MODELLING THE POTENTIAL ECOLOGICAL NICHES OF NOXIOUS KONGWA WEED IN TANZANIA FOR IMPROVED LAND USE MANAGEMENT

WILFRED GERARD MKONGERA

A DISSERTATION SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN LAND USE PLANNING AND MANAGEMENT OF SOKOINE UNIVERSITY OF AGRICULTURE. MOROGORO, TANZANIA.

2021

ABSTRACT

Noxious weeds are problematic in many parts of the world, greatly affecting areas of agriculture, forests, nature reserves, parks and other open spaces. *Astripomoea hyoscyamoides* also known as noxious Kongwa weed is a serious problem in agriculture sector particularly in Kongwa district. In order to manage the weed, the first step is identification of the potential habitats. Modelling is one of the best techniques in identifying weed's potential habitats because it can map large area with less time, less labor and less cost than other weed mapping techniques. The need for modelling the potential ecological niches of this weed has arisen in response to the increasing habitats of the weed in other places apart from its original locality of Kongwa district. Under present climate scenarios, model results showed that semi-arid lands of Tanzania are the most suitable habitats for the weed whereby the highly suitable habitats were found to be in Dodoma, Singida and Manyara regions. Moderately suitable habitats were found in Arusha and Lindi regions and some parts of Tanga, Kilimanjaro, Mtwara, Njombe, Mbeya, Rukwa, Ruvuma and Morogoro regions. Under future climate scenarios, Kongwa weed is predicted to be heading to the Lake zone part of Tanzania around Lake Victoria. The new regions which are likely to be invaded by the Kongwa weed in the future were found to be; Mara, Simiyu, Shinyanga and some parts of Kagera region. In determining the risk posed by different pathways in spreading the weed. Results showed that livestock movements and transportation of fodder posed the greatest risk in spreading the weed. The findings from this study have shown that Kongwa weed can establish itself in many parts of the country and therefore there is a need for coordinated efforts from both government, research institutions and the general public to consolidate plans to manage the weed such as controlled and monitored movement of livestock, transportation of agricultural produce and inputs.

DECLARATION

I, Wilfred Gerard Mkongera, do hereby declare to the Senate of Sokoine University of Agriculture that this dissertation is my own original work done within the period of registration and that it has neither been submitted nor being concurrently submitted in any other institution.

________________________ __________________

Wilfred Gerard Mkongera Date

(MSc. Candidate)

The above declaration is confirmed by:

________________________ __________________

Dr. P. Hieronimo Date

(Supervisor)

________________________ __________________

Prof. N. I. Kihupi Date

(Supervisor)

________________________ __________________

Dr. I. S. Selemani Date

(Supervisor)

COPYRIGHT

ACKNOWLEDGEMENTS

First and foremost, praises and thanksgivings to the Almighty God, for his showers of blessings throughout the successful completion of my dissertation.

I would like to express my deep and sincere gratitude to my supervisors Dr. P. Hieronimo, Professor N. I. Kihupi and Dr. I. S. Selemani for their effective supervision and professional guidance in my dissertation work.

I would also like to acknowledge my employer Tanzania Meteorological Authority (TMA) for granting me study leave to pursue my MSc. studies and the financial support.

Special thanks go to Prof. Anthony Zozimus Sangeda from the Department of Animal Aquaculture and Range sciences (SUA) for his valuable academic support and I would also like to appreciate the financial support I received from the European Union (EU) during the data collection process of this work. The funds were provided to me through Erasmus program, Mobility project and COSTECH, by participating in the research project on "Enhancing Rangeland Productivity and Community Livelihoods through Integrated management of Noxious Weeds in Kongwa District".

Much thanks are also extended to Prof. Mona Dahms from Aalborg University in Denmark for her valuable support to me during my five months study tour in Aalborg University. I would also like to express my sincerely appreciation to staffs at TALIRI Kongwa, Kongwa District Commissioner and the Kongwa community for their cooperation during my field survey in Kongwa district.

Lastly but not the least, I wish to express my sincere gratitude to my wife Mwajuma Abdallah and my daughter Nirvana Mkongera, for their great tolerance during my absence from the family.

DEDICATION

To my Parents, Mr. Gerard Joseph Makala and my mother Mrs. Grace Makala who built a strong foundation for my education, also to my wife Mwajuma Abdallah, and my daughter Nirvana Mkongera.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF ABBREVIATIONS AND SYMBOLS

ASCII	American Standard Code for Information Interchange
AUC	Area Under the Curve
CEC	Cation Exchange Capacity
DEM	Digital Elevation Model
ENM	Ecological Niche Modelling
ENSO	El Nino Southern Oscillation
FAO	Food and Agriculture Organization of the United Nations
GIS	Geographical Information System
GPS	Global Positioning System
Ha	Hectare
IOD	Indian Ocean Dipole
IPCC	Intergovernmental Panel on Climate Change
IPPC	International Plant Protection Convention
ISRIC	International Soil Reference and Information Center
ITCZ	Intertropical Convergence Zone
IUCN	International Union for Conservation of Nature
IWM	Integrated Weed Management
Km	Kilometer
M	Meter
MAM	March April May
MAXENT	Maximum Entropy
MJO	Madden Julian Oscillation
MOWI	Ministry of Water and Irrigation
NAFORMA	National Forest Resources Monitoring and Assessment

