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Impact of climate change on the commercial suitability of the drought-tolerant *Eucalyptus camaldulensis* in sub-Saharan Africa

REWARD NYABOTE

B191528B

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DECLARATION

The signatories confirm that they have examined and given their approval for this research project to be marked in accordance with the criteria and guidelines of the department.

Student: NYABOTE REWARD B191528B

Signature………………………….. Date……………………………

Supervisor Prof L. Jimu

Signature………………………….. Date……………………………

DEDICATION

To my family, I dedicate this project research.

ACKNOWLEDGEMENTS

I am sincerely expressing my gratitude to my supervisor Prof L. Jimu for providing their knowledge, advice and supervision during my period of study. His patience and understanding are also grateful to this effort of study. My gratitude to Mr Mohamad for providing technical support on the device maintenance and repair such that the accomplishment to my studies is enhanced. My appreciation also goes to my colleagues and my family for the continuous care and support they have provided during this research. Their motivation and encouragement inspired me to work on this research topic. Above all, I am deeply thankful to God for providing me with wisdom, strength and insight on this project. His revelation, unwavering love and his endless blessings guided me from the beginning till the end of my entire research study.

ABSTRACT

In the absence of widespread cooperation and participation in an appropriate and effective systematic observation, mitigation, and adaptation measures, the world is currently experiencing an unprecedented climate change phenomenon that is likely to result in a crisis of species survival, distribution, and socioeconomic development. The study of the research aimed at determining climate change impact on the commercial suitability of the drought-tolerant *Eucalyptus camaldulensis* in Sub-Saharan Africa. The distribution of *E. camaldulensis* in Sub-Saharan Africa was modelled using the maximum Entropy (MaxEnt) technique in R software version 4.2.2 after data of species occurrence was retrieved from GBIF database (http://gbif.org). Two Representative Concentration Pathways (RCPs) climate tool models, namely RCP 8.5 model and RCP 2.6 model, project the distribution of the species ecology to the years 2050 and 2070. Current predicted suitability portrayed that the geographical habitats for *E. camaldulensis* are in line with the species' present range, they are significantly correlated with a range of 0.4 and above in predicted suitability areas. The ecological niche models for *E. camaldulensis* under 2 climatic scenarios, predicted significant changes in the future predicted suitability. All scenarios highlighted a wide range of shrink, proving that climate change have an impact on the survival of *E. camaldulensis* though it is a drought tolerant species, hence loss of biodiversity in near future. According to the results, it is expected that difficult climatic circumstances will endanger extinction since the distribution of the species is likely to be severely affected by climate change under (RCP 8.5) model scenario. It is recommended that suitability areas that are predicted in this research can help in planning and assessing the suitable adaptation measures to be put in place, such as encouraging the use of drought tolerant varieties, to lessen the possible negative climate change effects on E. camaldulensis.

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AUC	Area Under the Cave
BIO	Bioclimatic Variables
CMIP5	Coupled Model Comparison Project phase 5
CO^2	Carbon dioxide
DDC	Data Distribution Centre
ENM	Ecological Niche Modelling
GBIF	Global Biodiversity Information Facility
GCMs	Global Climate Models
IPCC	Intergovernmental Panel on Climate Change
MaxEnt	Maximum Entropy
NDVI	Normalised Difference Vegetation Index
RCP	Representative Concentration Pathway
WPS	World Climate Project
%	Percent
°C	Degrees Celsius
Mm	Millimetre

CHAPTER 1

INTRODUCTION

1.1 Background to the Study

In the 19th century, *Eucalyptus* genus developed into a key multi-purpose supply of lumber for a variety of industrial uses, including the production of pulp and paper, energy, charcoal, furniture, and infrastructure.(Hirsch, Michael H Allsopp, *et al.*, 2020). With more than 700 species, the *Eucalyptus* genus primarily evolved in Australia (Hirsch, Michael H. Allsopp, *et al.*, 2020). The trees grow in open tall forests and woodlands, and they can be found in a variety of climates, from semi-arid regions with low rainfall to sea level habitats with subalpine elevations. Several species have been reported to exist outside of Australia's borders. (Crisp *et al.*, 2001). Today, in the tropical zone, plantations on *Eucalyptus* occupy 12 million acres at least, with 90% of those being created after 1955 (Bayle, 2019). Early in the 20th century, a sizable number of *Eucalyptus* plantations were planted alongside railway tracks in Brazil and South Africa, producing charcoal for engines. There are currently an estimated 16–19 million hectares of forests planted in a number of South American, Asia, southern European, and African nations (Payn *et al.*, 2015). In commercial plantations, *E. grandis, E. globulus, E. camaldulensis,* with their hybrids make up species majority of (around 80%). *E. globulus* is favored in temperate climates, whereas *E. urophylla*, and their hybrids are mainly planted in tropical and subtropical regions (Payn *et al.*, 2015). The invention of cloning techniques, which was played a key influence in choosing the foundation of the Popular Republic of Congo in 1975 of enormous areas of commercial *Eucalyptus* plantations (Oyono *et al.*, 2013). Early in the 20th century, the genus was brought to East Africa, where by the early 1970s, there were 95,684 ha of *Eucalyptus* trees in Sudan, Kenya, Uganda, Ethiopia and Rwanda (Bayle, 2019).

