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Ecological Niche Modelling of *Brachystegia spiciformis* in Southern Africa.

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DECLARATION

The undersigned certify that they have read this research project and have approved its submission for marking in relation to the department's guidelines and regulations.

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DEDICATIONS

To my brother for all his hard work.

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ABSTRACT

Climate change is a serious global environmental issue, negatively impacting species distribution. *Brachystegia spiciformis* is a tree species that is endemic to Southern Africa. The tree species is currently identified as 'Least Concern' according to the IUCN Red List of Endangered Species, as it is not significantly threatened by habitat degradation or population decline, among others. However, the likely effects of climate change on this species remain unaccounted for and hence require further study. Understanding why species inhabit their current locations and forecasting where they might relocate under various climate change scenarios is crucial to biodiversity conservation. Considering how climate change is progressing, species modelling is one of the powerful tools that can aid biodiversity conservation as it helps predict species distribution under different climate change possibilities. This study determined to model the current distribution of *B. spiciformis* and predict its distributions under distinct environmental future scenarios using the Maximum Entropy (Maxent) method. The future distribution was forecasted for 2061-2080 and 2081-2100 under three Shared Socio-economic Pathways, which are SSP126, SSP245 and SSP585 scenarios. Four thousand sixty-six species presence records and five bioclimatic variables (Bio 1, Bio 3, Bio 5, Bio 13 and Bio 15) were used to model the species' distribution. The results suggest that annual mean Temperature (Bio1), precipitation of the wettest month (Bio13) and precipitation seasonality (Bio15) were the most important variables determining the current distribution of *B. spiciformis*. While the species' current range appears relatively stable, the future projections indicate a potential northward shift in suitable habitat under all climate change scenarios. By 2100, the suitable area is predicted to decrease by 15-32% compared to the current distribution. Even though the findings of this particular study give valuable insight into the potential impacts of climate change on this essential species in Southern Africa, the outcomes must be grasped cautiously and further research is needed to develop robust conservation and management strategies. Integrating these ecological niche modelling results with on-the-ground monitoring and adaptation measures will ensure the long-term persistence of *B. spiciformis* in the region.

Contents

LIST OF ACRONYMS

BIO	Bioclimatic variable.
GBIF	Global Biodiversity Information Facility.
IPCC	Intergovernmental Panel on Climate Change.
IUCN	International Union for Conservation of Nature.
MaxEnt	Maximum Entropy.
SSPs	Shared Socio-economic Pathways.
SDMs	Species Distribution Models.
%	Percent.
^{o}C	Degrees Celsius.
RCP	Represented Concentration Pathway
AUC	Area Under Cover
ROC	Receiver Operating Characteristic
KM^2	Square kilometre
B. spiciformis	*Brachystegia spiciformis*

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND TO THE STUDY.

The miombo woodland is an expansive African dry-climate ecosystem identified by the predominance of *Brachystegia* species, whether exclusively or combined with *Julbernardia globiflora* (FAO, 2018). It is estimated to span an area of approximately 2.7 million square kilometres across seven regional countries (Angola, Democratic Republic of Congo, Malawi, Mozambique, Tanzania, Zambia and Zimbabwe) (Rodrigues, 2016). The miombo woodlands are known for their significant contribution to carbon sequestration. They are estimated to store around 1.7-2 billion tons of carbon or roughly 1.3 to 1.5 tons per hectare (Chidumayo, 2012). This carbon storage capacity has made the woodlands gain the attention of efforts such as the Reducing Emissions from Deforestation and Forest Degradation (REDD+) program (Kalaba et al. 2015). The woodland also provides forest-based commodities that contribute to food security and the well-being of local communities and sustain more than one hundred million people living in rural areas and over fifty million individuals residing in urban settings (FAO,2018). These items include nuts and fruits, which are essential sources of income. Miombo woodlands also serve a pivotal function in protecting water catchments from soil erosion, ensuring the reliability of water sources for household purposes, irrigation and hydroelectric power (Nielsen et al., 2016). Van Koppen (1999) postulated that the miombo roots contribute to the recycling of nutrients as nutrients that would otherwise become inaccessible in the deeper soil horizons are retained while the water vapour released through forest trees' transpiration helps govern moderate rainfall patterns. One significant species found in Miombo woodland is *Brachystegia spiciformis,* whose wood is used for construction and manufacturing beehives and furniture (Bond et al. 2010). The miombo woodland ecosystem is mutually vital as a provider of fuelwood and biochar (Louppe, 2010).

Miombo woodlands face many threats which impact their ecological integrity and the services being provided. These threats include agricultural expansion (FAO, 2010), energy production demands (Rodrigues, 2016), logging poles and clearing access routes, wildland fire (Chidumayo, 1995), pitch canker disease (Van de Merwe, 2008) and climate change. Several studies demonstrated the effects of climate change on the population sizes as well as geographic distributions of multiple plant species, including *Brachystegia spiciformis* (Pienaar et al. 2015), increasing frequency of extreme droughts, decrease in water availability and forest fires, which is affecting the growth, structure and natural conditions for *B. spiciformis* (Freire, Rodrigues and Tomé, 2019). Although *B. spiciformis* is categorised as a species of 'Least Concern' according to the Red Data List of Southern African Plants because there does not appear to be an imminent threat from human-caused disruption nor alien invasive species, the potential risk that climate change poses to this environment-specialised species continues to be unclear

The current threats to the Miombo woodlands call for strategies to help conserve the remaining species for future generations through sustainable forest management and restoration. Knowing the reason for occurrence in areas where the species is found and forecasting where they might relocate under various climate change scenarios is crucial for conserving biodiversity (Tasneem, 2017). Ecological Niche Modelling (ENM), also known as Species Distribution Model (SDM), is a method used to predict the distribution of species based on environmental factors (Elith et al. 2006). As per the study by Elith (2006), one of the critical applications of ENM is in the realm of conservation planning, as it can help spot areas significant for the stable presence of particular species and predict how species might respond to changes in its environment, for example, climate change. These models use models such as Shared Socio-economic Pathways, for instance, SSP126, SSP45 and SSP85, that estimate the potential future levels of greenhouse gases (IPPC, 2014). SSP126 is a model that represents a lower level of greenhouse gas emissions used to predict the effects of global warming at 1.5℃ above natural levels. SSP245 is a model that represents a medium level of greenhouse gas emissions used to predict the impact of global warming at 2.0℃ above unaltered levels. In contrast, SSP585 represents a high level of greenhouse gas emissions and is used in predicting the effects of global warming at 2.6℃ above pre-human impact levels. The information derived from these models is then used to inform conservative efforts and help ensure the species' survival.

1.2 PROBLEM STATEMENT.

Brachystegia spiciformis is a tree species endemic to Southern Africa currently classified as 'Least Concern' by the IUCN. However, the potential effects of climate change on the distribution and suitability of this species remain largely unaccounted for. Understanding how species like *B. spiciformis* may respond to future climate change scenarios remains crucial for biodiversity conservation efforts in the region. While the current distribution of *B. spiciformis* is well documented, forecasting how this distribution may shift under different climate change projections is needed to anticipate and plan for potential impacts on this ecologically important tree species. Without such predictive modelling, the long-term viability of *B. spiciformis* populations in Southern Africa could be jeopardised by climate change. Addressing this knowledge gap through ecological niche modelling is crucial in enacting appropriate conservation tactics for this species.

1.3 SIGNIFICANCE OF THE STUDY.

The outcomes of this study could be helpful to conservationists as well as natural resources managers because by understanding the potential distribution of *Brachystegia spiciformis* under future conditions, they can make informed decisions on how best they can protect and manage the species, which will help to increase the population of this tree species. This proactive research approach can be crucial in conserving this species' present and future distribution ranges. Not only does it benefit these two, but the findings can inform policy decisions and help local communities who depend on the Miombo woodlands to know how best to utilise and protect them. Since ecological niche models can predict how species' suitable habitats may shift in response to climate change, this allows policymakers to implement early detection and rapid response programs as well as develop regulations and control measures to limit its impact, for instance, the development of climate-resilient land-use plans, establishment of migration corridors and the identification of potential climate refugia for vulnerable species.

1.4 STUDY AIM.

To determine the potential impacts of climate change on the distribution of *B. spiciformis.*

1.5 OBJECTIVES.

1) To determine current suitability areas for *B. spiciformis.*
2) To determine climatic variables affecting *B. spiciformis* distribution under SSP126, SSP245 and SSP585 change scenarios for 2080 and 2100.
3) To predict the area suitable for *B. spiciformis* under both current and future predicted scenarios.

1.6 RESEARCH QUESTIONS

1) What is the current potential distribution of *B. spiciformis* in Southern Africa?
2) What climatic variables will significantly impact *B. spiciformis distribution* in 2080 and 2100?
3) What are the likely habitats of *B. spiciformis* suitable for 2080 and 2100?