OLI	Operational Land Imager
OND	October November December
pH	Potential Hydrogen
RCP	Representative Concentration Pathway
REDD	Reducing Emission from Deforestation and from Forest Degradation
ROC	Receiver Operating Characteristics
SPSS	Statistical Package for Social Sciences
TMA	Tanzania Meteorological Authority
URT	United Republic of Tanzania
USDA	United States Department of Agriculture
USGS	United States Geological Survey
WSSA	Weed Sciences Society of America

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background Information

Weeds are the leading pest which can reduce agricultural yield tremendously. Worldwide, weeds alone accounts for about 34% of reduction in agricultural produce followed by animal pest which accounts for 18% of the global agricultural losses (Oerke, 2006). Economic and yield losses in the agricultural sector due to weeds are result of competition for water, soil nutrients, space and light between weeds and the crops or pasture plus the extra costs encountered in controlling the weeds. Moreover, weeds can also act as vectors of insects and pathogens which can attack crops and foliage (Chauhan, 2020).

However, the level of losses due to weeds in agriculture sector will depends on the type of the weed, severity of infestation, duration of infestation, competitive ability of crops in suppressing weeds, climatic and edaphic conditions which affect the growth of the weeds and crops (Gharde *et al*., 2018).

Climate and land use changes are among the drivers to the entry and establishment of the invasive weed species to different parts of Tanzania (URT, 2012). *Astripomoea hyoscyamoides* weed famously known as Kongwa weed is one of the noxious weeds existing in Tanzania (Nkombe *et al.*, 2018). In Tanzania, the weed has been so common in Kongwa district and has affected the district severely hence named as Kongwa weed (Nkombe *et al.*, 2018).

Though little information is known about the origin of the Kongwa weed, it is probably originated from Malawi, Kenya or Tanzania (Hyde *et al.*, 2021). Kongwa weed have characteristics that are similar to most of the other noxious weed species such as fast growth, rapid reproduction and high dispersal ability (Mwalongo *et al*., 2020). *Astripomoea hyoscyamoides* (Kongwa weed) is an annual dry land noxious weed having alternate simple leaves, white flowers with purple center and its height can reach up to approximately two meters high at fully maturity (Nkombe *et al*., 2018).

The rapid spreading ability of this weed has led to decrease in the area (size) of the productive land supporting the population of agro-pastoralists and pastoralists found in Kongwa district (Mwalongo *et al.*, 2020). For example, it was reported that in Kongwa ranch the weed has tremendously suppressed the desirable pastures for livestock (Mwalongo *et al*., 2020). In addition to that, the weed has also posed a serious threat to crop production by competing with them for nutrients, water, space and light and hence affecting the farmers' livelihoods (Nkomb*e et* al., 2018).

1.2 Problem Statement and Study Justification

1.2.1 Problem statement

Noxious Kongwa weed is a threat to the rangeland and arable land of pastoralists and farmers particularly in Kongwa district as it depletes essential requirements such as soil nutrients, water and increased competition for sunlight necessary for crop growth and pasture production. The reduction in soil nutrients, water and space for crop and pasture growth due to Kongwa has led to the decrease of productive land which in turn has accelerated land use conflicts between farmers and pastoralists in Kongwa district (Mbonde, 2015).

Management of noxious weeds requires understanding of spatial and temporal distribution of particular weed as well and their dispersal routes and mechanisms. In the process of managing the consequences of the Kongwa weed, it was deemed necessary to predict the current and future distribution of weeds for determining the best Integrated Weed Management (IWM) measures. Determining the current and future potential ecological niches of weeds is an important first step toward implementation of any Integrated Weed Management (IWM) plans.

1.2.2 Justification

This study is of greater importance to decision or policy makers when considering the plans to control the weed. Spatial and temporal distribution of Kongwa weeds shows where the control resources need to be allocated and which areas needs to be given first priority in managing the weed.

In addition to that the study also serve as an alert to establish preventive measures in areas which currently may not be occupied by the weed but have environmental characteristics that can favor growth of the Kongwa weed. Moreover, the study identifies the risk posed by different pathways which are responsible for spreading the weed, thereby giving guidance to decision makers on how to stop or minimize further spread of this weed.

1.3 Objectives

1.3.1 Overall Objective

The overall objective of this study is to determine the spatial and temporal distribution of Kongwa weed in Tanzania in order to enhance the effective weed managemenet

1.3.2 Specific Objectives

i. Map existing land cover/use in realized ecological niches of Kongwa weed in order to identify land cover/use types associated with Kongwa weed,

ii. To model the current and future potential ecological niches of noxious Kongwa weed in Tanzania and

iii. To assess pathways to spread of noxious Kongwa weed in Tanzania.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Weeds Classification

Weed is defined as "any plant or vegetation that interferes with the objectives of farming or forestry, such as growing crops, grazing animals or cultivating forest plantations" (Ian, 2008). Weed may also be defined as "plant that is growing where it is not wanted by humans" (FAO, 2011). For the purpose of planning and establishing control and management measures against them, weeds are usually classified into several groups based on their morphology (e.g. grasses weeds), life cycle (e.g. annuals, biennials and perennials weeds), habitat (e.g. terrestrial or aquatic weeds), origin (e.g. indigenous or exotic/alien weeds), nature of stem (e.g. woody or herbaceous weeds), climate type (e.g. tropical, temperate weeds), soil type (e.g. red soils weeds), ecological affinities (e.g. weeds of wetlands, weeds of garden land) special classification (e.g. poisonous weeds, parasitic weeds, noxious weeds), (Rana and Rana, 2016). Kongwa weed is classified as noxious weed under special classification, because of the special attention it has brought to the society and authority.

