023; Uwimbabazi et al., 2023) among others. MPs have greatly contributed to the modern human medicine for example, use of quinine extracted from Cinchona species, artemisinin extracted from Artemisia annua in the treatment of malaria (Bickii et al., 2007). It has been found that the primary medicines of most individuals in developing countries is from medicinal plant extracts (Tabuti et al., 2023; Mguni et al., 2023). MPs have since time in memorial shown to have capability of boosting immunity for both human and animal health (Mbinile et al., 2020; Xego et al., 2016; Daniel et al., 2019) in treating various ailments such as malaria, diabetes mellitus and other infections. The extracts from these medicinal plants have been used locally as antimalarials (Jullian et al., 2006: Muthaura et al., 2015; Kiraithe et al., 2016; Kutima et al., 2014) and for anti-inflammatory activities (Imphat et al., 2021; Lawal et al., 2019; Alam et al., 2020; Schultz et al., 2021) as well as other ailments such as cancer (Kudamba et al., 2023), cough (Asiimwe et al., 2021; Daniel et al., 2019; Ssenku et al., 2022), fever (Abubakar et al., 2022; Adebayo & Krettli, 2011; Chaniad et al., 2022, 2023; Nworu et al., 2017) and others. This has been supported by research that they contain various secondary metabolites (SMs) for example terpenoids, saponins, tannins, phenols, glycosides,

tembetarine, nitidine, skimianine, flavonoids, and benzophenanthridine alkaloids (Mbinile et al., 2020; Chrian et al., 2011). The majority of the plant parts that have been used for the treatment of infections and disorders are the stem barks (Adia et al., 2016; Choudhury Barua et al., 2018; Lawal et al., 2019; Schultz et al., 2021; Waiganjo et al., 2020) and leaves (Acero et al., 2018; Adia et al., 2016; Anywar et al., 2020b, 2022; Asiimwe et al., 2021; Dadhwal & Banerjee, 2023; Gao et al., 2024; Kiraithe et al., 2016; Nalumansi et al., 2017; Okot et al., 2020; Ouédraogo et al., 2019; Ssenku et al., 2022; Tajbakhsh et al., 2021; Tocai et al., 2023; Waiganjo et al., 2020).

However, extinction threats to the medicinal plants are highly associated with various environmental variables which include; temperature, (Tian et al., 2022; Mbinile et al., 2020) Mbinile et al., 2020), soil factors (P. Yang et al., 2025), precipitation (Devine et al., 2017) and elevation or altitude gradient. Among the listed variables, temperature takes an upper hand due to the effects of global warming which have led to an increase in global temperature by 0.6ºC and prediction shows the increase to continue up to a range of 2.6-4.8ºC in the near future (Xu et al., 2022). These threats lead to the reduction in the population and uneven distribution of the medicinal plants. Some plants are very sensitive to rapid changes in temperature and water stress, therefore, they tend to deteriorate in the population and distribution and hence become endangered when harsh conditions arise (Kurpis et al., 2019). The human populations will be limited from access to medicinal plants leading to their displacement from traditional homelands. Apart from the above environmental variables, other threats leading to the extinction of the medicinal plants include anthropogenic effects such as cutting for poles, charcoal burning, bush burning, using as fodder (Dokata et al., 2023; Mbinile et al., 2020b), procedures of medicinal harvesting (Dokata et al., 2023) and over-harvesting of the medicinal plants (Nenungwi et al., 2025). Some MPs are harvested by uprooting, and debarking; for the case of uprooting, the population of the plants in the habitat decreases and also the susceptibility of the plants to extinction increases. Although debarking does not have an acute effect to the population of the MPs, it leads to detrimental effects such as entry of pathogens, interrupted flow of food through the phloem and can lead to death of the tree (Mbinile et al., 2020b). It is supported by research that recovery of bark after debarking on some medicinal plant tree species is unlikely (Dokata et al., 2023). The plant species are not only used for treatment of diseases but also other uses such as livestock feeds, timber, poles, and wood fuel (Mbinile et al, 2020; Kamau et al., 2017), and their harvesting to serve these purposes has also been accounted for the change in population of the medicinal plants.

Conservation strategies of the selected MPs seem to be difficult as the distribution and factors affecting the distribution have not been well documented. As a result, some plants are seen to behave or are favored differently by the various factors while others are not. As some plants are affected by climatic changes such that they migrate to other habitats (Olalubi et al., 2021; Siahaan et al., 2019; Tang et al., 2020; Tian et al., 2022; Xu et al., 2022; Kurpis et al., 2019), some which are resistant to the climatic changes remain in their habitats. It becomes challenging to come up with conservation strategy in cases where some plants show resistance to environmental changes although their phytochemical compositions change (Appau et al., 2024; J. Zhang et al., 2020). This

will in turn affect the pharmaceutical properties of the extracts from the medicinal plants (J. Zhang et al., 2020) thus increase their potential to cause harm to the population or their dosage will be difficult to be prescribed. Therefore, without keen interventions, the beneficial aspects of the medicinal plants will not be realized and it may lead to discarding of the would-be effective plants in preventing infection. Also, in-situ and ex-situ conservation strategies have been put in place but with less success since there still remains the unsuitable harvesting of the specimens (Dokata et al., 2023), also mimicking environmental conditions in the lab can be hard. Also, providing all the suitable conditions for proper growth may also be difficult since many soil factors and other environmental variables contribute to both plant growth, productivity and phytochemistry (L. Chen et al., 2025). However, to ensure effectiveness in the conservation strategies of the plant species, modelling using species distribution models (SDMs) has been ventured to ensure that accurate predictions of the plant spatial distributions in relation to various climatic variables (Guo et al., 2016; Kurpis et al., 2019; Monteiro et al., 2023; Phillips et al., 2017; Pramanik et al., 2018; Tian et al., 2022; Xu et al., 2022). Species modelling has been tried using different SDMs although some have shown inaccuracy, some have been supported as having high degree of accuracy. Some SDMs have failed in that the prediction seldom come true or others provide predictions that contradict each other. However, MaxEnt (Abdelaal et al., 2019; Cobos et al., 2019; Fang et al., 2022; Xu et al., 2022) has been used for long and has given accurate results with time.

The spatial distribution of medicinal plants is not only predisposed to threats from climate changes such as temperature (Tian et al., 2022; Mbinile et al., 2020) precipitation (Devine et al., 2017) and human activities (Wraith & Pickering, 2018; Welk et al., 2019) but also due to other factors such as soil factors (P. Yang et al., 2025), resource availability and other disturbances in the ecosystem (M. et al., 2005; McMillen, 2012). Also, the distribution of some of the medicinal plants for example Zanthoxylum chalybeum has been influenced by dormancy of the seeds, sometimes due to loss of viability of the seeds. Therefore, there is delay and difficulty of germination when seeds are planted (Okeyo et al., 2011; Purohit et al., 2015; 2016). This seed dormancy has been attributed to the fact that their seed coats are hard and also the contain oils within them (Okeyo et al., 2011). Also, it has been reported by some literature that the seeds lose viability over time. However, these plants' distribution can be enhanced by applying dormancy breakers such as sulphuric acid (Purohit et al., 2015) to ensure quick germination and hence growth for their redistribution, and also another way to break dormancy is by washing the seeds in soap solution to remove the oil film and fruit appendages on the testa before incubation in the case of zanthoxylum species (Okeyo et al., 2011). Other propagation methods such as air layering (Purohit et al., 2016) to ensure that growth is continuous in case strategies to break dormancy fail. The distribution of the medicinal plants is also influenced by altitude or elevation gradient. This in conjunction with harsh climatic conditions tend to push lowland plants to highland habitats where they outcompete the highland plants for the same habitat. As a result, the highland plants that are less competitive and only restricted to one habitat tend to reduce in distribution (Kurpis et al., 2019; Abdelaal et al., 2019). Also, distribution in some areas is influenced by grazing mechanisms (Mbinile et al., 2020; Dokata et al., 2023) by the domesticated animals and also those of the wild. This effect is very paramount

when the animals forage the seedlings. They feed on the apical shoot resulting in inhibition of growth of the plants resulting from reduced production of auxins due to absence of apical meristems. As it is said that "a forest cannot exist without young trees," the plant species are destined to be endangered. Despite these threats to the selected medicinal plants, very little has been done or is being planned for their conservation strategies.

Although many studies have been carried out on medicinal plants worldwide, there is an existing gap in the distribution of medicinal plants in the Eastern region of Uganda. This has been majorly due to poor documentation of the MPs and factors affecting their distribution. As a result, the indigenous knowledge about medicinal plant trees and their beneficial effects are likely to be lost (Baker et al., 2023) and as such, the future generation will be left without knowledge of the natural health products. In this study, the various factors leading to extinction of the selected MPs will be discussed and the various strategies to ensure conservation as well. The MPs of focus in this study are; *Zanthoxylum chalybeum, Mondia whitei, Gymnosporia senegalensis, Rhoicissus tridentata, Croton macrostachyus, Kigelia africana, Warburgia ugandaensis, Albizia coriaria, and Tephrozia linearis*. The IUCN Red list of threatened species still categorizes most of these plants as those with stable population although they are highly exploited locally leading to extinction. Also, climate and land use changes (Mbinile et al., 2020; Olalubi et al., 2021) and other factors have made them become endangered. As a result, there is great need to preserve the continuously decaying indigenous knowledge about the medicinal plants. Also, extinction of some of the medicinal plants due to their various economic activities including production of timber, poles, fuelwood and feed for animals and also some are harvested for export to western and the middle east countries (Mbinile et al., 2020b).