CHAPTER 2: LITERATURE REVIEW

2.1 THE CURRENT DISTRIBUTION OF *BRACHYSTEGIA SPICIFORMIS.*

Brachystegia spiciformis is a prevalent species in the miombo woodlands (fig 2.1) (Campbell et al., 2002). Various environmental factors, including soil type, climate and topography, influence its distribution. The environment of the Miombo woodlands is characterised by a long dry season and a short wet season (McNaughton et al., 1994). *Brachystegia spiciformis* is found in coastal and upland deciduous woodland and open forest habitats. *B. spiciformis* is found in various areas, including banks of rivers and even on poorly drained, shallow soils (Louppe et al., 2012). This tree species typically occurs around 2,000 to 2,350 meters above sea level, with an annual precipitation of 500 to 1200mm. However, the total rainfall during the productive period (summer) is of greater significance than the overall yearly precipitation (Louppe et al., 2012). This plant thrives best in warm, subtropical climates with an average annual temperature of around 19-20°C. It does not do well in cold, wet conditions. Like many plants native to tropical regions, this species requires a hot, dry period before its growing season begins (Pienaar et al., 2015).

Figure 2.1 A map showing the current distribution of miombo woodlands in Southern Africa (Seymour et al., 2014)

2.2 Climatic Variables That Have An Impact On The Distribution Of *Brachystegia Spiciformis.*

Climate influences the geographic distribution of plants both regionally and globally. As a result, species' response to changing environmental conditions is likely predominantly determined by the population dynamics at the range margins (Pienaar et al., 2015). The distribution of *Brachystegia spiciformis* is influenced by various climatic variables, mainly temperature and precipitation.

Temperature contributes significantly to determining the area suitable for *B. spiciformis*. According to Pienaar et al. (2015), the miombo has an annual temperature range of 15 to 25 ºC, and these are temperatures preferred by *B. spiciformis*, meaning temperatures below or beyond these can limit the growth and distribution of these species. Kumbiya et al. (2010) explained that when temperatures are high, the stomata (pores) in the leaves of *Brachystegia spiciformis* are more open. This allows more water to evaporate from the leaves, leading to increased water loss. Warmer temperatures can potentially improve trees' growth and productivity as plant respiration increases with rising temperatures (Sendall et al., 2015). However, increased temperatures combined with dry conditions in the planting season can cause tree stress and a decline in tree growth (Jew et al., 2016).

Brachystegia spiciformis, a deciduous tree, thrives in areas with a distinct wet and dry season because it is well adapted to a seasonal rainfall pattern with an annual rainfall total of 800-1500mm. Adesina et al. (2019) postulated that rainfall affects the distribution of the miombo in two ways. They mentioned that, firstly, it affects the growth and survival of the trees because if there is not enough rainfall, the trees will not be able to grow and reproduce. Secondly, rainfall affects water availability in the soil (Adesina et al., 2019). According to Caley et al. (2010), if there is not enough rainfall, the soil will be drier and less available for the trees, affecting their growth and survival. Extreme rainfall events such as floods affect species diversity and regeneration because they increase soil erosion, nutrient deposition risks and spread of diseases.

According to Craig et al. (2003), *B. spiciformis* prefers high humidity with a relative humidity of around 70 to 80%. One study found that humidity affects the tree's ability to take up water from the soil and regulates its internal water balance (Prince et al., 2006), indicating that it can impact the distribution and characteristics of this tree species. However, it should be noted that humidity works in conjunction with other factors, such as precipitation and soil, contributing to the habitat preferences of *B. spiciformis*.

2.4 EFFECTS OF CLIMATE CHANGE ON PLANT SPECIES DISTRIBUTION

Climate contributes significantly to forest function, and climate shifts, such as temperature increases and rainfall reduction, can impact forests directly. These impacts differ by region and type of forest, for instance. In some cases, a warmer climate may boost tree growth and productivity, but in other forest types, the same warming trend could have the opposite effect and decrease tree growth. (United Nations, 2023). Climate change will trigger natural disturbances such as invasive species and forest fires. According to the IPCC (2014), sub-Saharan Africa is projected to undergo more significant warming than the rest of the world. Plus, changes in climate patterns will be accompanied by an array of shifting environmental phenomena, including varying and unpredictable rainfall and a rise in natural disasters. These changing climate phenomena are predicted to affect the region significantly as sub-Saharan Africa may face more challenges adapting to the rapid environmental shifts than other parts of the world. IPCC's climate change projections point to a future with more climatic instability and weather-related hazards for this vulnerable region, such as droughts. Climate change impacts population sizes and the spread of various plants, such as Brachystegia spiciformis (Pienaar et al. 2015), by increasing droughts, water scarcity, and forest fire frequency. These climatic changes negatively affect the growth, structure and overall environmental conditions that *Brachystegia spiciformis* relies on. As a result, this plant species' population size and geographic range are being altered. Banda et al. (2017) discovered that droughts and increased temperatures may lead to widespread mortality of *Brachystegia spiciformis,* especially in sandy soils.

Species abandon their preferred habitats as favourable conditions are altered (Walther et al., 2002). In these scenarios, these species respond by adapting to the new climate, migrating to areas where favourable conditions are offered or simply going extinct (Freeth *et al.* 2008). The survival of other species depends on dispersal abilities, enabling them to colonise new places (Williams *et al.* 2005). The Assis et al. (2016b) study used niche modelling to study how climate change may influence the distribution and genetic diversity of *Laminaria hyperborea* in Europe. Their model results indicated that shifts in climatic conditions, such as rising temperatures, could lead to a decline in suitable habitat in areas where this kelp species has historically been found. Additionally, the model projections indicate that *Laminaria hyperborea* may undergo a northward range shift in response to these changing environmental conditions.

Lohbeck et al. (2016) reported that climate change may impact the seed dispersal and regeneration of *Brachystegia spiciformis*. The authors suggest that the changing climate may affect the ability of trees to produce seeds and the dispersal of those seeds by animals, thereby affecting their future occurrences.

A decrease in rainfall can cause trees to grow stunted and fail to grow. A study by Eggermont et al. (2015) supported this by observing that a reduction in rainfall could reduce the size of the *Brachystegia spiciformis* range by up to 50%. Le Page et al. (2019) found that decreased precipitation and increased temperatures could reduce the growth and reproduction of *Brachystegia spiciformis,* thereby reducing the viability of the species. This is because warmer temperatures alter weather patterns and disturb natural systems' typical balance and equilibrium. Conversely, heavy rainfall events can lead to the erosion of forest soils, causing the release of stored carbon back into the atmosphere (United Nations Environmental Protection Agency, 2023), causing temperatures to rise.

The Couce et al. (2013) study simulated the potential consequences of increased sea surface temperature and ocean acidification on shallow coral reefs globally. Their model results suggest that rising temperatures will be the primary driver leading to a decline in the suitability of these habitats, particularly in the Indo-Pacific region. However, the model also indicates that the increasing temperatures could potentially enable a poleward expansion of suitable areas for coral reef development in some locations.

Marthur et al. 2024 studied the spatial patterns of probable occurrence and abundance patterns of the plant species *Indigofera oblongifolia* (Forssk) in India using three distinct periods (current, 2050 and 2070) as well as multiple greenhouse gas emission situations (RCPs 2.6, 4.5, 6.0 and 8.5). The researchers also incorporated non-meteorological factors, e.g., global livestock population and man-induced environmental change, into their model. The results showed that the ecological drivers outdid non-meteorological predictors in the context of upgrading the quality of the species distribution models. Precipitation Seasonality was identified as the primary and critical determinant influencing the optimal habitat preference for *Indigofera oblongifolia*. The study found that in India, the species tends to occupy smaller, more dispersed populations, whereas in Africa, it is found in more continuous regions.

Jinga et al. (2019) performed a study to model the current geographic distribution of the miombo woodland ecosystems in sub-Saharan Africa. It utilised 17 representative tree species found in miombo woodlands and predicted how those distributions might change under distinct future climate change scenarios. The researchers used the MaxEnt species distribution model, incorporating 3,429 occurrence records for the tree species and various environmental predictor variables like climate, precipitation, temperature and soil characteristics. When projecting the future distributions out to 2050 and 2070 under different Representative Concentration Pathway (RCP) climate change scenarios, the study found that 9 of the miombo tree species were projected to experience significant habitat shrinkage. This shrinkage was particularly severe by 2070 under the high-emissions RCP8.5 scenario for species like *Afzelia quanzensis* (-13% range loss), *Albizia antunesiana* (-15% range loss) and *Brachystegia microphylla* (-14% range loss). According to them, a 5-15% change in global climate patterns is predicted to cause a significant reduction in precipitation across Southern Africa, which poses a considerable threat to the woodlands in particular, as they are heavily influenced by more significant fluctuations between wet and dry extremes seasonal patterns and drier interior and wetter coastal zones. The predicted effect of climate change in Southern Africa and amplified disturbances regimes in the woodland such as human disturbances (deforestation, agriculture among others) represent a major loss of roughly 40% of the trees' populations by the middle of the century. This raises significant concern that the decline of mature trees across the landscapes may cause a change of these woodlands into shrubs or grassland ecosystems. The authors concluded that the miombo tree species projected to have the most substantial range reductions should be prioritised for climate change mitigation and conservation efforts. They also emphasised the need to protect all miombo woodland tree species from unsustainable harvesting practices.