A noxious weed has been defined by Weed Science Society of America (WSSA) as "any plant designated by federal, state or local government officials as injurious to public health, agriculture, recreation, wildlife or property" (WSSA, 2016). When a weed is categorized as noxious, authorities can order some measures like quarantines to be implemented in order to contain or eradicate the weed and control its spread. The following are some of the characteristics that noxious weeds can possess; toxic, aggressiveness, parasitic, vector for diseases or insects, difficulty to control, can be native or new to an area (USDA, 2008).

2.2 Description of Ecological Niche, Potential Ecological Niche and Realized Ecological Niche

“Ecological niche is a term that describes the position of a species within an ecosystem, the overall environmental conditions necessary for persistence of the species, and its ecological role in the ecosystem” (Polechová and Storch, 2019). That is to say, ecological niche includes all of the interactions between the organism together with its surrounding biotic and abiotic environment necessary for its survival and persistence.

Potential niche or fundamental niche is defined as “the total range of environmental conditions that are suitable for existence without the influence of interspecific competition or predation from other species” (Pidwirny, 2006). It is the theoretical habitat and may not be fully occupied due to the presence of other competing species. On the other hand, realized niche describes that part of the fundamental niche that is occupied by the species (Pidwirny, 2006).

2.3 Weed’s Impacts on Land Uses

Land use can be defined as “the arrangements, activities and inputs people undertake in a certain land-cover type to produce, change or maintain it” (Gregrio and Jansen, 2000). The reduction in crop yield and crop quality is directly related with competition for water, nutrients, light and space between crops and the weeds under agricultural land use. Reduction in yield and crop quality due to weeds varies from crop to crop and is estimated to be 50-100% in rice, 50-80% in wheat, 55-90% in maize, 40-80% in sorghum, 50% in common bean, 80% in cotton and 90% in cassava in Africa (Gianessi, 2009).

Besides the direct losses in crop yield brought by weed’s competition, there are also other indirect ways by which weeds affect agriculture land use. For example, in fields infested with weeds, field management practices such as harvesting can become difficult because some weeds can cause itching to the labor and sometimes harvesting process can be troublesome to the point of causing excessive wearing and tearing of the farm harvesting machines and hence leading to increased cost of production to repair the tools and the increased labor in separating the weed seeds from the grain and other agricultural produce (Walsh *et al.,* 2018).

In livestock keeping land use, some weeds for example wild onion and wild garlic causes cow milk to have odd smell when the animals are being fed from fodders mixed with such weeds (Palai, 2010). Some weeds such as *Halogeton glomeratus* (a common weed in arid and semi-arid areas) causes sickness and sometimes death to livestock due to their higher levels of nitrates, glucosites, alkaloids, tannins or xalates. Leaves of weed specie called lantana camara have been reported to cause jaundice in livestock (Palai, 2010). Puncture wine scientifically known as *Tribulus terrestris* a weed mostly found in dryland have been observed to induces extra sensitivity to light in sheep and puncture of the livestock skin (Palai, 2010). In pastureland such as Kongwa ranch, the Kongwa weed invasion in the year 2018 is reported to have reduced production of pasture tremendously (Mwalongo, *et al.,* 2020).

2.4 Impacts of Climate Change on the Distribution of Weeds

Climate plays a vital role in the whole process of weeds growth from its germination up to maturity stage. Water is one of the primary ingredients needed for successfully development of weeds. Water is used for transportation of plants nutrients and plays a significant role in plant's photosynthesis activities (Al-Huqail *et al.,* 2020). Rainfall as one of the important parameters of climate is the main source of water in plants (Kyei-Mensah *et al*., 2019).

Climate change particularly increases in Earth's surface temperature has prompted the establishment and spread of noxious weeds in Tanzania (URT, 2012). The impact of climate change on weeds may be manifested in the form of geographic range expansions (i.e. migration or introduction to new areas), alterations in species life cycles, and population dynamics (Ramesh *et al.,* 2017). The main drivers for climate change impacts on the distribution of weeds include increased temperature, changed rainfall patterns, increased carbon dioxide levels, persistent drought and changed land use patterns (Scott *et al.,* 2014). Moreover, weeds have shown strong response (i.e. greater growth and reproductive response) to increases in atmospheric carbon dioxide gas concentration which is a key greenhouse gas that drives global climate change (Bajwa *et al*., 2019).

2.5 Pathways for Weed Spread in Tanzania

Pathway has been defined as "any means that allows the entry or spread of a pest" (IPPC, 2017). Several potential pathways exist for weed spread in Tanzania. A study done by Hemp (2008) indicated that the increase in tourism activities in Mount Kilimanjaro has increased the risk for spread of alien weed species particularly *Poa annua* (a weed of European origin) on the upper zones of Kilimanjaro mountain. The other evidence for spread of weed species in Tanzania via tourism sector is shown by the increasingly invasion of weeds in Serengeti-Mara ecosystem (Witt *et al.,* 2017). Elisante *et al.* (2013) showed that one of the problems facing the Ngorongoro conservation area was weed invasion and they postulated that road construction activities, movement of vehicle, tourism activities to be the major pathways for invasion of weed species particularly *Datura stramonium*.

Another study by Mtenga *et al.* (2019) indicated that water, wind, animals' movements, farm machinery and vehicles to be the major pathways for spread of a noxious Carrot weed (a weed of Mexico origin) in Africa where by currently the weed is in greater abundancy in Arusha region and significantly affect biodiversity in Africa.