Eucalyptus camaldulensis is known for its tolerance to drought and its ability to grow in water logged soils, which has made it popular for planting along river banks and in other riparian zones (Doody *et al*., 2018). It is widely planted in Africa for commercial wood production due to its superior stem form, coppicing ability, easy workability characteristics and environmental conservation as well as for fuel wood, charcoal, and other purposes (Bayle, 2019). Early in the

1900s, *Eucalyptus* species were introduced into Zimbabwe to provide the country's demand for fuel, sawn timber, and hardwood poles. Since then, a number of species have been grown in plantations, especially in the country's Eastern Highlands (Shi *et al.*, 2012). Eucalypts occupied about 29 314 hectares (25%) of the nation's 119 130 hectares of plantation land as of 2001. About 3% of the GDP comes from *Eucalyptus* species, together with pines (Jimu, Wingfield, *et al*., 1900). For the aim of growing poles and fuelwood, eucalyptus species are commonly planted in rural areas in addition to being grown in well managed plantations.

Eucalyptus genus is most typically planted species in the tropics and subtropics, and it is second only to pines in its significance as plants plantation worldwide. There are more than 900 species of *eucalypts* worldwide, in addition to unidentified hybrids and variations (Alebachew *et al*, 2015). *E. camaldulensis* is the most widely grown tree for building and fuelwood, and it is also the first tree exploited as a commercial crop. It is grown extensively in Ethiopia's Amhara region. *Eucalyptus* trees are mostly valued for their timber, which has high yields per unit area and year and quick growth (Alebachew *et al*., 2015).

The development, organization, distribution, and diversity composition of *Eucalyptus* species are significantly impacted by climate change. High temperatures cause vapor pressure deficits, which can enhance the possibility of evapotranspiration, and have a detrimental effect on the synthesis of macromolecules (proteins and DNA), (Hirsch, Michael H. Allsopp, *et al.*, 2020). Additionally, it i/s claimed that *Eucalyptus* grows more efficiently and productively when it is cultivated in managed plantations at advantageous locations or in environments with ample supply of water and nutrients. In comparison to many other species, *E. camaldulensis* produces a lot of food in hot temperatures and infertile barren soil (Alebachew, *et al*., 2015).

One of the greatest tree species is the *Eucalyptus* since it grows quickly and can fix more (CO^2) through photosynthesis, acting as a carbon sink. As compared to many other tree species, it can yield higher biomass, eucalyptus is an effective producer of biomass (Alebachew *et al*., 2015). It is well recognized that biomass production and carbon sequestration are inversely correlated. The yearly production rates of wood for *E. globulus* in the Ethiopian highlands vary depending on the soil type, stand age, and rotation cycle, from 168 to 2,900 kg/ha/year may be produced., showing higher biomass carbon sequestration (Alebachew *et al*., 2015). On the other hand, inter-planting nitrogen-fixing Acacia and Albizia species with *Eucalyptus* species can help with carbon sequestration. Consequently, *Eucalyptus* plantations can significantly reduce climate change (Alebachew *et al*., 2015).

1.2 Problem Statement

There is insufficient knowledge about how climate change will impact the future cultivation of *E. camaldulensis* species in sub-Saharan Africa, despite the fact that several studies on the tree species have been conducted in this continent**.** Although *E. camaldulensis* is known to be drought tolerant, it's not clear whether its elasticity will be enough to withstand the increasing temperatures and droughts projected to increase in sub-Saharan Africa. Climate change tolerance is important for the continued cultivation of the species in plantations and possibly substitution of drought-intolerant *Eucalyptus* species currently cultivated in Sub-Saharan Africa.

1.3 Justification of the Study

Ecological niche modeling for *E. camaldulensis* is essential because it can be used to predict areas where the species will probably flourish and where it may face challenges due to changing climate as well as the possible range of the species and forecasting future suitable sites in Sub-Saharan Africa. Making decisions requires the knowledge of the environmental factors influencing the occurrence of *E. camaldulensis* species since it gives a starting point for land use planning, implementing adaptive management strategies and conservation initiatives in view of current and future situations, such as to priorities afforestation and reforestation efforts. (ENM) It can provide valuable information for identify key factors that influence the species distribution and can inform research on the species biology and ecology. Lastly, it can provide insight into the probable distributional effects of climate change and abundance of this species in Sub-Saharan Africa.

1.4 Aim of the Study

The focus of this study is to project the impact of climate change on the viability of *Eucalyptus* forests plantations in sub-Saharan Africa.

1.5 Objectives

The objectives of this study are to determine:

The current suitability of *E. camaldulensis* in forest plantations of sub-Saharan Africa.

Resilience of *E. camaldulensis* domesticated in sub-Saharan African forest plantations to climate change.

Climatic variables that affect the cultivation of *E. camaldulensis* in Sub- Saharan Africa.

1.6 Research Questions

1. Which areas are currently suitable for the cultivation of *E. camaldulensis* in sub-Saharan Africa?
2. How will climate change affect the future cultivation of *E. camaldulensis* in sub-Saharan Africa?
3. What climatic factors that will have the biggest influence on the cultivation of *E. camaldulensis.*

CHAPTER 2

LITERATURE REVIEW

2.1 *Eucalyptus camaldulensis* Species Ecology

Of all the eucalypt species, *Eucalyptus camaldulensis*, sometimes called river red gum, has the widest native range. It occurs in all of Australia's mainland states (Hirsch, Michael H. Allsopp, *et al.*, 2020). It is primarily found around waterways and on floodplains, where it frequently makes up a significant portion of woods and riparian forests (Good *et al*., 2017). The species commonly grows in monospecific stands as a result of the leaves that have allelopathic compounds and impede the growth of various species and the exceptional ability of established plants to resist both floods and droughts (Good, Smith and Pettit, 2017). The species can however, combine stands of different riparian plants in some places (Orwa, 2009). Since 1900, the species has been widely planted across Africa and is now common in tropical Africa, where it is probably the most common tree in shelterbelts, woodlots and fuel wood plots but less significant in extensive plantations.