1.2 Statement of the Problem

Various factors (biotic and abiotic) (Bedane et al., 2023) affect the growth and productivity of the medicinal plants and thus have challenged their distribution. Several environmental variables (EVs) have been noted among which the climatic factors have an upper hand in influencing the distribution of the medicinal plants. They (EVs) pose threats that can either directly or indirectly affect the plants. Variations in these climatic factors have been driven by many other factors where the human activities have manifested most. Human induced climate change due to emission of greenhouse gases, reduction of carbon sinks (wetlands and forests) has led to the global rise in temperatures and decline in precipitation (Kurpis et al., 2019). For example, deforestation, bush burning, agricultural extension, settlements, grazing among others. Climatic threats have been shown through fluctuations in temperature and precipitation (Devine et al., 2017; Pozo-Gómez et al., 2020; Stehelin, 2020; Tenaw et al., 2024; Wangalwa et al., 2021; J. Zhang et al., 2020; M. Zhang et al., 2021). Elevated temperatures (Devine et al., 2017) have caused migration of some medicinal plant species from low land habitats with higher temperatures to higher gradients with moderately low temperatures. This has increased competition for space and nutrients in the highland habitats hence making the less competitive ones extinct (Pompe et al., 2010; Abdelaal et al., 2019). Other factors affecting the distribution of the selected medicinal

plants have arisen from the use of the medicinal plants for other purposes such as construction of houses, cattle sheds, charcoal, firewood (Mbinile et al., 2020a, 2020b; Mguni et al., 2023; Mollel et al., 2024). While others are due to the nature of the harvesting style used or procedure of harvesting the plant medicines (Mbinile et al., 2020a), the rate of harvesting (Kurpis et al., 2019). Also, agricultural extension due to introduction of other cultivars which could be invasive species (Manzoor et al., 2020; Shackleton et al., 2017; Witt et al., 2020) that outcompete the native species.

Achieving feasible and sustainable management strategies for managing the spatial distribution of medicinal plants poses a considerable challenge. Despite efforts for ex-situ conservation (Koch et al., 2021; Ouédraogo et al., 2019; Rosche et al., 2022; Stehelin, 2020; Wangalwa et al., 2021) of the endangered species, very little has yielded because some of the plants have shown alterations in their growth, distribution and phytochemical composition of the plants. Also, the soil microbial activity of the microbes in the rhizosphere soils greatly affects the plant root growth and hence distribution (L. Chen et al., 2025; Moiloa, 2016). The microbial activity has been reported to vary basing on the different soil factors and other environmental factors hence making ex-situ conservation an impossible strategy. These microbes affect the kind of nutrients and rate of absorption of nutrients responsible for the growth and productivity of the plants. In situ conservation practices are the most appropriate since the plants remain in their natural habitat, however, this is only achievable if the plants have a random spatial distribution (Olalubi et al., 2021). On the other hand, it has proven to be unachievable because the plants still face the challenges in place, hence affecting their distribution (Mollel et al., 2024).

Therefore, the need to carry out an accurate study of the current distribution of the medicinal plants and how the different environmental variables influence it. Also, there should be accurate predictions for potential habitats and their suitability for the various medicinal plants in relationship to the predicted change in the environmental variables. Therefore, in this study, we will document the distribution of the selected medicinal plants in relation to the environmental variables. We will proceed to predict the future distribution of the medicinal plants basing on how the different environmental variables are predicted to change and suggest possible conservation strategies.

1.3 Aim of study

To investigate the spatial distribution of the selected medicinal plants in relation to environmental factors

1.3.1 Specific objectives

To map the current distribution of selected medicinal plants in Eastern Uganda.

To investigate effect of the different environmental variables on the distribution of the selected medicinal plants.

To examine the relationship between the presence data of the selected medicinal plants and distribution.

To predict the potential habitat suitability for future distribution of the selected medicinal plants with change in the environmental variables in Eastern Uganda.

1.4 Research questions

1. how is the distribution of the selected medicinal plants affected by the changes in environmental variables?

2. how has climate change and change in other environmental variables affected the productivity, growth and distribution of the selected medicinal plants?

3. how will continuous fluctuation in environmental variables affect the distribution of the selected medicinal plants?

4. what percentage of suitable habitats will be available in the future?

5. which conservation strategies have been put in place to address the challenge?

1.5 Hypothesis

1.5.1 Null hypothesis:

There is no relationship between the distribution of the selected medicinal plants in their habitats and the different environmental variables.

1.5.2 Alternative hypothesis:

There is a difference in the distribution of the selected medicinal plants in their different habitats in relationship with the environmental variables.

1.6 Justification of the study

Climatic factors (temperature and precipitation) among the five environmental variables have been reported to greatly affect the distribution of the medicinal plants (Devine et al., 2017; Mbinile et al., 2020; Xu et al., 2022). Fluctuations in these variables (precipitation and temperature) can result into alterations in the distribution of the medicinal plants within their habitats. It has been reported by some SDMs that some medicinal plants will migrate to new habitats that would be favorable (Xu et al., 2022). While those that are habitat specific, become wiped out hence their extinction (Pompe et al., 2010). Fluctuations in these environmental variables has been influenced by human activities leading to changes in climate for example, deforestation, urbanization, agricultural extension among others. The harvesting style which includes debarking and uprooting as well as the rate or frequency of harvesting pose a threat to the distribution of the selected medicinal plants in their habitats (Mbinile et al., 2020b; Baghersad et

al., 2024; Daniel et al., 2019; Mollel et al., 2024; Ouédraogo et al., 2019; Stas et al., 2017; Wangalwa et al., 2021; Xego et al., 2016). Most of the plants are harvested by debarking and this accounts for the damage caused to the medicinal plant species hence affecting their wellbeing and growth to survive other environmental aspects since regeneration of bark has shown failure. While the rate of harvesting driven by the high market demand for the medicinal plant products (Brzić et al., 2023; Green et al., 2022; Haddad, LA, et al., 2015; J. Zhang et al., 2020; M. Zhang et al., 2021), or legality of the harvesting process. Also, there exists other anthropogenic threats facing the medicinal plants such as cultivation of invasive species which out compete the native species (Manzoor et al., 2020; Medley, 2010; Shackleton et al., 2017; Siegert et al., 2014; Witt et al., 2020) and other commercial plant trees to which more benefits are attached as compared to the medicinal plants.

Also, most individuals today have abandoned the indigenous trees most especially the medicinal plant trees and have resorted to planting commercial trees. They tend to clear the local trees and replace them with commercial ones in the search for money. As a result, there is an increased risk of disease. There has been less documentation of the medicinal plants about their ethnobotanical uses, harvesting methods, effects of the various environmental variables on their distribution (Mollel et al., 2024). This has limited the prediction of the future distribution and the potential habitats as well as appropriate conservation strategies of the selected medicinal plants. This has been shown by the fact that the medicinal plants are affected differently by environmental variables.

One of the objectives of this study is to predict the future potential habitats of the selected medicinal plants and their distribution in relation to environmental variables and thus come up with strategies to conserve the endangered species in their natural habitats. And this study will encompass assessment of the possible strategies to curb the unprecedented distribution of the medicinal plants.

1.7 Significance of the study

This study will focus on studying the spatial distribution of selected medicinal plants: *Zanthoxylum chalybeum*, *Maytenus senegalensis*, *Croton macrostachyus*, *Mondia whitei*, *Kigelia africana*, *Tephrosia linearis*, *Albizia coriaria* and *Warburgia ugandaensis* in relation to environmental variables. It will involve identifying the distribution patterns in relation to the environmental variables of temperature, precipitation, land use or cover, soil factors and elevation gradient. The study will encompass establishment of the relationship between human activities and the variation of these variables. This will enable proper identification of conservation strategies for the conservation of the medicinal plants. Also, the population will be sensitized on the best harvesting practices in cases where harvesting practices have made the species become endangered.

It will also go ahead to predict the potential habitats and their suitability for the future distribution of the selected medicinal plants. The prediction will be done using MaxEnt software and spatial

distribution models will be developed. The results from this will be used by different organizations and other pharmaceuticals to ensure sustained harvesting of the plant medicines.

Finally, it will highlight on the possible diseases that are likely to affect the human population if the medicinal plants are displaced far away from their habitats.

CHAPTER TWO LITERATURE REVIEW

2.1 Historical background of use of medicinal plants

In Africa, traditional medicine encompasses a diverse range of practices, including herbalism and spiritualism, where some diseases are believed to be "African" since they can only be traditionally treated locally or by herbalists (Green et al., 2022). Indigenous knowledge on the management of "African" diseases using medicinal plants was handed down orally from generation to generation by tribal societies of tropical Africa (Rodríguez-Calderón et al., 2019). As a result of the rapid westernization of these societies, there is a pressing need to record this local knowledge before it is lost forever (Gumisiriza et al., 2021; Rodríguez-Calderón et al., 2019). In these societies, the elders usually select some individuals whom they think will be very good at performing their work and thus introduce them to the various plants used to treat various ailments (Choudhury Barua et al., 2018; Rodríguez-Calderón et al., 2019). Some of the medicinal plant trees have been used in the treatment of some diseases in both humans and animals (Mbinile et al., 2020a, 2020b).

Currently, there is heightened application of plant medicines as health care (Appau et al., 2024; Mollel et al., 2024). For example, more than two thirds of the world's 36.9 million people living with HIV/AIDS reside in Sub-Saharan Africa and mostly use Z. Chalybeum and W. Ugandaensis for management of the ailment (HIV/AIDS) (Anywar et al., 2020a). Medicinal plants have also been used in the management of Opportunistic infections (OIs) associated with HIV/AIDS. These have been reported to be the major cause of mortality and morbidity among HIV/AIDS patients in poor countries. There is widespread use of medicinal plant species to manage the HIV infection (Nakibuuka & Mugabi, 2022; Anywar et al.,2020a, 2020b, 2021) and it's associated OI in Uganda (Anywar et al., 2020a), even by patients already on antiretroviral drugs (ARV). However, much of this information remains undocumented (Mollel et al., 2024) and unverified. Despite concerns about toxicity, potentially harmful effects and herb-drug interactions, the use of herbal medicines remains widely practiced by people living with HIV/AIDS (PLHIV) in Uganda (Anywar et al., 2020a; 2020b; 2021; Nakibuuka & Mugabi, 2022).

The global consumption of herbal medicine is increasing steadily. This has been due to the less side effects in the drugs as compared with the western medicines (Appau et al., 2024; Mollel et al., 2024). Also, due to low costs of the medicinal plant extracts, and easy access to consumers (Mollel et al., 2024; Appau et al., 2024). This has in turn posed an extinction risk to medicinal plants. Uganda is among the top ten countries with a high threat of herbal medicine extinction (Ofcansky, 2018) due to the rampant harvesting rate and also illegal export of the medicinal plants. Also, other human activities such as deforestation, grazing cattle, agriculture, and settlement endanger the plant species. Also, Traditional Medicinal Knowledge (TMK) erosion since most people have adopted the use of western medicines. Also, inadequate documentation (Mollel et al., 2024) of the available medicinal plants concerning the diseases they treat and how to be consumed sustainably, plus many more unclear hindrances. Also, the efficacy testing (Alam et al., 2020) of

the medicines have been tried using clinical analysis, and in-vitro or ex-vivo trials to ensure rightful dosage is taken up (Appau et al., 2024; Nguta et al., 2011). Recently, many plants have been reported in various papers as having the capacity to treat common diseases such as cancer, malaria, diarrhoea, asthma among others with the selected medicinal plants dominating most of the papers.