Survey of the weed called *Parthenium hysterophorus* (a weed of South and Central American origin) in Kenya, Uganda and Tanzania found that the weed was much present in residential areas, construction sites, drainage trenches, dumpsites, rangelands and crop land, suggesting that the spread pathways of the weed follow patterns of disturbance on the land (Wabuyele *et al*., 2014).

Hulme *et al.* (2013) found that, interference from human activities in the montane forests of East Africa was a major reason for spread of invasive trees species in the montane forests.

Kilawe *et al*. (2017) have indicated that Mrashia (*Prosopis Juliflora*) invasive tree weed specie, was spread in Tanzania in 1988 by traders from Kenya who were using donkey as a means of transport. It was assumed that, the weed was spread through donkey's dung and it was further spread to other parts of Tanzania through livestock movements especially cattle movements across Tanzania's districts. From the discussion above, the following possible pathways for weed spread within Tanzania have been identified and are summarized in Table 1.

Table 1: Potential Pathways for Weed Spread in Tanzania

Pathway	Description
Water dispersal	Distribution of weed seeds or propagules via water ways e.g., flood streams, rivers, irrigation etc.
Wind dispersal	Distribution of weed seeds by wind
Escape from research sites	Accidental escape from plant research sites
Landscaping/Construction activities	Contamination of soil, sand and gravel
Ornamental plant trade	Distribution via sales of garden plants
Introduction via tourism	Distribution by human movement via clothing and footwear.
Introduction via exotic plant species	Importation and exportation of contaminated exotic plant species
Livestock movements and stock fodder transportation	Distribution via faeces and/or livestock fur or hoofs and contamination of hay
Agricultural produce and Inputs	Contaminated grain and crop seeds
Farming tools, equipment, machines, footwear and clothing	Contamination of tools used in infested lands

2.6 Ecological Niche Modelling

Ecological niche modelling (ENM) is a widely used tool for prediction of the distribution of species by determining the relation between the species occurrence at a certain area and the environmental characteristics of an area (Warren and Seifert, 2011). Ecological niche modelling is based on “Ecological Niche theory” which states that species can only thrive within a definite range of environmental conditions (Melo-Merino *et al.,* 2020).

Ecological niche modelling methods are commonly used in ecology and environmental management studies (Peterson *et al.*, 2015). Among the most common use of ENM are evaluation of the relative suitability of a known habitat occupied by the species (Guisan and Zimmermann, 2000; Thorn *et al.,* 2009), conservation planning (Guisan *et al.,* 2013), determining invasive potential of weeds (Jimenez *et al.*, 2011) to approximate the relative suitability of habitat in geographic areas not known to be occupied by the species (Radinger and Wolter, 2015) and modelling the impacts of climate change on the distribution of species (Pearson and Dawson, 2003).

There are three main groups of models under the category of ENM. The most common one is correlative models which estimate habitat requirements of species by correlating the known species habitat to a number of environmental variables (Franklin, 2010). The second group is mechanistic models which examine specie's physiological characteristics to determine a range of environment habitat in which the specie can persist (Kearney and Porter, 2009). The last group is process-oriented models which have the ability to determine both environmental as well as biological processes that limit the distribution of species (Peterson *et al.,* 2015).

2.7 Maxent (Maximum entropy) Model (Correlative Model)

Maxent is an algorithm for modelling species distributions from presence-only species data (Elith *et al.,* 2011). The maximum entropy model falls under the category of correlative models and is now available in the software Maxent (Phillips *et al*., 2006). The input in maxent model is a set of environmental variables (such as climatic data, soil data and topographical data) and the sample of species location data (e.g., latitudes and longitudes) where the species have been found to be presence. The record of locations where the specie has been found to be presence while neglecting the locations where the specie is absence is called species presence-only data (Elith *et al.*, 2011).

Maxent model has proved success when predicting habitats of species even with small number of available species presence-only data (Robelo and Jones, 2010; Garcia *et al.*, 2013; Marcer *et al.*, 2013). Since its introduction in 2004, Maxent has received wider number of users in producing large scale, species distribution maps from both government organizations and non-government organizations (Elith *et al.*, 2011).

Among the advantages of Maxent are; first it makes use of presence only data hence avoiding false positive and false negative errors that could be associated with absence data (Phillips and Elith, 2013). The second advantage is the continuous output map produced from Maxent which allows for fine distinctions to made between the levels of habitat suitability, such as high suitable, moderate suitable and not suitable habitats (Arnold *et al.*, 2014). However, the main limitation of Maxent model is possibility of model over-fitting, where by the model perform good only with the training data and perform poor with independent testing data incase species occurrence data are biased (Phillips and Dudik, 2008).

In this study Maxent model was selected because sampling of Kongwa weed location was done in areas which are already known to contain the weed (i.e., Kongwa and Kiteto districts). Therefore, the types of data recorded from these areas were species-presence only data which is the kind of data best suited to maxent model. In order to stop or minimize the ecological and economic consequences of Kongwa weed in Tanzania, this study aimed first to develop maps showing the current and future potential habitats of this weed to fill the knowledge gap of the potential suitable habitats of this weed in Tanzania.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Description of the Study Area

3.1.1 Location

United republic of Tanzania is located on the eastern coast of Africa between longitudes 29° and 41°E and latitudes 1° and 12°S. It is the largest country in East Africa with a total area of 947 600 km^2. The country is made up of two main parts which are Tanzania mainland covering an area of 945100 Km^2 (i.e. 99.74% of the total area) and the second part is islands of Zanzibar which cover a total area of 2500 km^2 (i.e. 0.26% of the total area) (URT, 2013). Administratively, Tanzania mainland consists of 26 regions while Zanzibar Island is made up of 5 regions, three in Unguja Island and 2 in Pemba Island (URT, 2013).