E. camaldulensis biophysical boundaries can be found in open woods and forest up to 700 meters in elevation, primarily along watercourses and on floodplains. Trees that have been planted can thrive in a range of temperatures, from cool to warm and humid to dry (Doody *et al.*, 2015). Natural stands experience annual rainfall ranging from 250 to 2500 mm, although planted trees can thrive in environments with just 150 mm of precipitation (Orwa, 2009). A high-water table or periodic flooding are essential for survival in desert regions. Africa's regions with an average yearly rainfall of 700–1200 mm experience the best growth. The dry season can last anywhere from 0 to 8 months. The average annual temperature is between 13 and 28 °C (Orwa, 2009). The coldest month's mean minimum temperature is between 3 and 22 °C, while the hottest month's mean maximum temperature is between 21 and 40 °C (Orwa, 2009). The river red gum may frequently endure up to 20 frosts each year, but it cannot tolerate temperatures below -10°C. It is grown in African tropical at elevations ranging between sea level and 2800 meters. (Orwa, 2009). It tolerates waterlogging and sporadic flooding but flourishes in deep, silty or loamy soils with a clay base and a reachable water table. *E. camaldulensis* species is most tolerant to acidic soils which has been identified (Orwa, 2009).

2.2 Significance of the Tree Species

The greatest benefit of *Eucalyptus* may be that it replaces native species used for fuel wood, preventing further deterioration of natural forests (Bayle, 2019). Additionally, some *Eucalyptus* species could reduce the likelihood of land degradation and desertification by providing firewood quickly (Bayle, 2019). River red gum is frequently planted for shade, windbreak, ornamental purposes, amenity needs, and as a source of nectar to create premium honey. It is intended to use saline groundwater to help restore saline land. It is cultivated in Somalia along roads and sand dunes (Bayle, 2019). Livestock might consume the leaves. *Eucalyptus camaldulensis* was frequently utilized for non-commercial plantings (mostly unrecorded) on private lands (Bayle, 2019). In a place like South Africa where water is scarce, the river red gum's rapid growth suggests significant water intake that has enormous hydrological effects. According to a study conducted in Pakistan, *E. camaldulensis* used up to three times as much water as some native trees during a greenhouse trial (Hirsch, Michael H. Allsopp, *et al.*, 2020).

The *Eucalyptus* oil that comes from *E. camaldulensis* is its essential oil. It is made from the leaves of primarily tropical origins (Ali and Usman, 2022). It has medical uses, including treating coughs and functions as an expectorant contains febrifuge, tonic, astringent, antiseptic, haemostatic, and vermifuge effects (Ali and Usman, 2022). Senegal uses a sugar-sweetened leaf decoction to cure stomach problems and dysmenorrhea. Fresh leaves are used in Sudan to cure rheumatism, and the smoke from burned leaves is inhaled to alleviate respiratory issues. The gum is used as an astringent, a remedy for diarrhoea, and a treatment for pharyngeal inflammations. Nigerians harvest chewing sticks from trees. Insects are repelled by burning leaves' smoke (Ali and Usman, 2022). Fast-growing plants are used in phytoremediation to transform, degrade, accumulate, stabilize, immobilize, or volatilize hazardous chemicals in order to purify soil and water. (Hirsch, Michael H. Allsopp, *et al.*, 2020).

2.3 Likely Impacts of Climate Change

Climate change is anticipated to alter precipitation patterns in many parts of Sub-Saharan Africa, threatening the development and survival of *Eucalyptus* trees (Shi *et al.*, 2012). Water stress and restricted growth may occur in *Eucalyptus* plantations in locations where rainfall drops, and flooding and soil erosion may occur in areas where rainfall increases (Shi *et al.*, 2012). Higher temperatures may cause greater evapotranspiration, exacerbating water stress in *Eucalyptus* plantings (Alebachew *et al*., 2015). Furthermore, increased temperatures may raise the risk of pests and diseases that damage *eucalyptus* plants (Jimu *et al.*, 1900). *E. camaldulensis* is vulnerable to several fungi that cause diseased leaves and damping off in nurseries (Jimu *et al*., 1900).

Climate change may alter soil fertility, affecting the growth and productivity of *Eucalyptus* plantations (Almeida *et al.*, 2010). Increased rainfall, for example, may cause nutrient loss from the soil, whilst higher temperatures may hasten the decomposition of organic materials (Almeida *et al.*, 2010). Higher (CO2) levels in the atmosphere may accelerate the growth of *Eucalyptus* trees, perhaps leading to higher yields in some places (Dusenge, Duarte and Way, 2019). However, it is crucial to highlight that the good effects of rising (CO2) concentrations are likely to be countered by other climate change impacts, changes such as in precipitation patterns and increased temperature (Dusenge *et al*., 2019).

Climate change disrupts species interactions and composition and has the potential to diminish biodiversity dramatically (Bayle, 2019), their high evapotranspiration rate may lead to a reduced water table. According to some reports, a high rate of soil water loss has a detrimental effect on nearby rainfall totals and could cause the area to become desertified (Bayle, 2019). *Eucalyptus* plantations, on the other hand, they are different not from plantations of any other tree or several native forest species with comparable structure and albedo in terms of their regional influence (Bayle, 2019). Overall, these studies emphasize the importance of managing *Eucalyptus* plantations carefully in the face of climate change, including the adoption of proper planting techniques, species selection, and irrigation tactics.