Medicinal plants have formed an integral part of many health care systems in Uganda (Asiimwe et al., 2021). They have been used in treatment of malaria parasite infections, bacterial infections (Schultz et al., 2020), management of DM, especially in developing countries, such as Uganda (Gang et al., 2023). In Uganda, DM prevalence rate has more than doubled in the last decade. Although management options for DM are various including conventional medicine, physical exercise and diet, use of traditional medicine has increasingly gained attention though there is little information about the medicinal plants used for managing DM in Uganda (Uwimbabazi et al., 2023). According to several ethnobotanical surveys conducted in Uganda, various medicinal plants are used in DM management. Meanwhile, ethnopharmacological studies have confirmed the anti-diabetic efficacy (Mguni et al., 2023; Uwimbabazi et al., 2023) of various plants and plant-derived formulations from Uganda. However, this information remains highly fragmented without a single repository for plants used in the management and treatment of DM in Uganda, hindering further investigations (Gang et al., 2023)

Traditional medicine has shown importance in preventing deaths from snake bites across the African continent. Traditional medicine practitioners (TMPs) have been treating snakebites in Uganda for long despite the fact that few studies have been conducted to document such vital and rich indigenous traditional knowledge before it is lost (Okot et al., 2020).

Also, they (MPs) have been of importance during the antenatal stage in pregnancy to manage different ailments in Africa. In Uganda, both medicinal and food plants are used to handle common pregnancy related conditions (Nalumansi et al., 2017). Also, the plants have been used to address injuries from burns, bruises and other damages encountered on the skin. Some of these medicinal plant extracts are fast in wound healing and hence prevent entry of other pathogens into the body. For example, the leaf of M. Senegalensis is placed on open wounds. Plant medicines have been used in addressing effects of some allergies, skin rushes and fungal infections of the skin, some are used for deworming, to combat tooth decay (Choudhury Barua et al., 2018; Kutima et al., 2014) itching of the eye, among others. Also, some herbalists have surfaced on drugs that can be used to cause abortions, give man power and others such as looking for marriage partners and other infections related to spiritual aspects.

2.2 Distribution of selected medicinal plants

Uganda has since time in memorial been considered the Pearl of Africa due to its richness in species biodiversity. The ecosystem of Uganda is very rich and it's made up of a variety of organisms; plants and animals. The plant ecosystem in Uganda is made up of various plant species (medicinal and non-medicinal plants). Information from GBIF shows greater diversity of plant species lies in the western and southwestern Uganda. It is highly diverse with montane climate

which compares to that of the Himalayas region (Pramanik et al., 2018). However, of recent this diversity has been affected by many factors; that is, climatic factors, soil factors, elevation gradient, land use and anthropogenic threats. (M. Zhang et al., 2022). Therefore, it tends to reduce in the various areas (Ofcansky, 2018). The climatic factors; temperature and precipitation (Devine et al., 2017) influence the distribution greatly and have been recorded to vary along with altitude/gradient (Ujawska et al., 2018) hence affecting their spatial distribution. Their fluctuations are majorly brought about by human activities. The spatial variations in plant diversity is also affected by elevation or gradient along the slope due to the fact that the amount or intensity of light being received by the plants varies (Tenaw et al., 2024). Also, topographic variability, species competition for nutrients, soil chemistry and texture play a role in the distribution of plants. The spatial distribution of the plant species is directly indicative of the environment in which the species is present (Ujawska et al., 2018). The uniqueness of the plant species is exhibited in different gradient changes due to topography.

Also, distribution of the medicinal plants has been shown to be influenced by the type of soil, soil microorganisms, nutrients and other soil factors. Most especially, soil microorganisms that have shown to participate in the metabolism of matter between plant roots and the soil environment hence affecting growth and distribution. These microbial communities also influence the distribution of the medicinal plants through improving their resistance to various plant stresses. Also, these organisms form symbiotic relationships with the medicinal plants impacting their physiology (Li et al., 2023). They do not only influence the distribution of the medicinal plants but also influences the bioactive components in the plants (L. Chen et al., 2025).

2.3 Threats to the distribution of the selected medicinal plants

Recently many medicinal plants are threatened from both local and global extinction (Mbinile et al., 2020a, 2020b). Reports in the recent years have it that very many plants have gone extinct in the past hundreds of years (Humphreys et al., 2019; Knapp et al., 2020). This extinction is due to both use of the medicinal plants, procedures involving use of their extraction for use and the impacts of various human activities on the habitats of the plants such as deforestation, agriculture, infrastructural developments, and other land uses have led to destruction of plant habitats for the MPs ([(]Tapia-Armijos et al., 2015; Tenaw et al., 2024). Climatic factors whose change has greatly been induced by the various human activities have led to the rise in global temperatures hence loss of habitats by some medicinal plants (Kurpis et al., 2019). Also, soil microorganisms, competition among others been altered by various human activities resulting in altered habitats for the MPs. Also, some MPs exist in small isolated populations that are at a risk of extinction (Id et al., 2023). More threats are arising from introduction of invasive species ([(]Siegert et al., 2014; Medley, 2010; Manzoor et al., 2020) and also increased herbivory (McGraw & Furedi, 2005; Augustine & DeCalesta, 2003; Furedi & McGraw, 2004).

There has been increased recommendation for use of MPs for treatment of various ailments and this has led to the uncontrolled and unsustainable harvesting (J.E. et al., 2011; McElhaney et al.,

2011; Kuhle et al., 2011; Ebeling et al., 2011; W. Chen et al., 2020). This has therefore posed a great challenge to the distribution of the medicinal plants. In addition to that, also the harvesting methods such as uprooting, debarking endangers some species (Mollel et al., 2024). Also, the propagation by seeds has shown to be inefficient because some medicinal plant seeds easily lose viability, others have thick oils within them inhibiting germination or when they undergo certain stages of dormancy (Mbinile et al., 2020b, 2020a). Threats have also been attributed to commercial issues; some countries do trade highly in the medicinal (Souther & Mcgraw, 2014). This left most of the highly valued plant species endangered (Robertson & Pollaro, 2023). Also, distribution of the medicinal plants is non-uniform because some are slow growing and if harvested it may take long to be replaced (regeneration) most especially when the methods used for harvesting are very crude for example debarking and uprooting (Wraith & Pickering, 2018; IUCN, 2020, 2022; Le Breton et al., 2019; Keith et al., 2015; Betts et al., 2020). Also, regeneration time for the different plants takes a lot of time after harvesting, therefore leaving some of the plants endangered.

2.3.1 Environmental variables

Many habitats have the different environmental variables manifesting in place and any alterations in these will render them unable to support survival of the medicinal plants (Koch et al., 2021; Welk et al., 2019). As a result, some medicinal plants are deemed to become extinct due to lack of proper habitats or some are out competed in their habitats. Some plant species will have to migrate from their habitats to new ones, as a result, may lead to expansion of their habitats (Monteiro et al., 2023). Some plant species will have to elevate to higher altitudes with favorable environmental variables thus will lead to an increase in competitive pressure (Shackleton et al., 2017; Harper et al., 2007; Pramanik et al., 2018). Climate change may result in some changes in certain plant species undergoing changes in some phenotypic characteristics so as to adapt to the existing condition. As a result, beneficial associations of these plants with other organisms such as insect pollinators will be affected resulting in poor productivity. Also, climate changes most especially warmer environments can lead to emergence of damaging insects and also some fungal pathogens that have a detrimental effect on the survival of plant species.

The distribution of the medicinal plants is highly affected by both temperature and drought stress. Some plants are very sensitive to rapid changes in temperature and water stress, therefore tend to dominate the moderate conditions and when extremes arise, they tend to deteriorate in the population and distribution. Some species are resistant and are able to survive such harsh conditions and tend to remain evenly distributed within their habitat. This reduced distribution and also biomass results in increased unsustainable levels of harvesting thus leading to extinction of some plant species and also a great impact to the economy will arise due to less that will be exported. Intense temperatures and droughts can impair the growth and reproductive success of the selected medicinal plants most especially those that are less adapted to the conditions. The changes in temperature and drought stress have not shown consistent results when testing for the concentrations of the active metabolites. Depending on the plant species, the concentration of the active metabolites might increase with increase in drought but reduce when an increase in

temperature occurs or vice versa. Elevated temperatures majorly tend to lower the phytochemical composition of the plants as well as content of other compounds such as oils.

Drought stress that is not severe to kill plants will result in the elevation of the concentration of bioactive compounds. This has been manifested through reduction in the biomass of the plants or actual increase in the concentration of the bioactive compounds. Drought stress has shown to increase the concentration of the bioactive compounds in various plant species with standing evidence given on phenolic compounds, essential oils and terpenes, alkaloids and glucosinolates (Applequist et al., 2020). Therefore, the possibility that the increase in drought will increase the phytochemical composition of the medicinal plants is high in selected regions. Increase in temperature has shown to counteract the effect of drought stress in the concentration or phytochemistry of the MPs. However, temperature has shown inconsistency in a way that it can either decrease or increase the phytochemical composition of the MPs.

Also, climate changes resulting from land use changes such as farming, mining and physical developments that alter richness in biodiversity of the areas. As a result, the plant species tend to be randomly distributed. Also, these land use activities alter the soil physiochemical properties such as pH, soil texture, moisture among others also affect the distribution of the plants (Appau et al., 2024). Other activities such as bush burning, deforestation can lead to destruction of the medicinal plants hence leading to their distribution.

Given the fact that most medicinal plants are slow-growing and habitat selective (Applequist et al., 2020), they will also be affected by changes in climate. Spatial distribution models by MaxEnt of recent have shown that some species will end up losing the existing habitats and later gain some other habitats (Pramanik et al., 2018; Sciences, 2022; S. Yang & Mountrakis, 2017). This will leave the human population disadvantaged by limited access for the medicinal plants and hence increased disease pressure. High altitude growing plant species face higher risk of extinction since most of the pressure pushes low land species to occupy highlands with seemingly favorable environmental conditions. The migration of the plant species is more likely to occur towards higher altitudes than towards low lands simply due to the steeper spatial gradient of temperature change (Applequist et al., 2020). Reports have it that changes in the environmental variables will endanger the plants due to pathogens for example mycotoxins.