3.1.2 Climate

Climate in Tanzania varies from place to place due to several factors such as altitude, geographical position, vegetation cover and proximity to water bodies. As a result, areas close to the Indian ocean experience hot and humid climate, central part of the country experience semi-arid climate while most of the remaining areas experience sub-tropical climate with the exceptions of high lands regions which experience very cool climate. The country generally receives mean annual rainfall between 500 millimeters to 2500 millimeters and above (NBS, 2017). Rainfall distribution in Tanzania follows two patterns. There are areas which receives two rainfall seasons in a year which are areas found at the northern coast, north eastern regions and areas around Lake Victoria basin. Rainfall in these regions is categorized as long rains and short rains. Long rains start at

March and ends in May (i.e. MAM) and short rains begin in October and ends in November (i.e. OND).

The other rainfall pattern in Tanzania is Unimodal pattern whereby areas falling under this category receive only single rainfall seasons which normally begins on November and ends in late April or early May. Areas which receive Unimodal rainfall pattern include western southern regions and some areas at the central part of Tanzania (Chang'a and Nduganda, 2008).

The main governing factor for the varying distribution pattern of rainfall in Tanzania is the movement of Intertropical convergence zone (ITCZ) (Camberlin and Okoola, 2003). The ITCZ moves southward across Tanzania during March to May (OND) period, while the northward movement occurs during March to May (OND) period (Camberlin and Okoola, 2003). Other factors which also has got an influence on the rainfall distribution in Tanzania includes Indian Ocean Dipole (IOD), Congo air mass, El Niño Southern Oscillation (ENSO), Madden Julian oscillation (MJO) and tropical cyclones (Omenyi *et al.*, 2008).

3.1.3 Vegetation cover

Tanzania is characterized by forest vegetation cover of various types. The country is estimated to have more than 10 000 plant species, among which hundreds of them are native species. The International Union for Conservation of Nature's (IUCN) red List have identified 305 plant species as threatened while about 276 plant species as endangered plant species (NAFORMA, 2015). Major types of forest found in Tanzania includes miombo woodlands in southern, central and western parts of Tanzania, the other type is Acacia-Commiphora woodlands found in the northern parts of the country, mangrove forests found along the cost of Indian Ocean, and dense closed forests found in mountainous areas (Burgess *et al.*, 2004).

3.1.4 Hydrology

There exist nine main hydrological basins in Tanzania mainland. Among them four basins drain its water in Indian Ocean which are Wami/Ruvu, Ruvuma, Pangani and Rufiji Rivers. Three of them are lake basins which are Lake Victoria basin, Lake Tanganyika basin and Lake Nyasa basin in which all of them drains their water in their respective Lakes. The remaining two are inland drainage basins with one over the north draining its water into Lake Manyara, Natron and Eyasi and the other one in south west drains its water in Lake Rukwa (MoWI, 2014).

3.1.5 Population

As per 2018 National Bureau of Statistics (NBS) population projection, the total population in Tanzania was projected to be 59 441 988 in 2021 of which 57 724 380 are estimated to be people in Tanzania Mainland and 1 717 608 to be people in Tanzania Zanzibar (URT, 2018).

3.2 Methods

3.2.1 Mapping existing land cover/use in realized ecological niches of Kongwa weed

Minimum clouds (less than 20%) Landsat 8 scenes of the year 2020 were downloaded from USGS Earth explorer websites (https://earthexplorer.usgs.gov/). Each of the downloaded scene contained the default 11 Landsat 8 OLI spectral bands. Despite of the downloaded 11 spectral bands only 6 bands were chosen i.e. band 2 (blue), band 3 (green), band 4 (red), band 5 (near-infrared), band 6 (short wavelength infrared 1), and band 7 (short wavelength infrared 2) each one having the spatial resolution of 30 m. These bands were selected because they are usually the most used bands for producing land cover map in most areas (Yu *et al.*, 2019). The other bands like band 1 which is specifically for coastal areas and aerosols, panchromatic band (band 8), band 9 (cirrus cloud detection band) and the thermal bands (band 10 and 11) were not applicable in this study.

Preprocessing of the downloaded scenes was done by using Semi-automatic classification plugin available in the Q GIS version 3.12 open-source software to correct for the atmospheric corrections and conversion of the digital numbers in the scenes to reflectance values.

The preprocessed scenes were joined to form a mosaic by using a mosaic tool available under raster dataset module in Arc GIS version 10.7. Mosaicking was done in order to obtain a single image for the whole study area. The next step was to perform land cover classification whereby supervised classification method was selected because this method gives more room for the researcher to fine tune the information in classes in accordance with his prior knowledge of the area thereby increasing the accuracy of the classification (Yiqiang *et al.*, 2010). In supervised classification the following steps were then followed to produce the land cover map.

Step 1: **Determining the number of classes and the types of land cover to be included**

National land cover classification system of National Forest Resources Monitoring and Assessment (NAFORMA) was applied to determine the number and the contents of land cover classes. In this system land cover is classified into eight classes which are forestland, woodland, bushland, grassland, cropland, open land, water bodies and other land cover such as buildings (NAFORMA, 2015). The description of each class as defined by NAFORMA is shown Appendix 1.