2.4 Ecological Niche Modelling

The term "ecological niche modelling" is often used to describe species distribution models (SDMs), which are a common technique in quantitative ecology (Peterson and Soberón, 2012) and the most widely used modelling framework in assessments of the impacts of climate change for predicting potential future range shifts of species (IPCC, 2022). The model is focused on modelling how the advantageous habitats accessible to a specific species would vary under various climatic change scenarios to forecast how biological systems will alter in response to climate change (A.P.M. Baede *et al*., 2001).

The (ENM) approach is predicated on the idea that climatic patterns, including precipitation, temperature, and seasonal variations, have a significant impact on species distribution, abundance, and diversity, also on societal structures and ecosystem health as a whole (Sintayehu, 2018). This approach aims to map a species' key physiological tolerances against a changing climate in order to determine the species' environmental niche, or the whole range of climatic conditions in which it is likely to exist (A.P.M. Baede *et al*., 2001). Once a species' "climatic space" has been determined, its location can be estimated using future climate change models or existing climatological data (Fick and Hijmans, 2017). Furthermore, georeferenced observations of biodiversity are required for (SDMs), in addition to geographic layers of environmental data, such as land cover, climate, soil characteristics, predictors or independent factors and the response or dependent variable (e.g., individual locations, species presence, species counts, species richness), (Fick and Hijmans, 2017).

The goal of this work is to create ecological niche models for the Australian-native *E. camaldulensis* species that can adapt to environmental circumstances in Sub-Saharan Africa in order to evaluate how different climatic factors affect the geographic range of the species. Based on 19 environmental variables, the Maxent Entropy approach was applied to forecast results using RCP 8.5 and RCP 2.6 forecasted for the years 2050 and 2070 (Phillips *et al.*, 2006). The MaxEnt model was introduced to forecast the possible distribution of *Eucalyptus* trees in Cameroon under the 2.6, 6.5, and 8.5 RCPs (Waititu *et al*., 2022). The results showed that in all three scenarios, the potential range of *Eucalyptus* species would be significantly smaller and relocate to higher elevations and latitudes. According to the authors' estimates, the amount of habitat that is appropriate for *Eucalyptus* species will decline by 20–70% by 2070, depending on the RCP scenario (Waititu *et al*, 2022). Environmental management increasingly employs ecological niche modelling as a tool to evaluate habitat suitability, investigate the consequences of climate change, and save endangered species (Peterson and Soberón, 2012). Environmental niche models are frequently employed to define niches, extend distributional trends, forecast uncharted distributional regions, assess the geographic potential of invading species, and forecast responses to shifting environmental conditions. (Peterson and Soberón, 2012).

The MaxEnt model was introduced to forecast the possible distribution of eucalyptus species in Kenya under the 2.6, 6.5, and 8.5 RCPs (Waititu *et al*., 2022). The scientists discovered that in all three scenarios, the potential range of *Eucalyptus* species would be significantly smaller and relocate to higher elevations and latitudes. According to the authors' estimates, the amount of habitat that is appropriate for *Eucalyptus* species will decline by 20–50% by 2070, depending on the RCP scenario (Waititu, Mundia and Sichangi, 2022). Also, in Gabon under the RCPs of 2.6 and 8.5, the researchers discovered that there would be a considerable reduction in the area of the range and a shift in the probable distribution of *Eucalyptus* species to higher elevations and latitudes (Justice *et al.*, 2001). The authors also anticipated a 15–60% decline in suitable habitat for *Eucalyptus* species by 2070 (Justice *et al.*, 2001). The findings indicate that the distribution of *Eucalyptus* species in Sub-Saharan Africa is anticipated to see substantial impacts from climate change, with potential range shifts and losses in suitable habitat (Justice *et al.*, 2001). It emphasizes how crucial it is to create plans to lessen the distribution's potential impact of climate change and preservation of *Eucalyptus* species.

CHAPTER 3

MATERIALS AND METHODS

3.1 Data Acquisition

Occurrence data for *E. camaldulensis* was downloaded directly from the GBIF database (http://gbif.org) (Beck *et al.*, 2014). Remove duplicates from the search results and only display instances that have latitude and longitude information. Save the filtered occurrence data in a format that works for you, such CSV or Excel. Find climatic information for the chosen RCP scenarios from a reliable source, like the IPCC Data Distribution Centre. Run the ecological niche modelling tool, such as MaxEnt using the occurrence data and climate data for each of the RCP scenarios, using statistical software such as R (Yackulic *et al.*, 2013). Adjust the model's parameters as needed after validating it with the proper metrics such as AUC (Jiménez-Valverde, 2012). Interpret the results and draw conclusions concerning the potential effects of upcoming climate change on the probable spread of *E. camaldulensis.* Additionally, the World Climate Project was used to produce matched future climate estimates for a significant number of Global Climate Models (GCMs) were used in the phase 5 Coupled Model Inter-comparison Project (CMIP5) (Fick and Hijmans, 2017). To calculate the difference between the present and upcoming forecasts of 2050 and 2070, (RCP8.5) and (RCP2.6) were utilized.

3.2 Climate Change Models and Environmental Data

The World Climate Project (http://worldclim.org) (Fick and Hijmans, 2017), provided the 19 bioclimatic predictors and altitude data which were obtained using R programming version 4.2.2., of October 2022 were the environmental data used in this investigation. The variables employed in the species distribution model were grouped to remotely sense biotic dependent variable obtained from normalized difference vegetation index (NDVI) statistics as shown in table below.

Table 1: Environmental variables used to predict *E. camaldulensis* in Africa.