Tasneem (2017) used the species distribution modelling approach (Maxent) to successfully classify the environmental niche of *Kumara plicatilis*, a tree-like aloe species native and restricted to the fynbos biome of South Africa. The modelling defined the spatial patterns of the species' possible distribution and abundance based on environmental demands. The results showed that the suitable habitat conditions for *Kumara plicatilis* are unevenly distributed around the central and southwestern fynbos region. Various climatic and biophysical factors including winter precipitation, temperature regimes and vegetation type, limit the species' distribution. The researchers then used climate change projections under the IPCC's 2014 'best-case' and 'worst-case' scenarios to model how the spatial occurrence patterns of *Kumara plicatilis* may change in the future. The models indicated that the species is projected to experience limited to severe declines in the available area of suitable habitat depending on the severity of future climate change. The findings show that *Kumara plications* spatial extent and local population persistence are highly sensitive to unsuitable climate and biophysical conditions. This could make the species vulnerable to local extinctions as the climate changes in the future.

CHAPTER 3: MATERIALS AND METHODS

3.1 DESCRIPTION OF THE STUDY AREA.

The study was done in the Southern African region. It was confined to seven countries where *B. spiciformis* is widely spread, including Zambia, the Democratic Republic of Congo, Mozambique, Zimbabwe, Tanzania, Angola and South Africa (Fig 3.1). The region is usually characterised by droughts in arid areas and floods in semi-arid areas due to excessive rainfall durations (World Meteorological Organization (WMO), 2021). The average rainfall for the study region is < 1000 mm per year (Davis, 2011). The rest of the study region is anticipated to obtain average to above normal precipitation around October to December 2021 and January to March 2022(World Meteorological Organization (WMO), 2021)

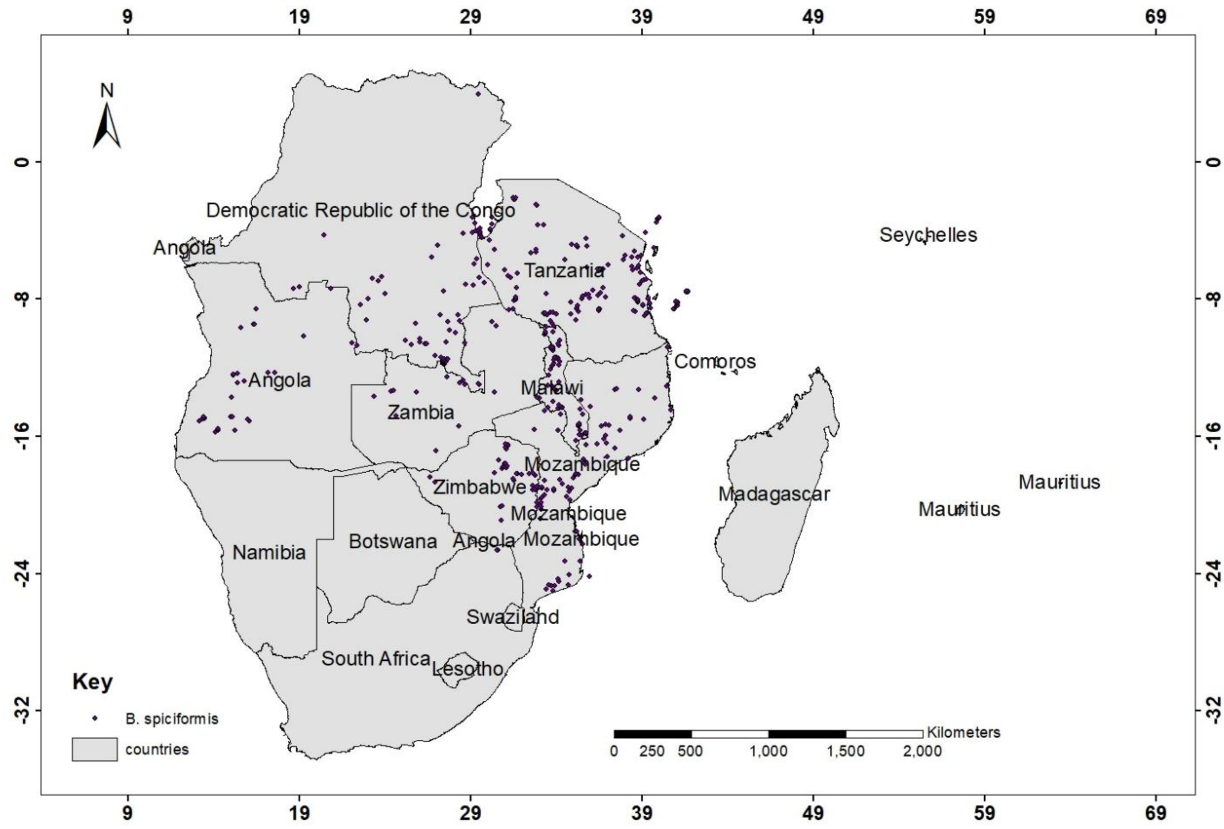


Figure 3.1 Study Area Map (Southern Africa)

3.2 DATA ACQUISITION.

The occurrence data for *B. spiciformis* was obtained from the GBIF, the Global Biodiversity Information Facility. (GBIF, http://gbif.org). Observed data was cleaned before running the model to ensure the species' data used have geographic locations by removing all species without coordinates. The current and future bioclimatic variables were obtained from the WorldClim dataset (http://worldclim.org, Hijmans et al. 2005) at a 2.5 arc second spatial resolution. The climatic data for this study was restricted to 5 bioclimatic predictors, which are Bio1 (Annual Mean Temperature), Bio3 (Isothermality), Bio5 (Maximum Temperature of the Wettest Month), Bio13 (Precipitation of the wettest month) and Bio15 (Precipitation Seasonality) since they had the highest correlation with other variables. Projections of future climate conditions based on an extensive collection of global climate models (GCMs) used in the Sixth Phase of the Coupled Model Intercomparison Project (CMIP6) were compiled from the WorldClim database. This compilation of matched climate model outputs allows for analysing and comparing how different climate models project future changes in factors like temperature, precipitation and other climatic variables under various greenhouse gas emission scenarios. SSP126, SSP585 and SSP245 were used to estimate change for the predictions of 2061-2080 and 2081-2100. These were used because climate models inherently have uncertainties, so using multiple scenarios (SSP126, SSP245 and SSP585) helps capture a range of possible future climates the species may encounter, which can provide more robust insights into potential climate change impacts.

ArcGIS 10.3 was then used for digitising the raster data collected from the GBIF and producing the vector shape file with captured occurrence areas for B. spiciformis. This process was done using the spatial analysis algorithm. The data was then exported to Microsoft Excel and fed into the Maximum Entropy (MaxEnt) module, a modular, rJava-based framework for reproducible modelling of species niches and distributions to improve data quality by processing occurrence data, yielding a total of 4066 random occurrence points (Haredasht et al., 2013)

3.3MODEL PARAMETERS

The predictions were based on raster geographic data sets (Makori et al. 2017). The bioclimatic variables used in this study were selected based on their relevance to the study, guided by thorough literature review. Variables employed in the distribution model (Table 3.1) were grouped into remotely sensed biotic variables derived from space-borne normalised difference vegetation index (NDVI) data.

Table 3.1: Climatic variables relevant to habitat suitability employed in this study:

Name	Variable	Units
Bio 1	Annual Mean Temperature	^{o}C
Bio 3	Isothermality (BIO2/BIO7) * (100)	^{o}C
Bio 5	Max Temperature of Warmest Month	^{o}C
Bio 13	Precipitation of Wettest Month	Mm
Bio 15	Precipitation Seasonality (Coefficient of Variation)	Mm

3.4 MODEL EVALUATION

A threshold-independent metric called the area Under the Curve (AUC) of the Receiver Operating Characteristic (ROC) analysis model was used to evaluate the performance of the model (Phillips and Dudik, 2008). The AUC represents the likelihood that the classifier correctly distinguishes presence locations (sensitivity) from absence or background locations (specificity) (Yackulic et al., 2013). An AUC value of 0 suggests an impossible occurrence region, while an AUC of 1 indicates a perfect occurrence prediction (Du et al., 2014).