Step 2: Creation of training samples

Visual image interpretation using different band combination (e.g. 6 5 2 for agriculture, 4 3 2 natural color) of Landsat 8 image was used to identify different features in the image. In addition to visual image interpretation, NAFORMA land cover classification map of the year 2013 together with high resolution images from the google earth was also used as an aid in differentiating different land cover classes. Ten to fifteen training sites for each class were then selected from the image in order to increase the variance of each class. Selecting few training sites (e.g. less than 5) for each class is not recommended because this might lead to the production of less accurate classification map, because some classes possess greater variability of pixel values. For example, pixel values of cropland at one point can be a little bit different from pix values of cropland at other point in the same region.

Step 3: Selection of the classification algorithm (method)

Although several (e.g. binary encoding, maximum likelihood, minimum distance, principal component analysis etc.) algorithms exists for performing classification under supervised classification system, no algorithm is suitable in all possible cases. To select the proper classification algorithm, you need to have the basic understanding of the mathematical principal behind the algorithms. In this task, maximum likelihood classification algorithm was chosen. Maximum likelihood algorithm is based on the assumption that the cells in each class and in each band are normally distributed (Sisodia *et al.*, 2014). It works under the principle of likelihood probability theorem of decision making whereby production of posterior probability distributions is guided or biased by prior probabilities (Nandi, 2019).

Step 4: Performing classification

Maximum likelihood tool of arc map 10.7 was used to perform the classification. First, evaluation of the distribution of the data in the bands and in training samples was done to see if they follow normal distribution. In addition to that, editing of the training samples was done under the training sample manager tool to check if they are representative of the intended classes and there are no overlaps between classes. After that signature file was created by using create signature file tool. Lastly the image, was classified by applying the Maximum Likelihood Classification tool. The tool assigns every pixel to the corresponding land cover class based on the variance and means of the class signatures stored in the signature file.

Step 5: Post-classification map processing

The resulting map from the classification by the Maximum Likelihood Classification algorithm contained some random noises due to misclassification done by the tool. To improve the appearance of the map major filtering technique was applied through majority filtering tool in Arc GIS 10.7. The techniques removed all the isolated pixels from the map. In addition to that ragged boundaries of the classes were smoothed out by using the boundary clean tool which helped to bring connectivity of adjacent regions.

Step 6: Accuracy assessment of the classified map

Field survey at the study area was done to collect 210 ground truth points (30 for each class) which were used for accuracy assessment of the formulated land cover map. Handheld GPS receiver was used to collect the ground truth points. The ground truth points were collected by Stratified random sampling method. A set of ground truth points was then created in the arc map 10.7 through the Create Accuracy Assessment Points tool. After confusion matrix was created, compute confusion matrix tool was run to obtain results of the assessment.

Step 7: Calculating classified area for each land cover over the land cover map

The produced land cover map was first converted to vector format by using the raster to polygon conversion tool in arc map 10.7. The Calculate Geometry tab on the area was chosen from the attribute table and hectares were chosen to be the unit for area of each land cover class. Total area for single land cover class was obtained by choosing the ‘select by attributes option and in the statistics tab, summation was chosen. Summary of the whole processes involved in the production of land cover map is shown in the flowchart below.