Name	Variable	Units
Bio 1	Annual Mean Temperature	^oC
Bio 2	Mean Diurnal Range (Mean of monthly (max temp - min temp))	^oC
Bio 3	Isothermality (BIO2/BIO7) * (100)	^oC
Bio 4	Temperature seasonality (standard deviation *100)	^oC
Bio 5	Max Temperature of Warmest Month	^oC
Bio 6	Min Temperature of Coldest Month	^oC
Bio 7	Temperature Annual Range (BIO5-BIO6)	^oC
Bio 8	Mean Temperature of Wettest Quarter	^oC
Bio 9	Mean Temperature of Driest Quarter	^oC
Bio 10	Mean Temperature of Warmest Quarter	^oC
Bio 11	Mean Temperature of Coldest Quarter	^oC
Bio 12	Annual Precipitation	Mm
Bio 13	Precipitation of Wettest Month	Mm
Bio 14	Precipitation of Driest Month	Mm
Bio 15	Precipitation Seasonality (Coefficient of Variation)	Mm
Bio 16	Precipitation of Wettest Quarter	Mm
Bio 17	Precipitation of Driest Quarter	Mm
Bio 18	Precipitation of Warmest Quarter	Mm
Bio 19	Precipitation of Coldest Quarter	Mm

3.3 Niche Modeling

Library packages namely raster, rgdal, maps, mapdata, dismo, rJava, maptools, and jsonlite command packages as well as other related ones, were installed into R using R studio version

4.2.2, 2022 (Econometrics, 2012). The bioclimatic factor variables includes (bio1, bio2, bio3, bio4, bio5, bi06, bio7, bio8, bio9, bio10, bio11, bio12, bio13, bio14, bio15, bio16, bio18, bio19) that have a high chance of affecting the occurrence of *Eucalyptus camaldulensis* species were directly downloaded into R version (4.2.2). Utilizing the Maxent method, which looks for the biggest combination of environmental reactions that best predicts the presence of the species, models of ecological niches were developed (Yackulic *et al.*, 2013). An area under curve (AUC) of receiver operating characteristic (ROC) analysis model with threshold independence was used to assess the model's effectiveness (Jiménez-Valverde, 2012). The area under a (ROC) curve illustrates the likelihood that a classifier correctly contrasts presence (sensitivity) with absence (specificity) or background points. (AUC) values of zero (0) signify an impossible occurrence zone in contrast to one (1), which stands for a flawless occurrence area (Jiménez-Valverde, 2012).

CHAPTER 4

RESULTS

4.1 Current Suitability of *Eucalyptus camaldulensis*

According to the methodology for estimating *E. camaldulensis's* current suitability, geographical habitats are in line with the species' present range. The results of the existing suitability distribution and its expected suitability are significantly correlated, according to the model. Based on the species' present suitability zones, it can be deduced that the maximum ranges, above 0, 6, are located in Sub-Saharan Africa in nations like South Africa (Lesotho, Cape Town, and Swaziland), and the scale steadily declines as the map advances north. Additionally, species exceeding 0, 6 are concentrated heavily in West African nations like Benin, Togo, and Burkina Faso, and their numbers gradually decline as they move west. Wide range of species distribution are scattered on scale between 0, 2 and 0, 4 in most countries like Botswana, Mozambique, Zambia, Malawi, Madagascar, Ghana, Nigeria, Ivory Coast, South of Sudan and Zimbabwe. The current suitability map also reveals some of the other countries that fall below the range of 0, 2 such as Namibia, Ethiopia, Kenya, Morocco, Egypt, Senegal and Western Sahara to mention a few. The map indicates that high concentration of above 0, 6 species distribution, there are favourable geographical conditions and those that fall below 0, 2, there are poor geographical conditions which inhibit the species suitability.

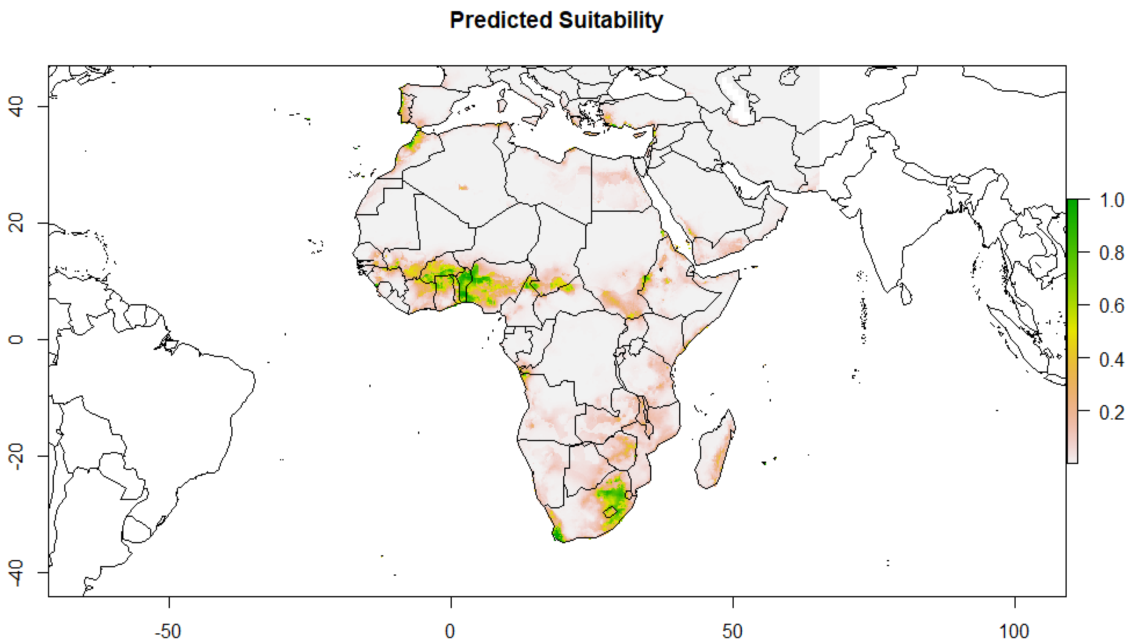


Figure 1: Current Predicted Suitability of *E. camaldulensis*.