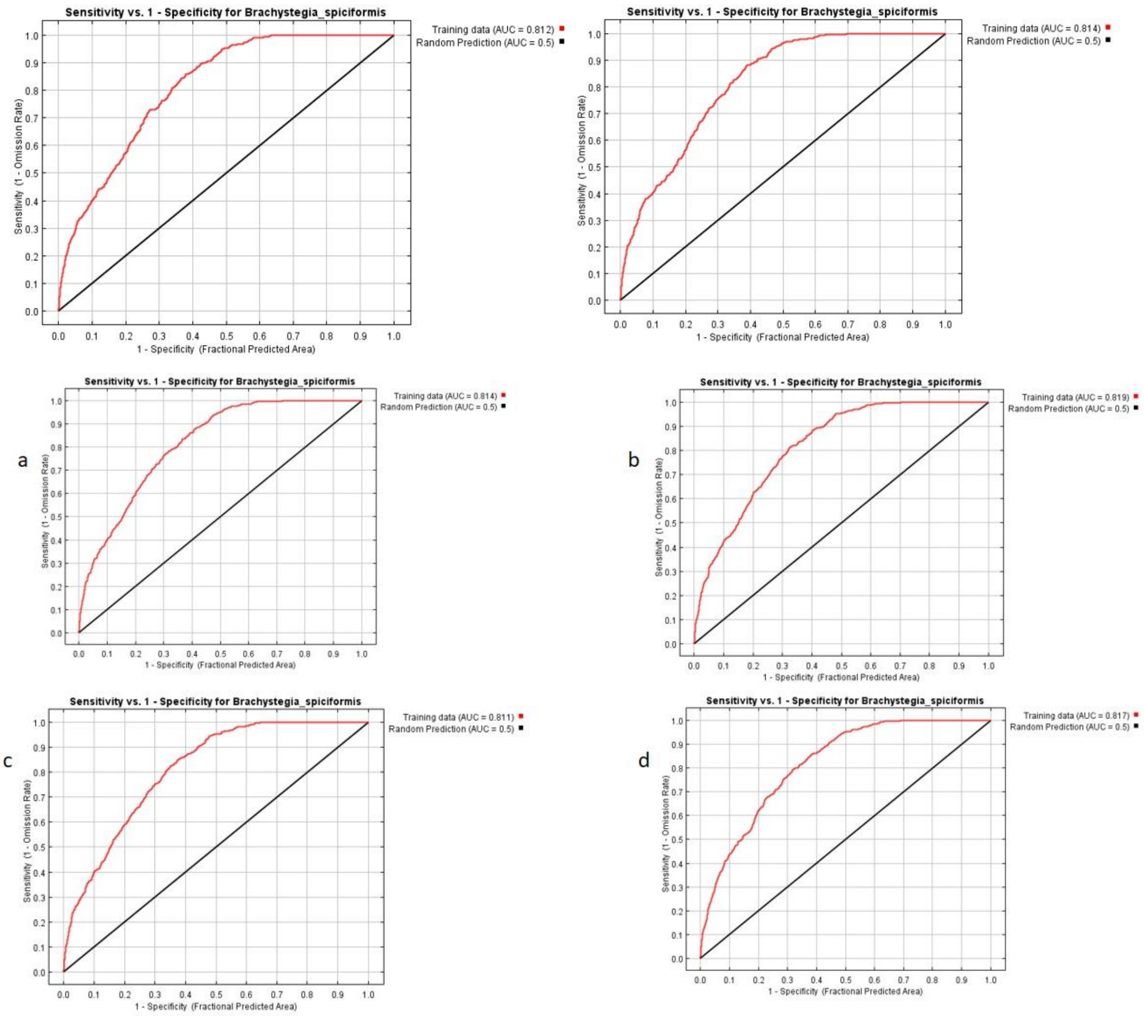
3.5 DATA ANALYSIS

The bio variables downloaded were geo-tiff images, so the library Raster package was used to extract them. The data was converted from geo-tiff images (raster) to American Standard Code for Information Change (ASCII) files using ArcGIS 10.3. Ecological niche models were constructed using MaxEnt, which attempts to identify the greatest mix of environmental reactions that best predicts the species' existence. Outputs from MaxEnt were further processed in ArcGIS to refine the model outputs.

CHAPTER 4: RESULTS.

4.1 Contribution Of Environmental Variables In Modelling Of *B. spiciformis.*

The model succeeded in explaining the variation in the probability of occurrence of *B. spiciformis* in Southern Africa. For the year 2080, the models presented high AUC values [under ssp126 (AUC = 0.812), under ssp245 (AUC = 0.814) and ssp585 (AUC = 0.819)]. For 2100, the models showed high AUC values (under ssp126 AUC was 0.814, ssp245, AUC was 0.811; under ssp585 scenario, AUC was 0.817).



Figures 4.1a &b show the Area Under Curve (AUC) of the Receiver Operating Characteristic (ROC) curves for the MaxEnt habitat models based on B. spiciformis for the year 2080 under (a) ssp245 (b)ssp585 respectively and 4.1c&d showing Area Under Curve (AUC) of the Receiver Operating Characteristic (ROC) curves for the MaxEnt habitat models based on B. spiciformis for the year 2100 under (a) ssp245 (b)ssp585 respectively.Figure 4.1(unlabelled) show the Area Under Curve (AUC) of the Receiver Operating Characteristic (ROC) curves for the MaxEnt habitat models based on B. spiciformis for the year 2080 and 2100 under ssp126 respectively

4.2: Contribution Of The Environmental Variable To *Brachystegia Spiciformis* Distribution.

The variable importance analysis showed that bio13 (Precipitation of wettest month) was the best predictor (47.6% in ssp126, 48.8% in ssp245 and 48.7% in ssp585 for 2080 and 46% in ssp126, 45.3% under ssp245 and 46.8% under ssp585 for 2100) and most important for the prediction of the potential distribution of *Brachystegia spiciformis* for the years 2080 and 2100 (Table 4.1). Bio15 (Precipitation seasonality) contributed 25.3% in ssp126, 25.8% in ssp245 and 29.9% in ssp585 for the year 2080 and 23% in ssp126, 26.7% in ssp245 and 32% in ssp585 for the year 2100. Bio5 under ssp126 contributed 15.3% and 17 % for 2080 and 2100, respectively. Under ssp245 (2080), Bio5 had a percentage contribution of 11.8 %. Bio1 was also an essential variable under ssp585, but the permutation percentage was significantly higher in Bio5 (10.7%) than in Bio1 (5.4%). Under ssp245 (2100), Bio5 was the third most important variable in predicting the potential distribution pattern of *B. spiciformis,* with a percentage contribution of 16 and 9.3 in ssp585. In 2100, Bio1 was the least essential variable with percentage contributions of 4.5 % under ssp126 and 4% under the ssp245 scenario, while Bio3 was the least under ssp585 (4.1%).

Table 4.1 Contribution Of The Environmental Variables Used In Maximum Entropy Modelling Of Brachystegia spiciformis (2080 and 2100).

SSP	**Variable**	**Percent contribution**	**Permutation importance**
(a)SSP126-2080	Bio1	3.4	5.7
	Bio3	8.4	9.8
	Bio5	15.3	14.4
	Bio13	47.6	51.6
	Bio15	25.3	18.6
(b)SSP245-2080	Bio1	4.7	4.3
	Bio3	8.9	9.2
	Bio5	11.8	10.3
	Bio13	48.8	55.7

	Bio15	25.8	20.5
(c)SSP585-2080	Bio1	9.1	5.4
	Bio3	4.6	7.8
	Bio5	7.7	10.7
	Bio13	48.7	51.6
	Bio15	29.9	24.5

	Variable	**Percent contribution**	**Permutation importance**
(a)SSP126-2100	Bio1	4.5	5.9
	Bio3	8.9	10
	Bio5	17	13.5
	Bio13	46	49.7
	Bio15	23	18.9
(a)SSP126-2100	Bio1	4	6.5
	Bio3	8	8.3
	Bio5	16	15.5
	Bio13	45.3	49.1
	Bio15	26.7	20.7
(b)SSP585-2100	Bio1	4.1	6.4
	Bio3	7.7	8.3
	Bio5	9.3	15.7
	Bio13	46.8	45
	Bio15	32	24.5

4.5: Present Suitability Of *Brachystegia spiciformis.*

The total area currently covered by *B. spiciformis* was predicted to be 556 781 km^2. The present suitability model of *B. spiciformis*, according to the model, shows that the tree species has a high occurrence in Angola, Tanzania, Zambia, Zimbabwe, Mozambique, and Malawi (Figure 4.1). This indicates that these areas exhibit favourable environmental conditions suitable for *B. spiciformis*. These conditions can include suitable temperatures, rainfall, soil type and other ecological conditions that promote the growth and survival of *B. spiciformis*. However, the tree species is patchy in countries like Zimbabwe, Zambia, and Mozambique, meaning it is limited to specific areas. South Africa, Botswana, and Namibia are the countries with the lowest occurrence of the tree species.