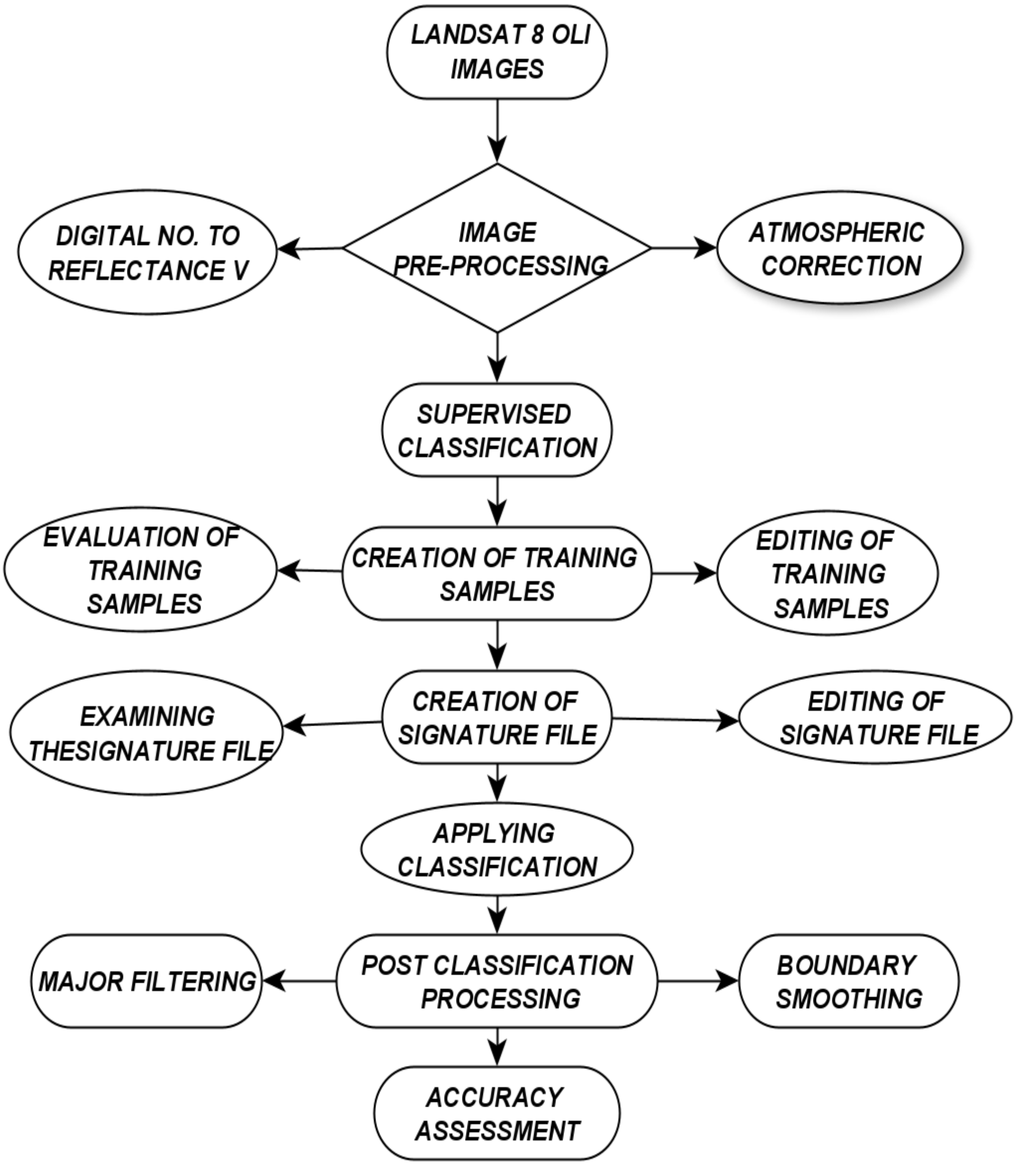


Figure 1: Flowchart of land cover classification processes

3.2.2 Modelling the current and future potential ecological niches of noxious Kongwa weed in Tanzania

3.2.2.1 Noxious Kongwa weed occurrence

Field surveys were conducted in both Kongwa and Kiteto districts to record the locations of the Kongwa weed. These areas were chosen as sampling area, because are the areas which have been reported to contain the weed and the model used in this study (Maxent) require weed presence-only data. Proportional stratified sampling method was used to record the presence of the weed. In this method of sampling, stratum with relatively large size will contain the largest number of sampling units compared to stratum with smallest size. Land cover classes from the prepared land cover map of Kongwa and Kiteto districts were used to establish the strata.

Since the purpose of this study was to model the potential ecological niches and not estimation of the quantitative abundances of the Kongwa weed, the number and length of the transect lines across strata were flexible depending on the variation of the terrain and the extent of the land cover type as per transect walk method (FAO, 2016).

Generally, the length of the transects, ranged from 5-8 km. In areas with mixed land cover types, few short transects were preferred than one long transect in order to give a chance for each stratum to have its own count of the location of the Kongwa weed (FAO, 2016). Along each transect line, observations were made at one-kilometer interval and the search for the weed was conducted on either side of the transect line. Garmin GPS hand receiver was used to determine and record the latitude and longitude of the weed occurrence.