4.2 Future Suitability of *E. camaldulensis*

The results in comparison between current predicted distribution and future predicted distribution under (RCP) model 2.6 for both year 2050 and 2070 shows that there is a significant visible shift in *E. camaldulensis* species geographical range suitability, driven by the shift in climatic scenarios in countries like South Africa (Lesotho and Swaziland). Its abundance shows < 0, 6 range of occurrence though it decreases significantly. The habitat in western African countries like Benin, Nigeria, Togo, and Ivory Coast is projected to be suitable for the cultivation of *E. camaldulensis* though it significantly shrinks its suitability range from 0, 8 to 0, 4 concentrations. This denotes that there is a reduction in species favourable geographical conditions. There will be a significant decrease of species distribution from 0, 4 to 0, 2 range in most countries like Mali, Burkina Faso, Ethiopia, Malawi, Mozambique, Botswana, Zambia, Democratic Republic of Congo, Libya, Egypt, Madagascar, and Zimbabwe to mention a few. The results shows that there is a decrease in species cultivation. Lastly, there will be a slight shift of species distribution below 0, 2 in countries like Angola, Namibia, Morocco, Somalia, Western

Sahara to list a few. The results shows that *E. camaldulensis* cultivation continuously deteriorating due to a decreased favourable species climatic condition.

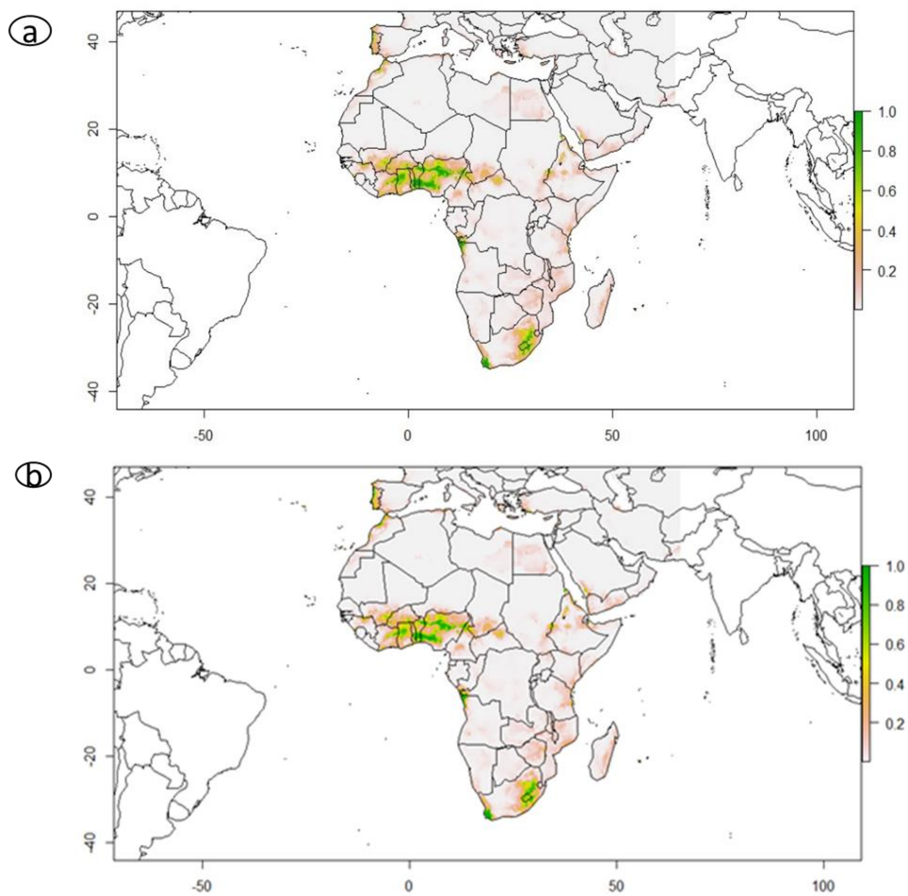
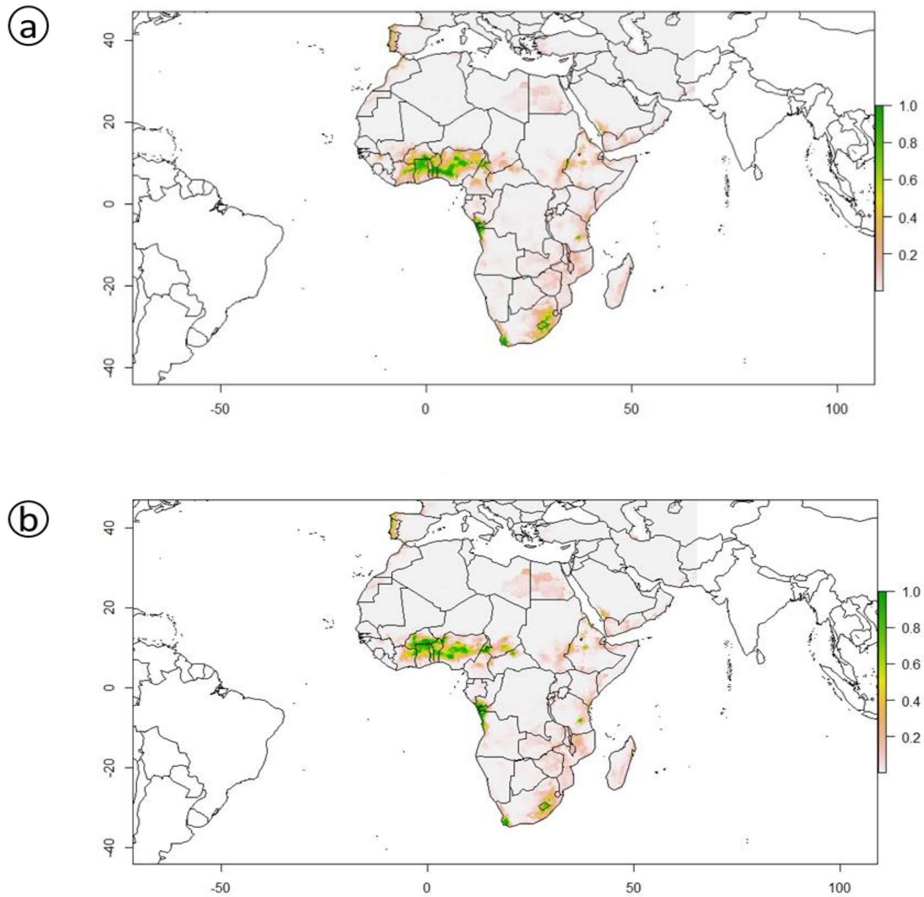