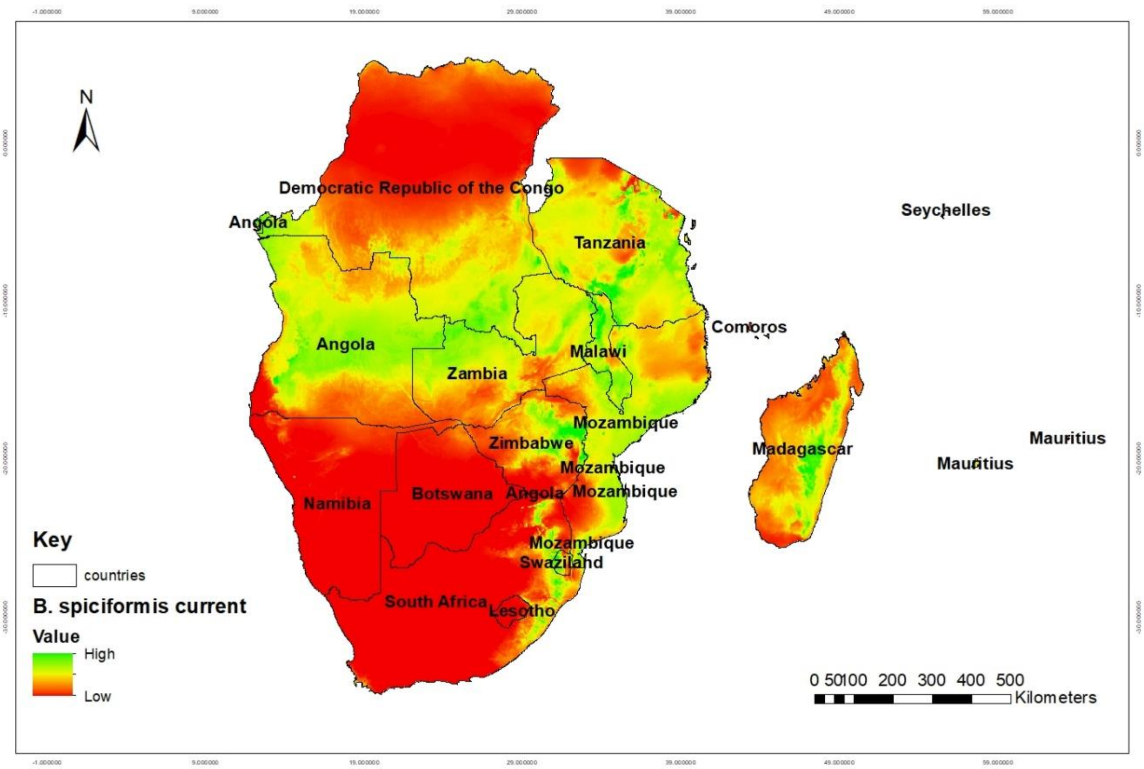
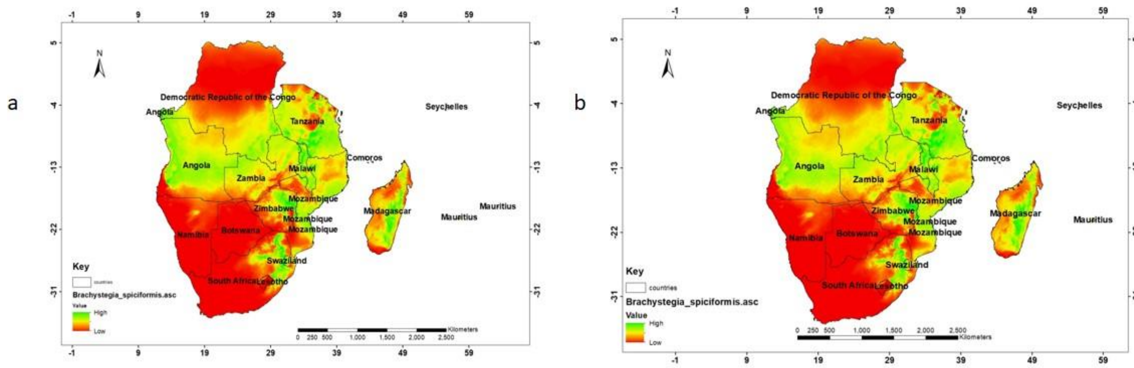


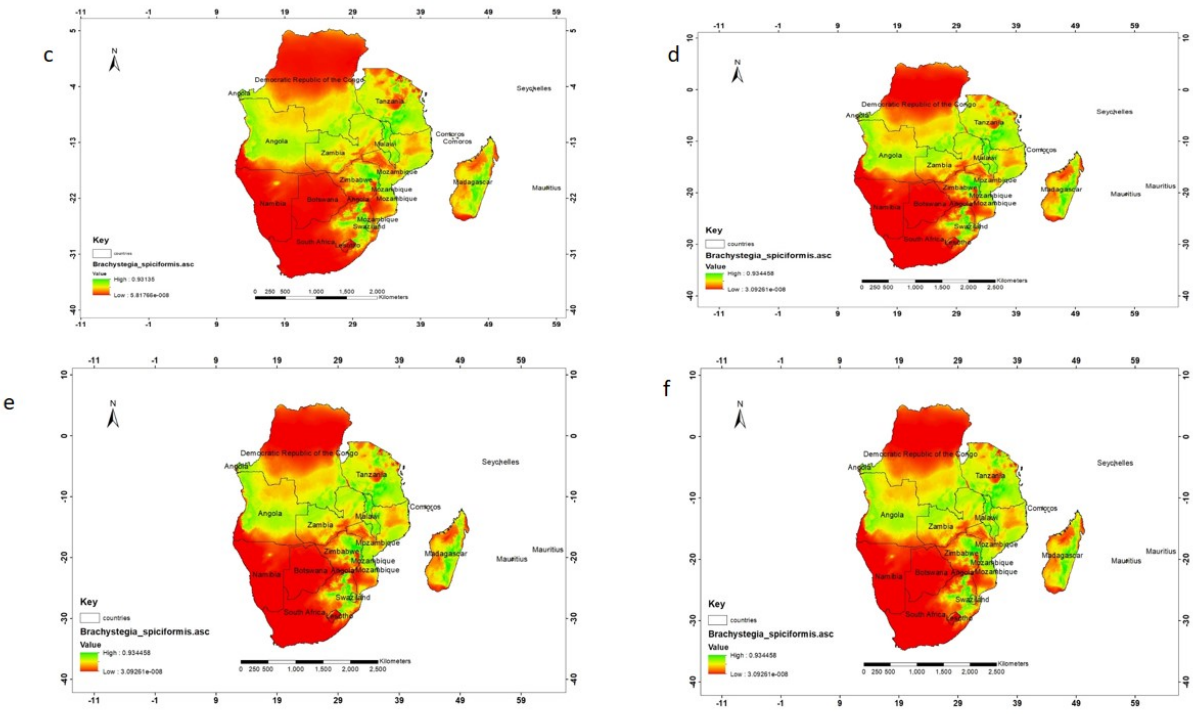
Figure 4.2 shows the current suitability areas of B. spiciformis in Southern Africa.

4.6 Future Suitability Of *Brachystegia spiciformis*

The results shown by the models for future suitability areas under ssp126, ssp245 and ssp585 for years 2080 and 2100 show that there has been a notable shift in habitat suitability under different climatic conditions driven by climate change causing a drastic change in the distribution of *B. spiciformis*. The results also predict a decline in the availability of suitable habitats caused by a shift in climatic conditions, as evidenced by the reduction or shrinking of habitats in countries like Zimbabwe, where the species are currently distributed. The possibility for favourable habitats for *B. spiciformis* under predicted suitability and species occurring there under different climatic scenarios of ssp126, ssp245 and ssp585 in years 2080 and 2100 is diminishingly slight.

In 2080 (ssp126), habitat suitability was projected to be 216 587.8 km^2 (38.9% of the total current area) and in 2100, it was 226.053km^2 (40.6% of the total area), which was slightly higher to that of 2080 showing an increase in suitability with time. The predicted suitable area under ssp245 was predicted to be 211 576.8 km^2 38% of the total area) and for ssp585, the predicted suitable area was 125 833km^2 which is 22.6% of the total area in Southern Africa against the current predicted area of 556 781 km^{2,} showing a decline in suitable area for *B. spiciformis* by the year 2080. For the year 2100, the estimated suitable area under ssp245 was predicted to be 208 236.1km^2 (37.4% of the total area) and for ssp585, the predicted suitable area was 177 613.1km^2 which is 31.9% of the total area currently covered by *B. spiciformis* (556 781 km^2).





Figures 4.3a &b show the future predicted suitability under ssp126 scenario versus the predicted suitability areas of Brachystegia spiciformis under ssp126 scenario for 2080 and 2100, respectively. Figure 4.3c&d: showing the future predicted suitability under ssp245 scenario versus predicted suitability areas of Brachystegia spiciformis under ssp585 scenario respectively for the year 2080 and e&f: showing the future predicted suitability under ssp245 scenario versus predicted suitability areas of Brachystegia spiciformis under ssp585 scenario respectively for the year 2100

4.7: Responses Of *B. spiciformis* To Bioclimatic Variables.