2.4 Decreased availability and extinction of medicinal plants

The decrease in the availability and hence extinction of MPs across the globe is attributed to many factors that include the anthropogenic (Tapia-Armijos et al., 2015; Mbinile et al., 2020a, 2020b) and the non-anthropogenic effects. Also, human medicine is greatly linked to medicinal plants since most of the medicinal supplements are obtained from them (Mguni et al., 2023). The global rate of extinction of medicinal plants of recent is very high due to the increased use of the medicinal plants. This has been so because the medicinal plants are readily available, widely accepted by many cultures and some perceive it to be safe and having a high efficacy (Ssenku et al., 2022; Mguni et al., 2023). Therefore, the increased demand for herbal medicines in the

developed and the developing countries as well other factors such as climatic changes are contributing to their extinction (Tapia-Armijos et al., 2015; Mbinile et al., 2020a, 2020b; Ssenku et al., 2022).

In Uganda, the use of herbal medicine has been estimated to be at >50% (Ssenku et al., 2022) with high consumption rate being associated with rural areas (Mukasa et al., 2023). This high consumption rate is accounted for by the fact that some rural areas have limited access to health facilities (Ssenku et al., 2022; Mguni et al., 2023). Sometimes the medical supplies are inadequate or costly, also there are few available medical practitioners who are poorly motivated (Mukasa et al., 2023; Mguni et al., 2023). Also, due to the wide acceptance that herbal medicines have minimal side effects compared to conventional drugs, their consumption has gone high (Mukasa et al., 2023; Mguni et al., 2023). Most of the field studies have reported that most of the methods for collecting the herbal medicines are destructive (Ssenku et al., 2022; Dokata et al., 2023). For example, uprooting and debarking endanger their survival or regeneration (Mollel et al., 2024). This has been brought about by the increasing proliferation of unregulated herbal medicine trade in urban centers (Mukasa et al., 2023; Ssenku et al., 2022; Mollel et al., 2024). The indiscriminate collection and overharvesting of medicinal plant species for commercial purposes threatens the conservation of plant diversity (Abuto et al., 2018).

Recently, Uganda is among the countries that are facing the greatest risk of future extinction of medicinal plants. Unfortunately, this coincided with Uganda's efforts towards upscaling herbal medicine use and its prospective integration into the main health care system. For example, Butaleja, a remote district in eastern Uganda with relatively poor infrastructure and service delivery has few pharmacies, licensed private drug shops, and affordable private clinics and this leaves the locals only able to use medicinal plants for disease treatment and health promotion.

2.5 Changes in plant quality and phytochemistry

In situations that arise when some plants can resist the changing of their habitats due to change in climatic conditions, the distribution of the plant species may not be affected but it may alter the composition of the medicinal plant. This may result in a change in the pharmacological properties of the medicinal plants hence the goal for utilization of the medicinal plants which is to derive health benefits is not realized (Applequist et al., 2020). If the composition of the medicinal plants changes in a detrimental way, the populations consuming the drugs will suffer and this will be rampant in less wealthy populations that are unable to perform chemical testing for the identity of the changes. Also, some plants may be abandoned due to decrease in their potency leading to misinterpretation by consumers as lacking efficacy. The plant phytochemistry has shown to be affected by majorly three factors; temperature, water stress and carbon dioxide concentration which counteract each other's effect. For example, in conditions where water stress causes an increase in phytochemical composition, increased temperature and carbon dioxide concentration have shown to decrease it. Therefore, this phytochemical composition has not shown to be easily predictable as the plants are affected differently by the variables. Also, as a result of the increased

emission scenario, there will be increased accumulation of the greenhouse gases. This will both lead to rise in temperature and also carbon dioxide concentration resulting in phytochemical composition change.

2.6 Models for spatial distribution

The spatial distribution of the selected medicinal plants can be modeled using various species distribution models (SDMs) (Bedane et al., 2023) such as the Maximum Entropy (MaxEnt) distribution, Bioclim, GAM, GLM and GARP among which, MaxEnt model shows optimum performance in terms of overall software utility and has been widely used since its development. The other variables are very efficient in modelling the distribution of the plant species with respect to only few environmental variables (Bedane et al., 2023). MaxEnt supersedes them (Cobos et al., 2019) due to its need for only environmental information and species occurrence data, and it will predict distribution of the medicinal plants for the changes in various environmental variables. Also, it can generate complex feedback to the used data and also its inherent features prevent model overfitting (Pramanik et al., 2018). It has been used to predict the potential distribution areas of rare and endangered medicinal and economic plants across the globe and also assess their extinction risk. It can also be used to predict the potential planting areas of various plant species under different climatic scenarios (Wu et al., 2019), predict suitability of given environments (Pramanik et al., 2018) and also describe the environmental necessities (Pramanik et al., 2018).

The data of selected medicinal plant species' natural distribution points and filtered climate factors are then imported into MaxEnt software. Q and P features are selected in the element-type part while the sub sample is chosen in the replicated run-type part. The modeling is then repeated several times and its RM value recorded. A test set made up of 30% of the distribution data is chosen while the 70% is left to serve as the training set. The maximum iteration is set at particular number of times to ensure sufficient time for the model to achieve convenience. After modeling with MaxEnt v3.4.1, the jackknife method is then used to test the weight with basis on the percent contribution of the selected climate factors (Pramanik et al., 2018). The receiver operating characteristic (ROC) curve is then plotted and the accuracy of the results evaluated using the area under curve (AUC) as the basis since it is not influenced by over fitting, and training over fitting data does not necessarily improve the fitting of independent test data (Warren & Seifert, 2011). The AUC values are then interpreted using the criteria such that < 0.6 means failure, 0.6-0.7 indicates poor prediction accuracy, 0.7-0.8 indicates fair prediction accuracy, 0.8-0.9 implies good prediction accuracy and 0.9-1.0 indicates excellent prediction accuracy (Pramanik et al., 2018).

2.7 Predicting potential habitats for the plants

Basing on the modelling results, Arcgis10.2 is used to visualize the prediction map of potential distribution regions in 1970-2000, 2050s and 2090s and the area of suitable distribution regions can be calculated. The accuracy of the distribution predictions can be tested for accuracy basing on the "sensitivity-specificity difference minimizer" and "sensitivity-specificity sum maximizer" criteria. During this study, the maximum training sensitivity plus specificity threshold

generated by MaxEnt are selected as the threshold to determine whether a region is suitable for the selected medicinal plants or not. Basing on research, the threshold given by MaxEnt is 0.1227 and is used to classify the potential distribution regions using criteria below. For values less than 0.1227, the region is classified as unsuitable, between 0.1227 to 0.4151 as a lowly suitable region, between 0.4151 to 0.7076 as a moderately suitable region and finally greater than 0.7076 is classified as highly suitable region

2.8 Conservation strategies

Plant biodiversity serves a great purpose and therefore need for proper quantification and documentation in relation to abiotic variables of the environment. Also, there needs to be accurate species modelling to predict potential habitats, their suitability and the distribution of the plants within them. Also, phytochemical composition studies are necessary to ensure no changes occur when ex-situ conservation is opted for. Several techniques are being used to assess the conservation status of species and prioritize conservation planning. Some of the techniques used are propagation through air layering, planting of seeds and use of lateral roots through application of rootex. For there to be apt conservation of the plant species, need to delve into discovery and comprehension of the linkages between plant species and environmental relationships is so significant (Tang et al., 2020). Also, there is need to understand the distribution patterns and diversity along altitudinal gradient. Conservation seems hard simply because some methods seem ineffective; for example, some seeds lose viability within a short time, others have hard seed coats while others have oil within the seed coats thus impeding germination. In some situations, the plants can sprout but with altered phytochemistry and thus inefficiency of the medicinal components. However, accurate study of soil factors, environmental factors and anthropogenic threats will enable proper conservation of the medicinal plants without altering their phytochemistry. This is mostly important for species that are native to particular environments and soils such that when mimicking their new environment for preservation and conservation will be appropriate. Also, for proper conservation of the MPs, there should be accurate study on the diversity of the phytochemical components of the plants (Abuto et al., 2018).

CHAPTER THREE MATERIALS AND METHODS

3.1 Description of the study area

The data was collected from several districts in Eastern and North Eastern Uganda. The regions respectively receive an annual rainfall of 1000 to 1600mm and less than 700mm per annum and their temperature respectively varies between 22 to 23ºC and 24 to over 30ºC. the regions cover an area of about 39,478.8km^2 and 27,528km^2 respectively. Most of its area is covered by grass land vegetation and having simple shrubs and small trees scattered within. The entire land is relatively flat and fertile for agriculture and having the major vegetation types as grassland, followed by wood vegetation, then bush lands and finally bushed grasslands. The area is greatly utilized by grazing ungulates such as herds of cattle of the local people.

3.2 Sampling design

A preliminary survey was conducted from 18th to 23rd December 2025 to trace the identity of the land use types present at areas for data collection. With the help of a topographic map of the study area, data from the global biodiversity information facility (GBIF), Makerere herbarium, published literature and also local knowledge of the site about occurrence and distribution of the selected medicinal in the different localities, we employed purposive sampling technique using data from GBIF, MUH and other published articles. Snow ball sampling was also used to reach other areas that preceding interviewees would inform about. The identified areas were sampled for the data needed. Survey routes (the pathways); that permitted or enabled access to different survey sites were used to observe the distribution of the selected medicinal plants in the area. An assessment of the environmental variables (temperature, precipitation, soil factors and others) was conducted, number of selected medicinal plants and also recording of coordinates of sampling plots where the selected medicinal plants were present or absent to attain distribution data. A hand-held global position system (GPS) was used to locate the coordinates of the sites for the plants' presence or absence data and also a self-made data collection sheet will be used to record the environmental variables. The collected data points were used to make predictions in MaxEnt software for 2040s and 2060s

3.3 Species distribution and data point

The data on the natural distribution points of the selected medicinal plants was collected in December, 2025 and January 2026 by visiting the Global Biodiversity Information Facility (GBIF), Makerere University Herbarium (MUH), published literature and also local knowledge of the site about occurrence and distribution of the selected MPs in the different localities. The total number of the distribution points obtained were recorded. ArcGIS was used to screen redundant data so as to avoid geographic autocorrelation of the distribution correlations and this will finally ensure acquisition of the natural distribution points of the selected medicinal plants.