Figure 2: Predicted distribution of *E. camaldulensis* for (RCP) 2.6 2050 (a) and 2070



(b).

Figure 3: Predicted distribution of *E. camaldulensis* for (RCP) 8.5 2050 (a) and 2070 (b).

(RCP _8.5 model) was noted to have adverse impacts on species geographical range suitability for both year 2050 and 2070 as compared to current prediction. Under the RCP _8.5 model, area suitable for the cultivation of *E. camaldulensis* is projected to shrink by both 2050 and 2070 in countries like South Africa, Nigeria, Benin, and Burkina Faso (> 0.8 to 0.6). In countries like Mozambique, Ethiopia, Egypt, Kenya, DRC and Zimbabwe, the land suitability drastically goes down (>0.2). The model also shows countries like Botswana, Angola, Namibia and Morocco the species geographical range will extinct in the year 2050 and 2070. The model revealed that *E. camaldulensis* will be a critically endangered species under (RCP model 8.5) for both year 2050 and 2070 as compared to the current prediction suitability as shown in (figure 3) above.

The results of this analysis suggested a significant relationship between bioclimatic factors and the anticipated distribution of *E. camaldulensis*, the predictions of the models shows that findings were accurate with (AUC) Area Under the Roc Curve of about 0.981 true as shown in (Figure 4a) below.

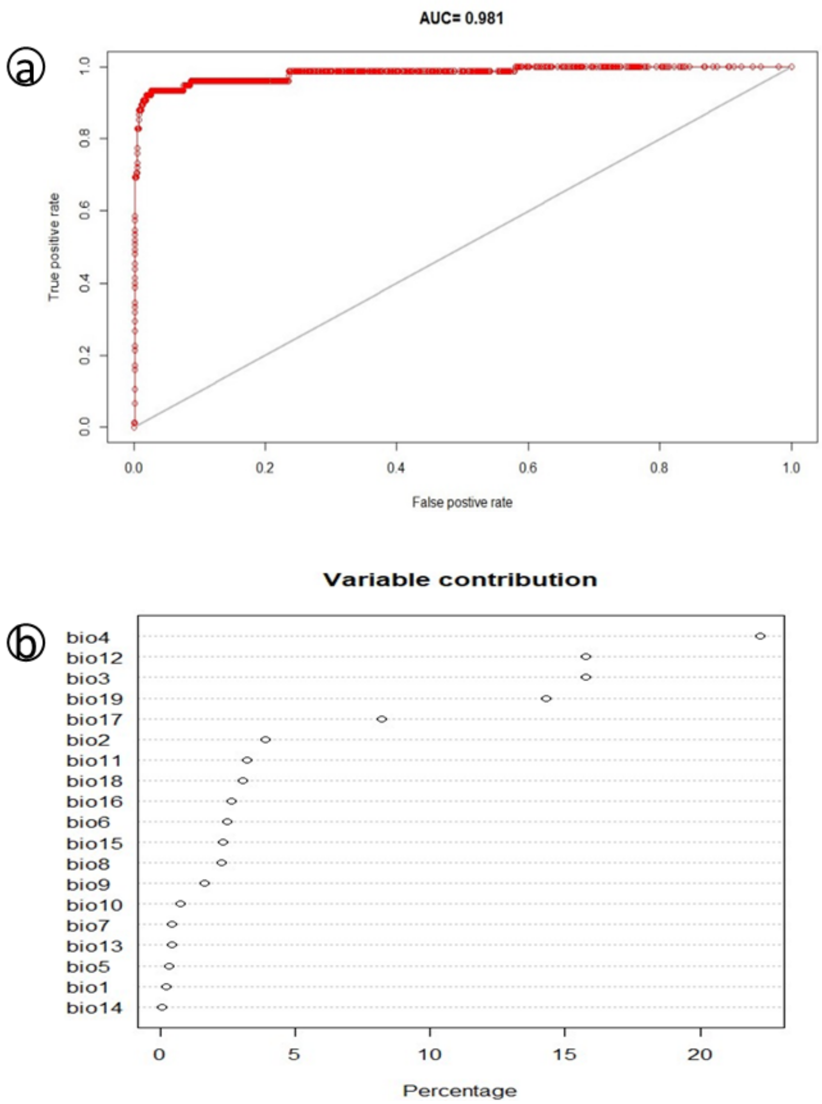


Figure 4: AUC (a) and Variable contribution (b).