According to ssp126, ssp245 and ssp585, *B. spiciformis* will not thrive in areas with extremely low temperatures (Bio1) between 0-14ºC for the years 2080 and 2100, and it will grow best in areas ranging from 20 to 22 ºC. Therefore, the species will fail to adapt to the increasing temperatures or climate change and areas with a temperature range between 28-30 ºC will be unsuitable for *B. spiciformis.*

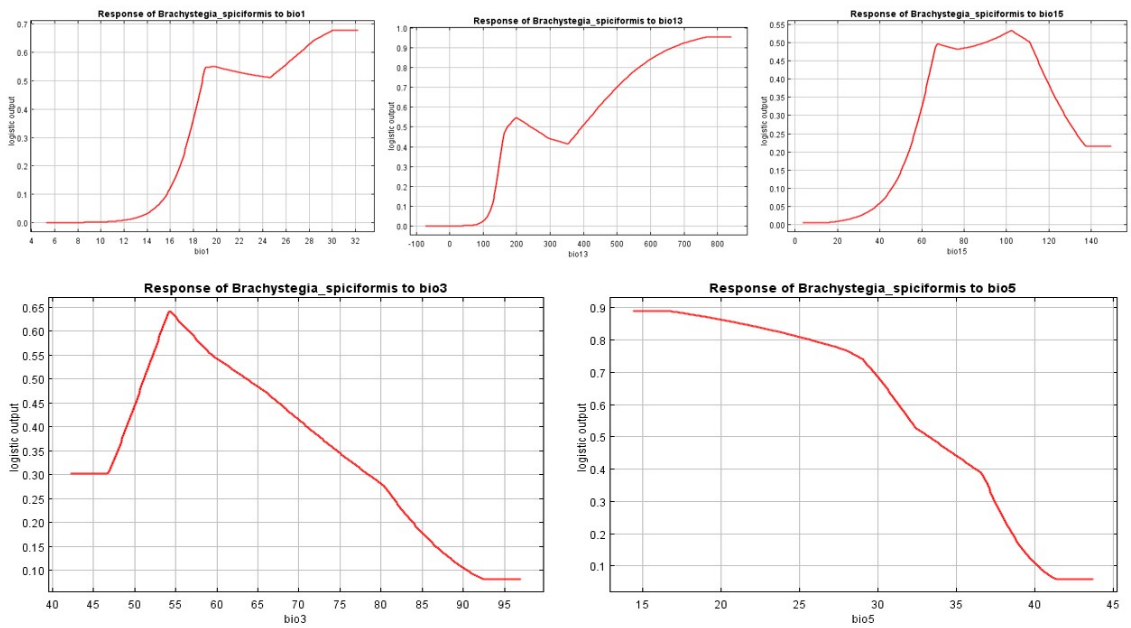
The results predicted that, in 2080 and 2100, areas receiving very little rainfall (Bio13), below 100mm, under both scenarios will be unfit for *B. spiciformis*; the probability of occurrence in such regions is minimal. Maximum occurrence will be in areas receiving an average rainfall of around 700mm and above.

Bio15, which is precipitation seasonality, also significantly impacts the distribution of *B. spiciformis*. This refers to precipitation patterns during the year and includes precipitation's timing, intensity and duration. All SSP scenarios show that *B. spiciformis* will adapt to a precipitation seasonality of 65-110mm, with the highest occurrence in areas with a precipitation seasonality of 110mm and decline as the temperature seasonality increases above this range.

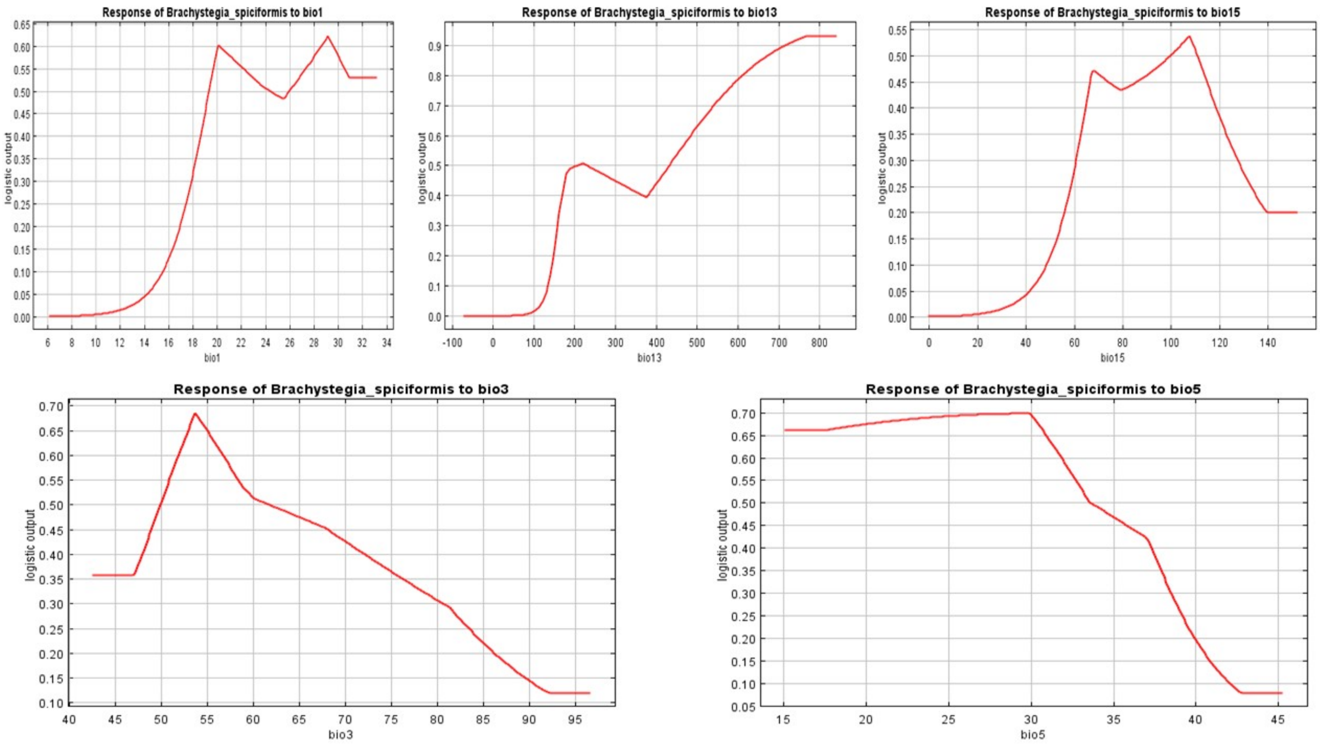
Bio3(Isothermality), which shows the similarity in temperature between day and night compared to the variation between summer and winter, also contributes to the distribution of *B. spiciformis.* All scenarios show that the species will thrive in areas with an Isothermality value of 55ºC, and places with an Isothermality greater than this will not be conducive for the species. The lowest occurrence will be in areas with an Isothermality value of 80+

According to the response curves, *B. spiciformis* will flourish in areas with a maximum temperature of the wettest month (Bio5) of 15-20 ºC and decline as it increases to 45ºC and above.