3.4 Environmental variables

In this research five environmental variables of temperature related to the 19 global climatic factors with a geographic resolution of (current, 2040s and 2060s) was obtained in June 2026 by visiting the World Climate Data Website (www.worldclim.org). According to Pramanik et al (2018) Two circulation models (BCC-CSM2-MR and MRI-ESM2-0 IN CMIP6) were selected and in which three shared socioeconomic paths (sustainable path; SSP126, middle path; SSP245, and fossil fuel-based development path; SSP585) were chosen to increase the reliability of climate data. On the basis of the distribution areas of the selected medicinal plants, Rv3.6.2 software will be employed to cut the climate data and convert it to the ".asc" format. The data of the 19 climatic parameters at each location will be extracted using the "Extract Multi Values to Points" feature of the Arcgis 10.2 program. The Pearson correlation coefficient matrix between the corresponding climate factors at each point will be calculated using the R v3.6.2 to determine their significant correlation with the threshold. The data on effective natural distribution will be screened and the 19 climate factors between 1970 and 2000 will be imported into MaxEnt3.4.1 for a four-time operation. The results will be analyzed by comparing the percent contribution and the Jackknife values; climate factors with a contribution rate of less than 0.5 will be deleted. The relatively most important one of the two significant correlation factors will be retained and this will result in 5 climate factors from 19 climate for modeling.

3.5 Data collection

There will be conduction of an assessment of the environmental variables (temperature, precipitation, soil factors, elevation gradient and land use), number of selected medicinal plants and also recording of coordinates of sampling points where the selected MPs will be present or absent to attain distribution data. A hand-held global position system (GPS) will be used to locate the coordinates of the sites for the plants' presence or absence data and also a self-made data collection sheet will be used to record the environmental variables. The mean annual climatic data of the study area will be obtained from the weather centers.

3.6 Data analysis

The spatial distribution data of the selected medicinal plants will be analyzed using Arc GIS (Arc Map version 10.6) to produce a distribution map. The selected medicinal plants' GPS coordinates will be recorded during data collection and the patterns across the entire study area will be compiled and thereafter will be converted to shapefile (.SHP) format. The kernel density tool within the ArcMap version 10.6 with a search radius of $1km^2$ area will be used to calculate the density and extent of distribution of the selected medicinal plants across the entire landscape. This tool creates a continuous surface with a specified radius distance in which only georeferenced coordinates points of the species falling within the neighborhood of the search radius will be considered in calculating density. The kernel tool will calculate density units using the linear unit of the projection of the output spatial reference.

3.7 Model building

When carrying out species distribution models (SDMs) of rare samples, there can arise an imperfect match between the environmental variables and the occurrence data hence causing difficulties in model evaluation and thus model overfitting (Xu et al., 2022). However, MaxEnt has proven to be the most reliable SDM as compared to others in case of small sample simulations for example some studies have shown 15 as the minimum number of occurrence points for ecological niche modelling.

The Keum package in Rv3.6.1 was used to provide the judgement standard of the optimal model. Specifically, combinations of element types were considered and regularization multipliers (RM) were set at an interval to form parameter combinations. The parameter combinations were evaluated and modelled. The optimum model for modeling was selected using a criterion like; (1) significance and omission rate ($E < 0.05$); and (2) model complexity AICc (delta <=2) (Cobos et al., 2019). As a result, two element types will be shifted out and RM will be noted.

The data of selected medicinal plant species' natural distribution points and filtered climate factors was imported into MaxEnt software. Q and P features were selected in the element-type part while the sub sample in the in the replicated run-type part. The modeling was repeated times and its RM recorded. A test set made up of 30% of the distribution data will be chosen while the 70% will be left to serve as the training set. The maximum iteration was set at to ensure sufficient time for the model to achieve convenience. After modeling with MaxEnt v3.4.1, the jackknife method was used to test the weight with basis on the percent contribution of the selected climate factors. The receiver operating characteristic (ROC) curve will be plotted and the accuracy of the results will be evaluated using the area under curve (AUC) as the basis since it is not influenced by over fitting, and training over fitting data does not necessarily improve the fitting of independent test data (Warren & Seifert, 2011).

CHAPTER FOUR PREDICTED FUTURE HABITAT SUITABILITY RESULTS

4.1 Overview of the modelling approach

This chapter presents the results of the species distribution modelling component of the study, in which Maximum Entropy (MaxEnt) modelling was used to generate current and future habitat suitability projections for nine medicinal plant species across Eastern Uganda. The underlying occurrence dataset 487 combined field and secondary records and the field-based habitat and elevation associations that motivate the modelling exercise are documented in full in the companion volume of this study, *Current Distribution and Habitat Associations of Selected Medicinal Plant Species in Eastern Uganda*, and are referenced here only where necessary to interpret the model outputs.

MaxEnt modelling was applied to each target species using the compiled occurrence records as input, combined with five environmental predictor layers: mean annual temperature (BIO1), annual precipitation (BIO12), precipitation seasonality (BIO15), topographic elevation (DEM), and land use/cover (LULC) derived from the ESA Climate Change Initiative Land Cover dataset. The ENMeval package in R was used to optimise feature class combinations and regularisation multiplier (RM) values, with model selection based on the Akaike Information Criterion corrected for small sample sizes (AICc). This approach to species distribution model configuration follows established protocols for low-sample-size scenarios (Warren & Seifert, 2011; Muscarella et al., 2014).

Model performance was evaluated using the Area Under the Receiver Operating Characteristic Curve (AUC), with AUC values ≥ 0.70 considered acceptable, ≥ 0.80 considered good, and ≥ 0.90 considered excellent model discrimination. Jackknife variable importance tests were conducted to identify the environmental variables contributing most significantly to each species' modelled distribution (Phillips et al., 2006). Two projection horizons were generated for each species 2040 and 2060 in addition to a current-conditions baseline, allowing direct comparison of present-day and future suitability surfaces under a common five-class suitability scale (very low, low, moderate, high, very high).

4.2 Current habitat suitability baseline

Current MaxEnt suitability surfaces were generated for all nine focal species and are mapped in Figures 4.1–4.9 below. This current-conditions baseline serves two purposes in this chapter: first, it is a check on model plausibility, since a credible baseline surface should broadly agree with the field and secondary occurrence patterns documented in the companion volume; second, and more importantly for the predictive aims of this study, it is the fixed reference point against which the 2040 and 2060 projections in section 4.3 are measured, so that genuine projected change can be distinguished from features that were already present under current conditions.

Two broad spatial groupings emerge from the current-conditions baseline. The first comprises species whose currently suitable habitat (moderate to very high suitability) is tightly confined to the southern and south-western margins of the study region principally the Albertine Rift landscapes around Lake Edward/Lake Albert and the Lake Victoria shoreline in the south-east while the entire northern, central, and eastern extent of the country is classified as very low suitability. *Warburgia ugandensis* and *Croton macrostachyus* both display this restricted pattern, consistent with the very small number of field and secondary occurrence records available for these species and with their documented association with highland and lakeshore forest margins.

The second grouping consists of species with broad current suitability across central and southern Uganda. *Kigelia africana*, *Rhoicissus tridentata*, *Albizia coriaria*, and *Gymnosporia senegalensis* (previously treated in this study as *Maytenus senegalensis*) all show moderate-to-high suitability across large parts of central, eastern, and southern Uganda, with only the far northern Karamoja sub-region remaining consistently unsuitable. *Zanthoxylum chalybeum* shows a distinct suitability core centred on the Lake Kyoga basin and the Mbale–Teso corridor in East-central Uganda, matching the bimodal elevation pattern documented for this species in the companion volume. *Mondia whitei* shows the inverse pattern, with high suitability concentrated in the north-west (West Nile margin and Albertine lowlands) and low suitability across most of eastern Uganda. *Tephrosia linearis* currently shows a comparatively even, moderate suitability across most of the country, with locally elevated suitability restricted to the extreme south-western and south-eastern corners. Across all nine species, elevation, mean annual temperature, and land use/cover were consistently identified among the top predictors a result that independently corroborates the field-based habitat and elevation associations reported in the companion volume, despite the two analyses drawing on largely separate lines of evidence (raw occurrence tabulation versus a fitted statistical model).

4.3 Projected future habitat suitability (2040 and 2060)

Future habitat suitability was projected for two-time horizons, 2040 and 2060, using the fitted MaxEnt models under projected changes in temperature, precipitation, and precipitation seasonality (Figures 4.1–4.9). Rather than a single uniform trajectory, the projections reveal three distinct patterns of change across the nine species, described in turn below.

The first and most common pattern, shown by *Warburgia ugandensis*, *Croton macrostachyus*, *Kigelia africana*, *Albizia coriaria*, *Rhoicissus tridentata*, *Zanthoxylum chalybeum*, *Gymnosporia senegalensis*, and *Mondia whitei*, is broad spatial stability: the overall geographic footprint of suitable and unsuitable habitat in 2040 and 2060 closely mirrors the current distribution, with only modest local intensification (a small increase in the extent of the "very high" suitability class within already-suitable areas) rather than large-scale range shift. For the two most spatially restricted species, *Warburgia ugandensis* and *Croton macrostachyus*, this stability is of particular concern: their suitable habitat neither expands nor relocates elsewhere in the country by 2060, meaning these species have no projected refugia beyond their current narrow southern range a pattern consistent with elevated extinction risk under continued habitat loss or disturbance within

that limited range. In other words, for these two species the projection changes the nature of the conservation problem rather than its urgency: the risk is not a coming wave of climate-driven habitat loss so much as the permanent absence of any climatic escape route from a range that is already small.

The second and most striking pattern is shown by *Tephrosia linearis*, which departs markedly from its currently even, moderate distribution. By 2040 the eastern half of the country shows a modest loss of suitability, and by 2060 this develops into a pronounced and spatially fragmented mosaic in north-eastern Uganda (the Karamoja–Teso corridor), combining large patches of very high suitability directly adjacent to patches of very low suitability. This fine-grained heterogeneity, rather than a smooth directional shift, suggests that *Tephrosia linearis* is disproportionately sensitive to the projected climatic changes and that its future distribution carries greater uncertainty than that of the other focal species. This finding, made possible only by comparing the current, 2040, and 2060 suitability surfaces directly, was not evident from the field and elevation data alone and represents a genuinely novel result of the spatial modelling component of this study one with direct bearing on conservation prioritisation, since *Tephrosia linearis* would not have been flagged as a species of particular concern on the basis of its current field-occurrence profile alone.