The result of this study shows that Temperature Seasonality (standard deviation*100) (bio4) was the most variable which influence the predicted land suitability for *E. camaldulensis* with about 24% influence on the two RCP models used for this study, followed by Annual Precipitation (bio12) and isothermally (bio3) both with about 16%. Other variables were Precipitation of Coldest Quarter (bio19) with 15% and influence of Precipitation of Driest Quarter with about 8% (bio17). Lastly, Mean Diurnal Range (bio2) with 4% and Mean Temperature of Driest Quarter (bio9) with about 2% as shown in (figure 4b) above.

CHAPTER 5

DISCUSSION

Species distribution models showed that the area suitable for the cultivation of *Eucalyptus camaldulensis* regularly deteriorated under RCP 2.6 and RCP 8.5 models of climate change. This species is predicted to be significantly impacted by climate change, which could affect its growth and survival by altering the temperature, precipitation, and other climatic conditions. The various causes of *E. camaldulensis* decline, differences between 2050 and 2070 years, and the present expected suitability using the 2.6 and 2.8 RCP models will all be included in this response.

One potential reason for *E. camaldulensis* deterioration between 2050 to 2070 years and current predicted suitability is increased temperature. Higher temperatures can lead to reduced growth and increased mortality in *E. camaldulensis* (Choat *et al.*, 2018). The results of this investigation demonstrate that temperature (Bio2, Bio4, and Bio9) (Ramírez and Bueno-cabrera, 2009) were crucial in characterizing the appropriateness for *E. camaldulensis* shown in (Figure 5b). High temperatures could, however, affect species abundance, migration patterns, and mating seasons, particularly in areas where ecotourism is a significant sector. Changes to essential habitats for wildlife and reptiles result in a loss of biodiversity, which has an effect on socioeconomic effects in future (Bayle, 2019).

Another potential reason for *E. camaldulensis* deterioration is changes in precipitation patterns. Changes in precipitation patterns can have significant impacts on the growth and survival of *E. camaldulensis*. Precipitation (Bio3, Bio12, Bio17, and Bio19) (Ramírez and Bueno-cabrera, 2009) variables also signifies the potential effect on the species (figure 5b). Another study by (Justice *et al.*, 2001) found a loss in potential distribution due to the expected decreasing the amount of precipitation and increasing the temperature in Sub-Saharan Africa under future climate scenarios. This could result in less moisture being available to the species, which could put it under more water stress. In addition, a result of negative socio-economic impacts in future as *E. camaldulensis* is an important source of timber and other products in various regions (Bayle, 2019).

(Waititu *et al.*, 2022) looked at the influence of biotic interactions on the distribution of *Eucalyptus camaldulensis* in Ethiopia in a different study. The study discovered that the growth and survival of *E. camaldulensis* were negatively impacted by the presence of other tree species, particularly Acacia and Boswell, competition for resources like nutrients and water may be the cause of this. Additionally, (Bayle, 2019) looked into how fire affected the spread of *Eucalyptus camaldulensis* in Sub-Saharan Africa. The study discovered that the region's frequent wildfires had a detrimental effect on *E. camaldulensis* growth and survival and that the species was more likely to exist in regions with less frequent fires. Increase frequency and severity of heatwaves, droughts and other extreme whether events impact species forest health making them more prone to diseases, wildfires and pests thus, reduced productivity and economic losses for industries that the species rely on (Jimu *et al.*, 1900). This however, lead to the deterioration of species niche in Sub-Saharan Africa under 2.6 and 8.5 RCP models for the years 2050 and 2070.

E. camaldulensis root system can adapt to varying water supply levels at various depths. The river red gum can adapt to a variety of climatic conditions, from tropical to desert and temperate zones, and a wide rainfall range zones from 250 – 1500 mm annual rainfall. According to some studies, flooding is not necessary for species regrowth in its natural habitat (Hirsch, Michael H. Allsopp, *et al.*, 2020). This clearly portrayed by the significant deterioration in the species distribution as shown in predicted suitability under 2.6 and 8.5 RCP models in chapter 4. The test dataset's Area under the Curve (AUC) value was 0, 98 demonstrating that the model was successful in replicating *Eucalyptus camaldulensis'* projected future habitat (Fig. 4a), demonstrating the validity of the study's conclusions.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Eucalyptus camaldulensis, tree species widely planted in forest plantations in Sub Saharan Africa, is likely to experience significant changes in its distribution and growth under the (2.6 and 2.8 RCP) climate change models scenarios. The species is projected to experience increased water stress, which may negatively impact its growth and distribution in some regions. The predicted distribution of the species indicates a range of deterioration under (RCP 2.6) and further shrinkage under the extreme scenario (RCP 8.5). However, climate change effects on *E. camaldulensis* will vary depending on the specific location, environmental conditions as well as other factors like land use and biotic interactions.

6.2 Recommendations

It is advised that suitable adaptation measures be put in place, such as encouraging the use of drought tolerant varieties, to lessen the possible adverse climate change effects on *E. camaldulensis*. Predicted suitability areas in this research can assist in assessing conservation means of the species at national and regional level, hence continuous assessment and monitoring in the field should be practiced to determine the range size of *E. camaldulensis* species for natural resources evaluation especially coming up with inventory list of threatened species. The outcome of this study can be used to figure out suitability areas for species regeneration. The approach used in this study can also be used to figure out suitability habitats and coming up with strategic mechanisms for protection and plans of *E. camaldulensis* species with significance in the region. Moreover, the output of the study can be referenced in developing *Eucalyptus* inventory lists which can be used for early prediction signs of climate change at local and global scale.

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