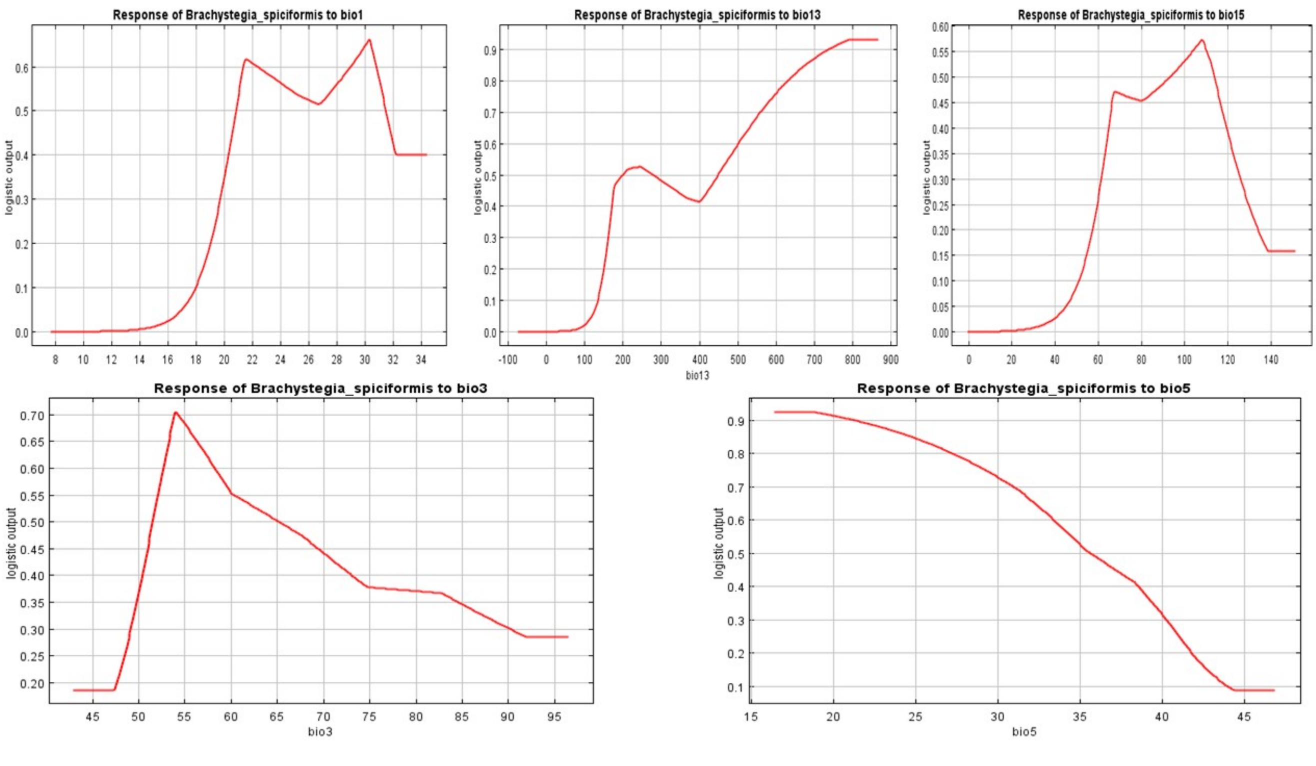
Figure 4.4 below shows how each bioclimatic or environmental variable affects the distribution of *B. spiciformis* (Maxent prediction), given that all other bio variables are at their average sample value.



4.4a: Responses of B. spiciformis to bioclimatic variables under ssp126 scenarios for 2080. (Logistic output represents the probability of detection)

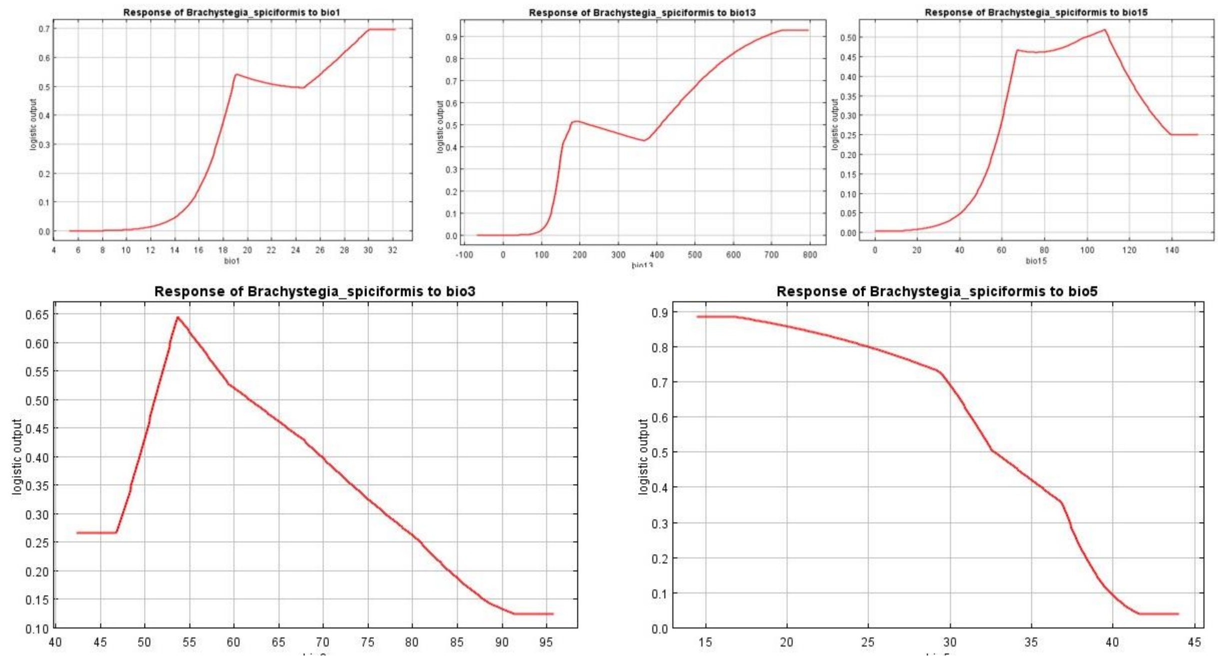


4.4b: Responses of B. spiciformis to bioclimatic variables under ssp245 scenarios for 2080. (Logistic output represents the probability of detection)

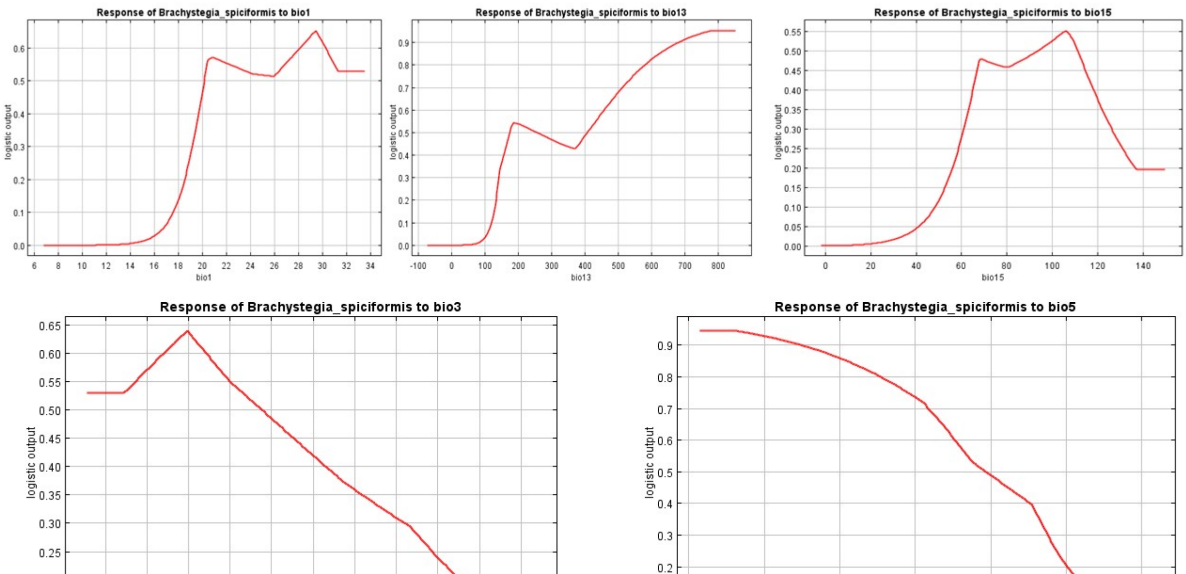


4.4c: Responses of B. spiciformis to bioclimatic variables under ssp585 scenarios for the year 2080..

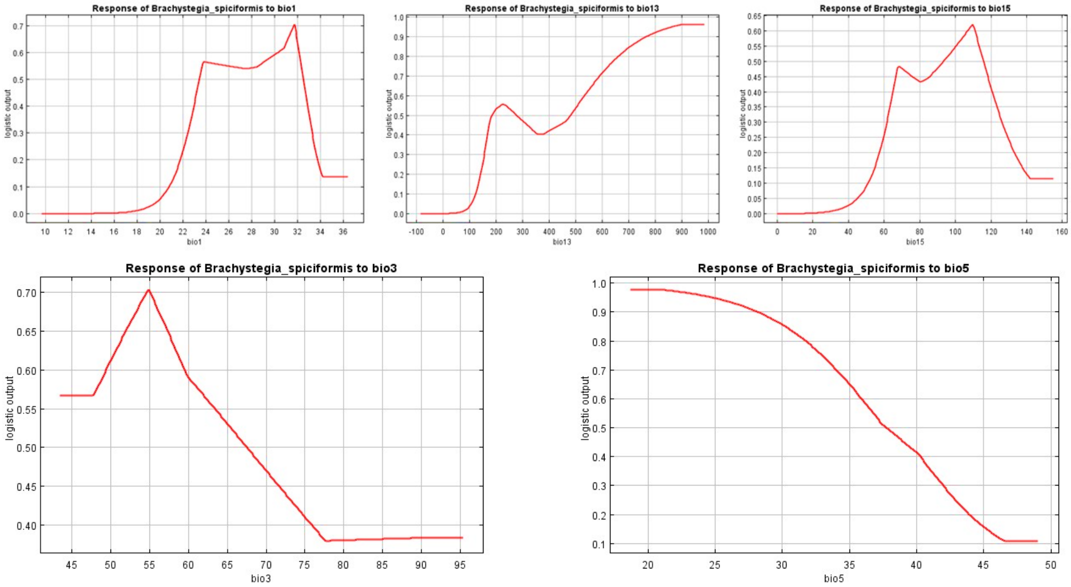
4.4: Responses of *B. spiciformis* to bioclimatic variables (2100)



4.5a: Responses of B. spiciformis to bioclimatic variables under ssp126 scenarios for the year 2100. (Logistic output represents the probability of detection)



4.5b: Responses of B. spiciformis to bioclimatic variables under ssp245 scenarios for the year 2100. (Logistic output represents the probability of detection)



4.5b: Responses of B. spiciformis to bioclimatic variables under ssp585 scenarios for the year 2100. (Logistic output represents the probability of detection)

CHAPTER 5: DISCUSSION.