The third pattern, implicit in the comparison between the first two, is that projected vulnerability under this modelling framework is not simply proportional to current rarity. *Warburgia ugandensis* is rare today and remains rare and static in the projections; *Tephrosia linearis* is moderately common today but is the one species whose spatial configuration is projected to change substantially. This distinction matters for how the projections in this chapter should be used: a species' current occurrence count, on its own, is an unreliable guide to which species most need forward-looking climate-adaptation attention.

4.3.1 Spatial patterns of current, 2040, and 2060 habitat suitability

Figures 4.1–4.9 present the MaxEnt-modelled habitat suitability surfaces for each of the nine focal species under current climatic conditions and under the 2040 and 2060 projections, using a common five-class suitability scale of very low, low, moderate, high, and very high. These maps form the spatial basis for the current-baseline and projected-future suitability findings discussed in sections 4.2 and 4.3 above, and each map should be read as a single time-series triptych current, 2040, 2060 for one species, rather than as three unrelated panels.

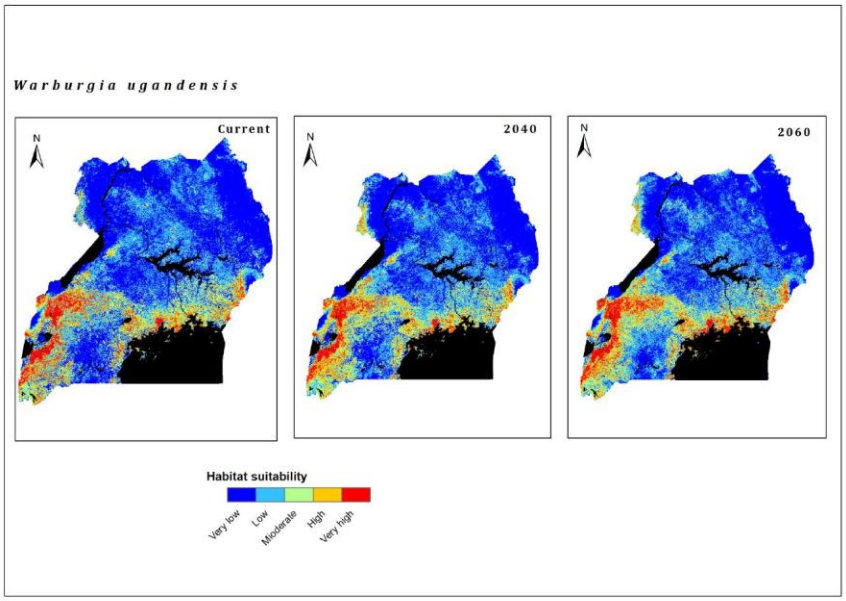

Figure 4.1: MaxEnt habitat suitability for Warburgia ugandensis under current, 2040 and 2060 conditions.

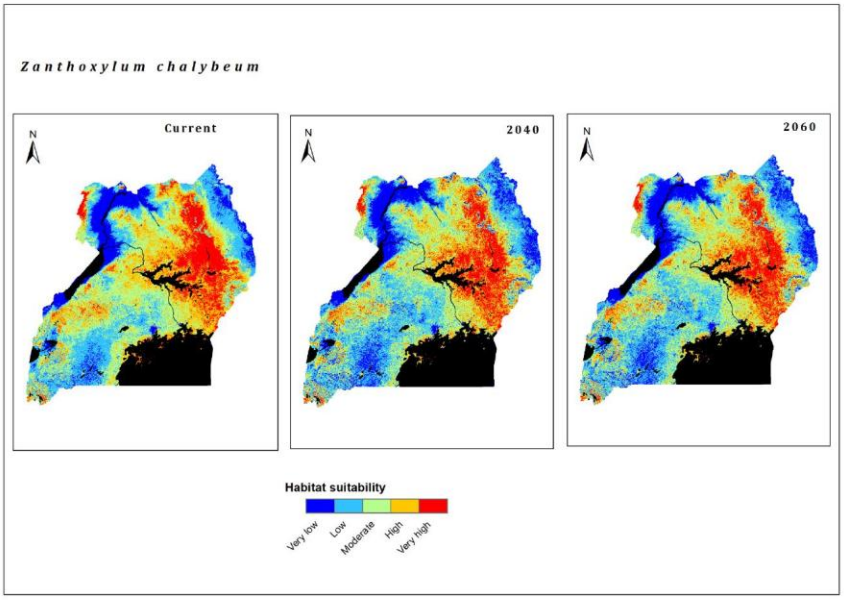

Figure 4.2: MaxEnt habitat suitability for Zanthoxylum chalybeum under current, 2040 and 2060 conditions.

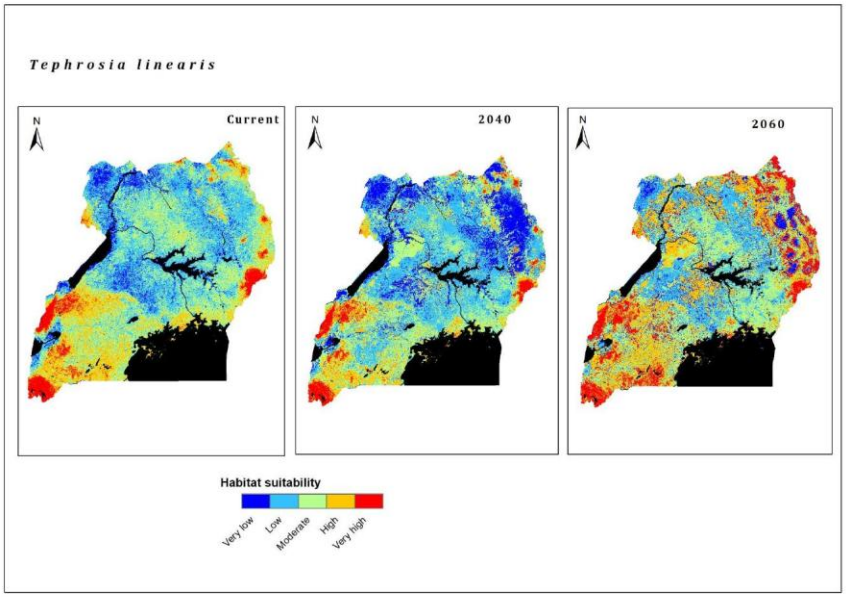

Figure 4.3: MaxEnt habitat suitability for Tephrosia linearis under current, 2040 and 2060 conditions.

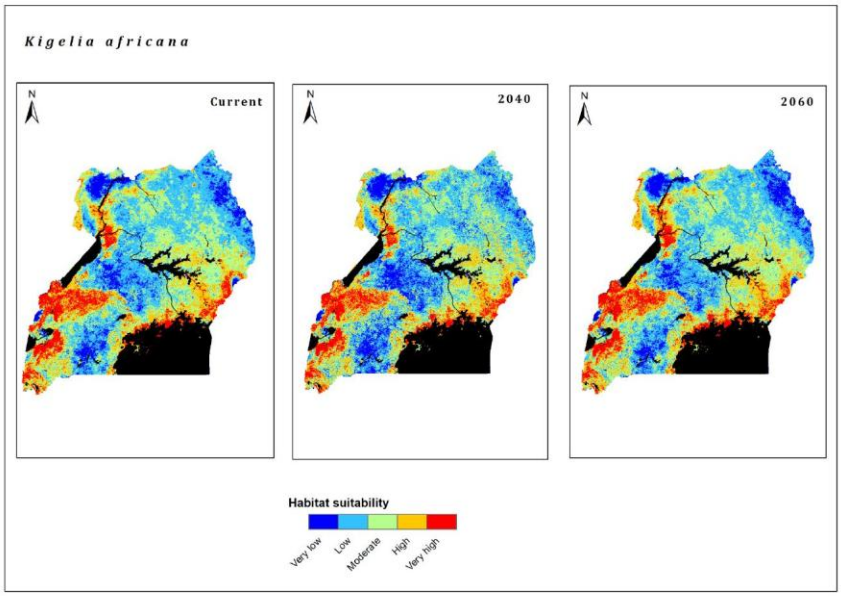

Figure 4.4: MaxEnt habitat suitability for Kigelia africana under current, 2040 and 2060 conditions.

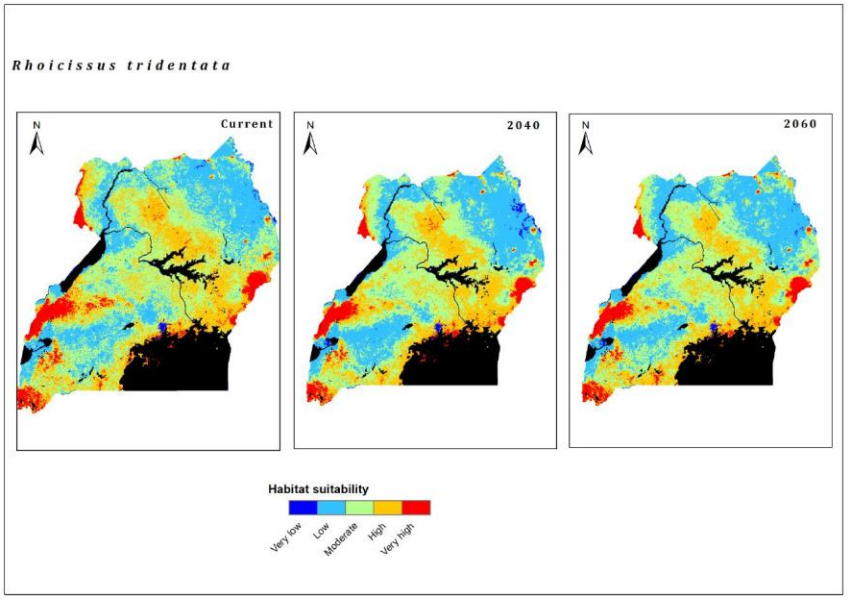

Figure 4.5: MaxEnt habitat suitability for Rhoicissus tridentata under current, 2040 and 2060 conditions.