The study investigated the most suitable environments for the species *B. spiciformis* to thrive in Southern Africa, both now and in the near future, under three climate change scenarios over two periods. The MaxEnt habitat models for *Brachystegia spiciformis* showed high AUC values (>0.8) for sssp126, ssp245 and ssp585 scenarios in 2080 and 2100, indicating that the model succeeded in modelling *B. spiciformis'* future possible habitat hence the basic findings of this study are robust and can be used as a foundation for further investigation or decision making. The most critical variable was bio13 (precipitation of the wettest month), contributing around 45-50% to the model predictions. This suggests precipitation during the wettest month is a critical factor in determining the distribution of *B. spiciformis.* The finding that precipitation-related variables (bio13 and bio15) are the dominant predictors *of B. spiciformis* distribution is quite telling. It suggests this tree species is highly dependent on rainfall patterns in terms of total precipitation during the wettest month and seasonal variability. This makes sense given that *B. spiciformis* is native to sub-Saharan Africa, a region characterised by distinct wet and dry seasons. The species' survival and growth are closely tied to the timing and amount of rainfall; hence, if climate change alters precipitation regimes in southern Africa, with potential shifts in the timing, intensity and seasonal rainfall distribution, this could significantly impact the future distribution of *B. spiciformis* populations. The second most important variable was bio15 (precipitation seasonality), contributing around 25-30% to the model. This indicates the species' distribution is also sensitive to the seasonal precipitation pattern. Other variables like bio1 (annual mean temperature), bio3 (Isothermality) and bio5 (max temperature of the wettest month) had more minor but still significant contributions to the model, generally between 5-15%. The study outcomes also showed that bioclimatic variables associated or linked to Temperature (Bio1, Bio3, Bio5) and precipitation (Bio13 and Bio15) played a crucial role in determining the suitable ecological niche for *B. spiciformis.*

5.2 Present Suitability Of *B. spiciformis*.

The current distribution model shows that *B. spiciformis* has a high occurrence in several countries in southern Africa, including Angola, Tanzania, Zambia, Zimbabwe, Mozambique and Malawi. These areas likely have favourable environmental conditions like suitable temperature, rainfall and soil types that promote the growth and survival of *B. spiciformis*. However, the species' distribution is patchy even within these countries, indicating that it is limited to specific suitable areas. Countries like South Africa, Botswana and Namibia have low occurrences of *B. spiciformis,* likely due to less favourable environmental conditions in those regions.

5.3 Implications For Future Climate Change Impacts.

The modelling results indicate that under all emission scenarios, ssp126, ssp245 and ssp585, the suitable habitat for *B. spiciformis* may shrink (2080 and 2100). Areas with high suitability may become less favourable if precipitation patterns change, potentially leading to range shifts or local population declines. *B. spiciformis'* occurrence and survival are influenced by a combination of factors: the local environmental conditions, the surrounding human-induced factors, and climatic variables like temperature and precipitation (Mudereri et al., 2019). According to Jinga et al. (2019), the availability of suitable habitats is likely to decline in the future as a result of the escalating impacts of climate change, which will pose a significant threat to the survival and population dynamics of various species as they face increasingly severe and intense environmental challenges. Evidence shows that by 2080, using SSP126, SSP245 and SSP585, the species occurrence will decline from 556 781km^2 to 226 053km^2, 211 576km^2 and 125 833km^2 respectively. The tree species' occurrence will continue to decrease by 2100 under both climatic scenarios, that is, by 340 194 km^2 (SSP126), 348 544,9km^2 (SSP245) and 379 167.9km^2 (SSP585), which is alarmingly serious and raises conservation concerns as also evidenced by Jinga et al., (2019).

Mittermeier et al. (2003) classified the woodlands as a global wilderness area where conservation should be emphasised. This implies that there is a need to protect the species from unstainable practices such as irreparable harvesting and other human-induced factors such as deforestation by using conservation activities such as reforestation and law enforcement to restrain illegal logging. The Government of the U.K. said that if greenhouse gas emissions are mitigated, species occurrence will remain unchanged. However, drawing judgement from the currently predicted suitability and future suitability, it is pretty interesting to note that, unlike most countries that are expected to be seriously affected by climate change (Chapano, 2003), Swaziland shows that it is not significantly altered by a shift in climatic scenarios and occurrence of *B. spiciformis* is likely to expand in this country (Fig 4.2a and b; Fig 4.3a and b). Kanzler, Nel and Ford, 2014 postulated that this might be due to implementing sound mitigation and climate change adaptation measures.

5.4 Model Limitations And Future Research

Although the MaxEnt models performed well, they only incorporated climatic variables and did not account for other potentially influential factors like soil characteristics and land use changes, among others; therefore, additional research taking into account other factors such as environmental and biotic factors can further refine our understanding of *B. spiciformis* habitat requirements and responses to climate change through techniques like field validation. Comparing the modelled habitat suitability to the actual occurrence and abundance of the species on the ground can help assess the accuracy and reliability of the predictions. However, it should be appreciated that this type of species distribution modelling technique provides a valuable framework for assessing climate change risks and informing conservation efforts for this and other ecologically important tree species in southern Africa and the world.

5.5 Spatial Patterns Of Habitat Suitability.

The model results indicate the relative importance of different environmental predictors and provide spatially explicit habitat suitability projections for *B. spiciformis*. Examining the distribution maps generated by the MaxEnt model can reveal interesting spatial patterns and potentially identify currently suitable regions that may become less so in the future. For example, the model may show core areas of high suitability that are likely to persist and peripheral regions where suitability is predicted to decline. This could inform targeted conservation efforts. Comparing the 2080 and 2100 projections can also highlight how the species' range may shift over time in response to climate change.

5.6 Interactions Between Variables.

The analysis so far has focused on the individual contributions of the different environmental variables. However, meaningful interactions between these variables likely shape the habitat suitability for *B. spiciformis*. For instance, the effect of precipitation may depend on the temperature regime, or the species' response to seasonality may be moderated by overall isothermality. Exploring these interactions could yield a more nuanced understanding of the species' ecological requirements.

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

6.1 CONCLUSIONS

According to the findings of this study, *B. spiciformis'* distribution is likely to be significantly altered by climate change. The suitable habitats for this prominent species are projected to decline under the three climate change scenarios (SSP126, SSP245 and SSP585). The predicted distribution models indicate that *B. spiciformis'* is forecasted to experience range deterioration under all climate change scenarios, not only for 2080 but also extending to 2100. This suggests that this species is at high risk of extinction due to the anticipated harsh climatic conditions. Swaziland is the only country where B. spiciformis is less likely to be altered by shifts in climatic scenarios. *B. spiciformis* is expected to expand in this country, possibly due to the implementation of sound mitigation and climate change adaptation measures.

The vulnerability of *B. spiciformis* is probably related to its habitat elasticity, meaning the species may have limited adaptability to the projected changes in environmental conditions. This finding highlights the urgent need for proactive conservation measures to safeguard this and other threatened tree species in Southern Africa, as the impacts of climate change are expected to intensify in the coming decades.

6.2 RECOMMENDATIONS.

The spatial predictions of habitat suitability of this study, especially the identification of core (regions that currently have high ecological value and intactness) versus future at-risk areas (regions predicted to be at high risk of environmental degradation or species loss in the future even though their ecological condition can be good now) can help conservation planners prioritise regions for active management and protection. Areas predicted to maintain high suitability over time may be targeted to preserve existing populations, while declining suitability zones could warrant interventions like ex-situ conservation efforts. Recognising the critical role that *B. spiciformis* plays in the miombo woodland ecosystems of southern Africa, the species distribution modelling can feed into land use planning and decision-making processes; for instance, areas projected to retain high habitat suitability could be targeted for conservation-oriented land uses such as designating them as protected areas or community forests while regions, where suitability is expected to decline, may be better suited for other forms of sustainable development that minimise impacts on *B. spiciformis* and associated biodiversity.

In addition, research incorporating not only climatic variables but also considering other factors such as land use changes in species modelling should be done to get a precise and more accurate understanding of *B. spiciformis'* habitat requirements. Not only that, the findings of this study should be compared to Ground Truth data to test the accuracy of the model.

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