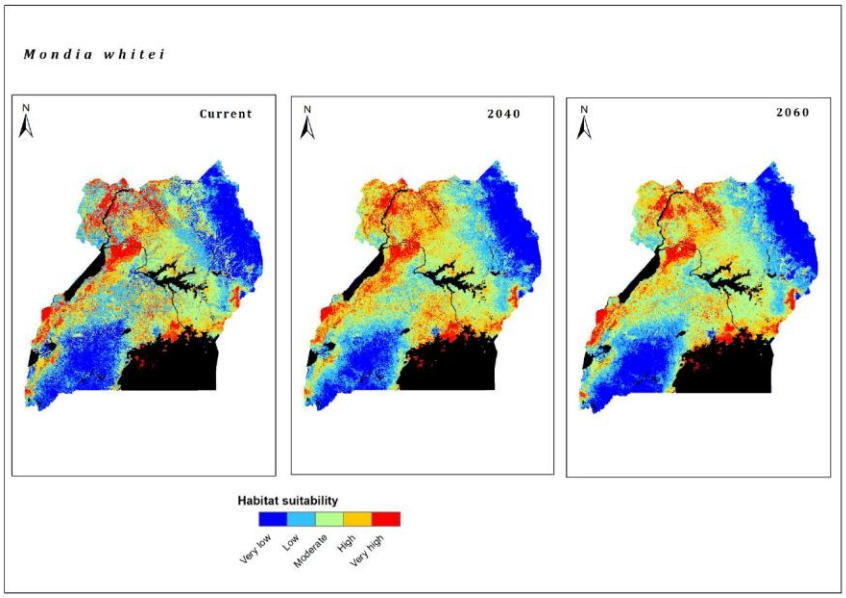

Figure 4.6: MaxEnt habitat suitability for Mondia whitei under current, 2040 and 2060 conditions.

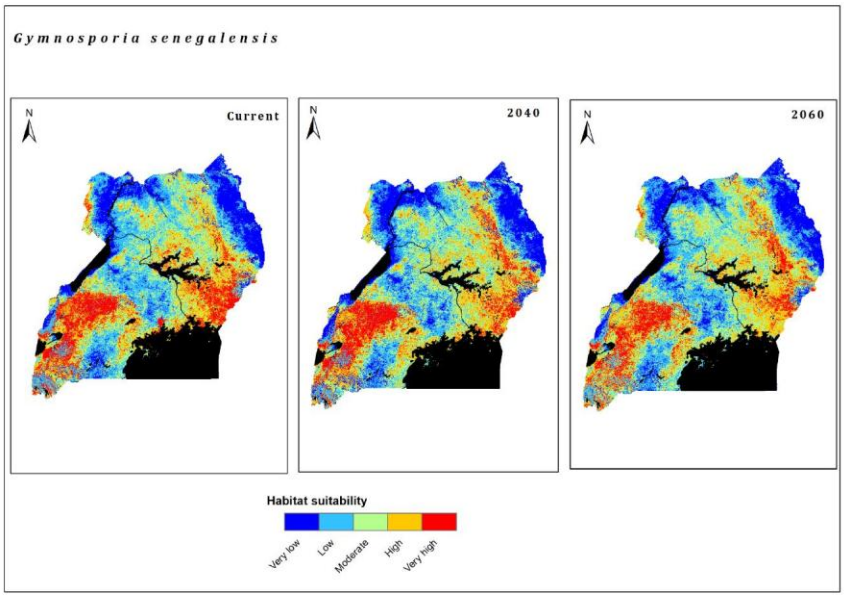

Figure 4.7: MaxEnt habitat suitability for Gymnosporia senegalensis under current, 2040 and 2060 conditions.

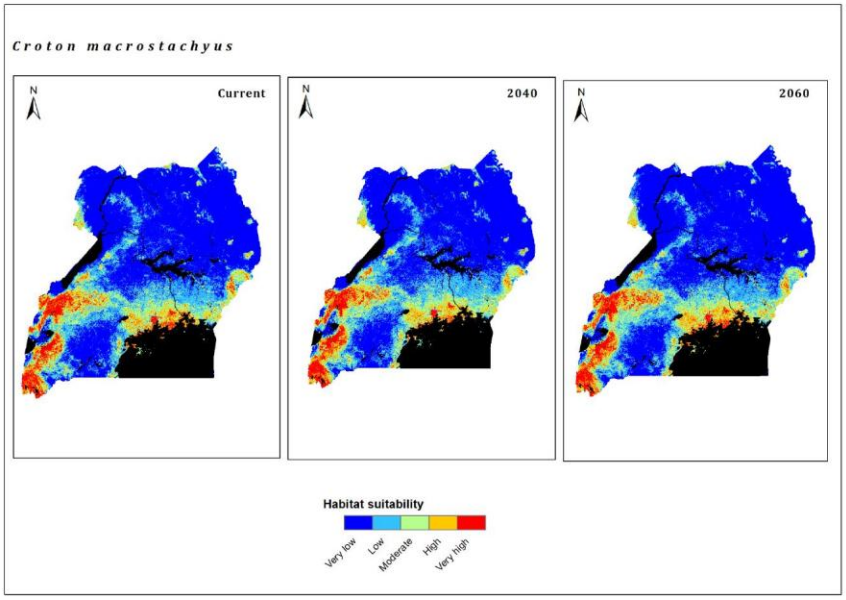

Figure 4.8: MaxEnt habitat suitability for Croton macrostachyus under current, 2040 and 2060 conditions.

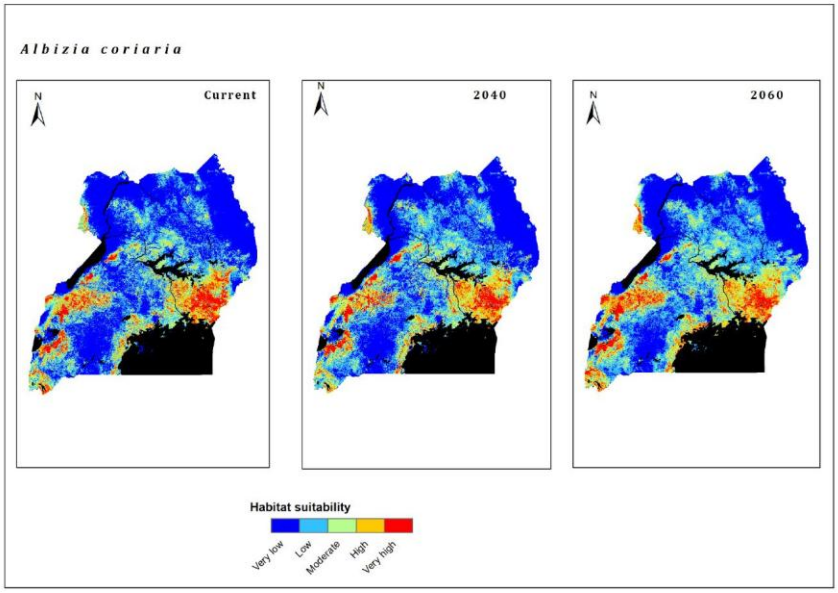

Figure 4.9: MaxEnt habitat suitability for Albizia coriaria under current, 2040 and 2060 conditions.

4.4 Summary of predicted future distribution findings

The MaxEnt current-to-2060 comparisons reported in this chapter show that seven of the nine species *Kigelia africana*, *Rhoicissus tridentata*, *Albizia coriaria*, *Zanthoxylum chalybeum*, *Gymnosporia senegalensis*, *Mondia whitei*, *Warburgia ugandensis*, and *Croton macrostachyus* (eight are named here because *Warburgia ugandensis* and *Croton macrostachyus* together make up two of the nine "stable" species alongside the other five) showed broadly stable suitability surfaces through 2040 and 2060. This stability is reassuring for the widely distributed generalists among them (*Kigelia africana*, *Albizia coriaria*, *Rhoicissus tridentata*), whose already-large suitable range is projected to persist largely unchanged. It is a source of continued concern rather than reassurance for *Warburgia ugandensis* and *Croton macrostachyus*, whose current suitable habitat is already confined to narrow southern refugia with no projected expansion elsewhere in the country under either the 2040 or 2060 horizon.

Tephrosia linearis is the only species projected to undergo substantial spatial reconfiguration, developing a fragmented mosaic of very-high and very-low suitability in north-eastern Uganda by 2060. Narrowly distributed, low-elevation species with fixed southern refugia *Warburgia*

ugandensis and *Croton macrostachyus* remain the species of greatest long-term conservation concern on the basis of these projections, since their suitable habitat does not expand elsewhere in the country even under the 2060 projection, while *Tephrosia linearis* represents a distinct and separately important concern: a currently moderate-abundance species whose future spatial configuration is genuinely uncertain.

CHAPTER FIVE DISCUSSION, CONCLUSIONS, AND RECOMMENDATIONS

5.1 Discussion

This chapter discusses the predictive-modelling findings presented in Chapter Four in the context of existing literature on climate change impacts on plant biodiversity, species distribution modelling, and conservation planning. The discussion addresses the study's fourth specific objective predicting the potential habitat suitability for future distribution of the selected medicinal plants under projected changes in environmental variables building on the current-distribution baseline established in the companion volume of this study.

5.1.1 Elevation as a proxy for climatic vulnerability

The strong interspecific differentiation in elevational niche breadth documented from the field dataset most especially the very narrow elevation standard deviation of *Maytenus senegalensis* (27.6 m) compared to the broad ranges of *Kigelia africana* (392.7 m) and *Zanthoxylum chalybeum* (406.7 m) has direct and quantifiable implications for climate change vulnerability assessment. Species with narrow, low-elevation niches are less able to buffer against temperature increases through upslope movement and are therefore theoretically at higher risk of range contraction and local extinction as warming proceeds (Thomas et al., 2004; Colwell et al., 2008; Raxworthy et al., 2008). The MaxEnt projections in Chapter Four allow this theoretical expectation to be tested directly against modelled outcomes, rather than left as an inference from elevation data alone.

Global temperatures have already risen by approximately 0.6°C and are projected to increase further by mid-century (Xu et al., 2022), with disproportionately large warming predicted for interior East Africa relative to coastal zones. The current-to-2060 MaxEnt comparisons presented in Chapter Four show that this warming does not translate into a uniform habitat-loss signal across the nine focal species. Instead, seven species including *Warburgia ugandensis* and *Croton macrostachyus*, the two species with the narrowest, lowest-elevation current ranges show projected suitability surfaces that remain geographically static through 2040 and 2060, neither expanding into new territory nor shifting toward higher elevations. For these species the concern is therefore less one of large-scale habitat loss and more one of persistent, fixed spatial restriction: their entire projected suitable range in 2060 is no larger than, and occupies the same footprint as, their current range, leaving no climatic refugium elsewhere in the study area should their existing southern strongholds be degraded by land conversion or overharvesting. This is an important refinement of the simple "narrow niche equals high vulnerability" heuristic: the modelling shows that for narrow-niche species in this dataset, the projected risk manifests as an absence of future escape routes rather than as a shrinking of the current range itself.

The finding that *Kigelia africana* retains a stable, wide suitability surface through to 2060 reflects its thermal generalism and broad habitat tolerance, consistent with the elevation and land-use breadth documented from the field data in the companion volume. A similar stability characterises *Rhoicissus tridentata*, *Albizia coriaria*, *Zanthoxylum chalybeum*, *Gymnosporia senegalensis*, and

Mondia whitei. The clear exception is *Tephrosia linearis*, whose currently even, moderate distribution is projected to fragment into a mosaic of very-high and very-low suitability across north-eastern Uganda by 2060 (Figure 4.3). Because this species is not currently a conservation priority based on field abundance alone, this spatial-modelling result highlights the practical value of projecting habitat suitability forward in time, rather than relying on current distribution patterns as a sole proxy for future vulnerability a species can be common today and still be a priority for forward-looking monitoring.

The implications of these projections extend beyond the ecological domain. If *Maytenus senegalensis* used widely for its antimalarial, anti-inflammatory, and antifungal properties loses significant habitat by the 2050s, communities in Eastern Uganda who depend on it as a primary healthcare resource will face increasing scarcity. This risk is compounded by the inability of poorer communities to substitute plant-based remedies with pharmaceutical alternatives, owing to cost and access barriers that are well documented across sub-Saharan Africa (Appau et al., 2024; Mollel et al., 2024; Mguni et al., 2023). The projections in this chapter therefore carry weight beyond conservation biology narrowly defined: they are also, in effect, an early-warning signal for future rural healthcare access in the study area.

5.2 Conclusions

This study has generated habitat suitability projections for nine selected medicinal plant species in Eastern Uganda under future climate change scenarios using MaxEnt modelling. The following principal conclusions are drawn from the current-to-2060 modelling comparisons:

MaxEnt current-to-2060 projections show that most focal species *Kigelia africana*, *Rhoicissus tridentata*, *Albizia coriaria*, *Zanthoxylum chalybeum*, *Gymnosporia senegalensis*, *Mondia whitei*, *Warburgia ugandensis*, and *Croton macrostachyus* have spatially stable projected suitability surfaces through 2040 and 2060.

This projected stability is a source of relative reassurance for the broadly distributed generalist species (*Kigelia africana*, *Albizia coriaria*, *Rhoicissus tridentata*), whose current wide suitability is not projected to contract.

This same projected stability is a source of concern rather than reassurance for *Warburgia ugandensis* and *Croton macrostachyus*, whose current suitable habitat is already confined to narrow south-western and south-eastern refugia with no projected expansion elsewhere by 2060.

Tephrosia linearis is the only species projected to undergo substantial spatial reconfiguration, developing a fragmented mosaic of very-high and very-low suitability in north-eastern Uganda by 2060 a finding not predictable from current field-occurrence abundance alone, and one that demonstrates the added value of forward projection over static distribution mapping.

Environmental variables particularly mean annual temperature, elevation, annual precipitation, and land use/cover were identified as the primary drivers of the modelled spatial distribution for

all nine focal species, consistent with published species distribution modelling literature for tropical medicinal plants (Tian et al., 2022; Yang et al., 2025).

Species with narrow current elevational niches are not automatically the species with the greatest projected habitat loss; rather, the projections show that narrow-niche species face a distinct risk of persistent spatial confinement, while at least one moderate-abundance, wide-niche species (*Tephrosia linearis*) faces a distinct risk of future spatial fragmentation. Both forms of projected vulnerability warrant conservation attention, but they call for different kinds of intervention.

5.3 Recommendations

Based on the predictive-modelling findings and conclusions of this study, the following evidence-based climate-adaptation and monitoring recommendations are proposed for the selected medicinal plant species in Eastern Uganda. *M. senegalensis* and *Z. chalybeum* can be conserved through monitoring of climate-driven range shifts at both the regional and national level, given their documented sensitivity to elevation and temperature gradients. *M. senegalensis* and *W. ugandaensis* can be conserved on a long-term basis through climate-adaptive translocation planning, either nationally or internationally, given the absence of projected climatic refugia within their current ranges.

5.3.1 Climate adaptation planning and monitoring

The projected habitat suitability patterns under climate change scenarios necessitate proactive adaptation planning at both the species and landscape level. The following climate-specific recommendations are proposed:

Establish long-term phenological monitoring plots for *Maytenus senegalensis* and *Zanthoxylum chalybeum* at multiple elevation bands across the study area to track flowering, fruiting, and recruitment in response to observed temperature and precipitation changes over time.

Identify and formally protect climate refugia — areas of high topographic complexity and local climate buffering where favourable conditions for thermally sensitive species are likely to persist under warming scenarios — particularly in the Elgon foothills and the Karamoja highlands.

Update MaxEnt habitat suitability projections every five years as new climate model ensembles and occurrence data become available, using the refined projections to guide adaptive management decisions and revise protected area boundaries where necessary. This recommendation applies with particular urgency to *Tephrosia linearis*, given the fine-grained and potentially uncertain spatial reconfiguration projected for this species by 2060.

Develop climate-adaptive translocation plans for *Maytenus senegalensis* and *Warburgia ugandaensis*, identifying suitable receptor sites at higher elevations where projected future conditions would support population establishment, since the current modelling shows no such sites emerging spontaneously within either species' existing range.

Engage with the Uganda Meteorological Authority to secure downscaled, district-level climate projections for Eastern Uganda, enabling more precise habitat suitability modelling and reducing uncertainty in conservation planning, particularly for species such as *Tephrosia linearis* whose projected range shows fine-scale spatial heterogeneity that coarse-resolution climate data may not adequately resolve.

5.3.2 Species-specific priorities emerging from the projections

For *Warburgia ugandensis* and *Croton macrostachyus*, whose projected 2060 suitability surfaces remain confined to their present narrow southern range, conservation priority should attach to protecting the existing range in its entirety, since the modelling identifies no alternative future refugia to fall back on. For *Tephrosia linearis*, priority should attach to establishing baseline monitoring now, before the projected 2040–2060 fragmentation becomes apparent on the ground, so that any early signs of the modelled pattern can be detected and responded to in time. For the remaining wide-ranging, climatically stable species (*Kigelia africana*, *Albizia coriaria*, *Rhoicissus tridentata*, *Zanthoxylum chalybeum*, *Gymnosporia senegalensis*, *Mondia whitei*), the projections support continued reliance on the habitat-based and harvesting-based conservation measures set out in the companion volume, without an additional climate-driven range-shift response being immediately necessary.

5.4 Limitations of the modelling and areas for further research

Several methodological limitations specific to the predictive modelling component of this study are acknowledged. First, the MaxEnt models presented here are based on equilibrium niche assumptions that is, that species are currently distributed in all climatically suitable areas within the study region. In practice, dispersal limitation, biotic interactions, and historical land-use change may mean that some suitable habitats are currently unoccupied. Incorporating spatially explicit dispersal models into future projections would improve the realism of range-shift predictions (Warren & Seifert, 2011).

Second, the small sample sizes available for several species most notably *Warburgia ugandensis* (17 combined field and secondary records) and *Mondia whitei* (6 secondary records) constrain the statistical confidence that can be placed in their modelled suitability surfaces, even where the ENMeval optimisation procedure described in section 4.1 was used to guard against overfitting. Projections for these species should be treated as provisional hypotheses for field verification rather than as settled predictions.

Third, the temporal heterogeneity of the underlying occurrence records (1937–2021) used to fit the MaxEnt models introduces potential distributional non-stationarity into the modelling input. Records from the late 20th century may document populations that no longer exist due to deforestation or overharvesting, which could bias the current-conditions baseline against which the 2040 and 2060 projections are compared. Future modelling work should consider stratifying

the input dataset by decade and comparing historical versus contemporary distribution models to quantify directional range shifts already under way.

Finally, the 2040 and 2060 projections rely on a limited set of general circulation model and emissions-scenario combinations; broadening the ensemble of climate models and socioeconomic pathways considered would allow the degree of agreement or disagreement across projections to be quantified, providing a more complete picture of the uncertainty surrounding the specific patterns (particularly the *Tephrosia linearis* fragmentation result) reported in this chapter.

5.5 Final remarks

The findings of this study contribute empirical evidence to a growing body of literature on the spatial ecology of medicinal plants in sub-Saharan Africa under climate change, providing the first integrated current-to-future habitat suitability projection for a suite of nine medicinal species across Eastern Uganda. The results demonstrate that projected climate change poses a significant and quantifiable additional threat to species already under pressure from overexploitation and habitat loss, but that this threat is not uniform: it manifests as persistent spatial confinement for narrow-niche southern-refugium species, and as spatial fragmentation for at least one currently wide-ranging species.

Uganda's biodiversity, including its rich medicinal flora, represents an irreplaceable natural heritage and a critical component of community health resilience for millions of rural Ugandans who rely on plant-based remedies as their primary form of healthcare (Ssenku et al., 2022; Appau et al., 2024). The conservation of this heritage demands urgent, multi-scaled, and evidence-informed action that anticipates future climatic conditions rather than responding only to present-day distribution patterns. The habitat suitability projections generated by this study provide a scientifically grounded foundation upon which climate-adaptive conservation actions can be planned, prioritised, and evaluated over time, complementing the current-distribution baseline established in the companion volume of this study.

It is hoped that the findings presented herein will serve not only as a contribution to academic literature, but as a practical decision-support tool for conservation practitioners, district-level natural resource managers, pharmaceutical researchers, and community health organisations working to safeguard the medicinal plant resources of Eastern Uganda against future environmental change.

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