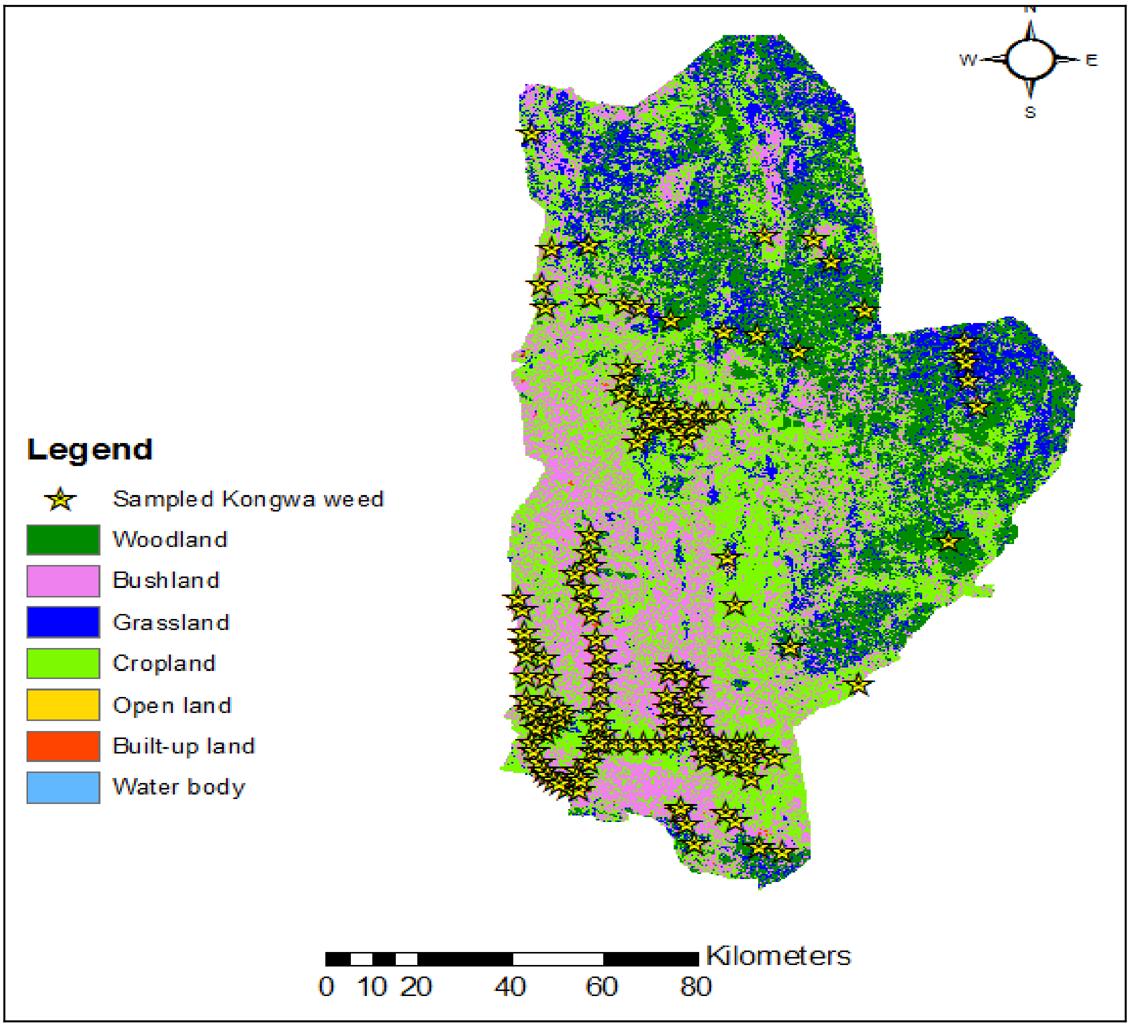


Figure 2: Distribution of sampled Kongwa weed occurrence in Kongwa and Kiteto Districts, Tanzania

3.2.2.2 Environmental data

Three categories of environmental data were used in this study to model the distribution of the Kongwa weed which are bioclimatic data, soil data and topographical data, because these variables have been found to have influence on the distribution of weeds and have been applied in various studies (Molloy *et al.*, 2014; Title and Bemmels, 2018).

A total of 19 bioclimatic variables, as summarized in Appendix 2, were obtained from the new January 2020 released 1-km grid WorldClim version 2.1 climate data available at https://worldclim.org/data/worldclim21.html. These climate data are the results of collection of monthly weather data from the world weather stations in the period 1970-2000 (Fick and Hijmans, 2017). The data were modelled under the 4.5 RCP (representative concentration pathways) scenario to represent near current climate (Fick and Hijmans, 2017). Bioclimatic variables have been widely used in many species distribution modelling of plants and animals (Joyner, 2010).

Future climate data were also downloaded from the 1-km grid worldiclim database. These data were obtained through the projection of the current climate data under IPCC-AR5 representative concentration pathway (RCP4.5) (Fick and Hijmans, 2017). The downloaded future climate data represents future climate for the period 2050 which were obtained by taking the average of the projected climate between the years 2041-2060 (Fick and Hijmans, 2017).

Topography is also another important environmental variable which influence species distribution (Esfanjani *et al.*, 2018). In this study, elevation data derived from SRTM (Shuttle Radar Topography Mission) was used to model the bioclimatic variables also downloaded from Worldclim version 2 database (Fick and Hijmans, 2017).

Soil data Cation Exchange Capacity (CEC), soil drainage condition, soil texture type, soil pH and organic carbon content at the depth of 5-15 cm were downloaded from the ISRIC African soil database. ISRIC African database have consolidated soil data from the year 2009 to 2016 from about 27000 locations in Africa to have representative soil information from any point in Africa (Leenaars *et al*, 2014). The spatial resolution of the downloaded soil parameters which were developed using the African Soil Profiles Database (AfSP) was 250 m (Hengl *et al.*, 2015). The downloaded soil layers were then clipped in arc map to obtain soil layers covering Tanzania region only.

3.2.2.3 Data processing

(a) Spatial filtering of occurrence data

The purpose of this task was to thin out occurrence points which were accidentally very close to each other. This task was important because points that are too close to each other could lead to problems like model overfitting. This task was done in R studio software using SP thin R package developed by (Aiello-Lannmens *et al*, 2015). After filtering the 154-occurrence data were reduced to 111 occurrence data.

(b) Assessment of correlation in environmental data (19-bioclimatic data, soil data and elevation data)

The Maximum Entropy algorithm (Maxent) uses species presence data (in latitude and longitude format and environmental data in raster format (ASCII format) to build ecological niche models. Before the model was built, correlation assessment was done in Active Perl free software and variables with correlation coefficient of greater than +0.75 or -0.75 were removed. Correlation assessment was important in order to avoid the problem of multicollinearity in the model whereby the model can by chance associate false variable with the specie presence and down-weight the true variable.

3.2.2.4 Running the model

Maximum entropy distribution model (Maxent, version 3.4.1) was used to model potential Kongwa weed ecological niches in Tanzania. The input in maxent model are species occurrence data in the form of latitudes and longitudes and the environmental data. The maxent model works by learning the environmental characteristics in an area where the species has been recorded to exist and then find other areas within a given domain with the most similar (Maximum entropy) environmental characteristics to where the species is present. After occurrence and environmental data were uploaded in the model, the model was run ten times, i.e. ten replications, and the threshold rule of minimum presence was chosen to categorize the area into different classes of habitat suitability.

Maxent model produces logistic output maps with values ranging from 0 to 1 whereby area with logistic values close to 1 are termed as highly suitable habitats, while areas with logistic values close to 0 are said to be not suitable habitats for the subject species. For this study areas with logistic values below 0.2 were categorized as less suitable, areas with logistic values between 0.2-0.6 as suitable and areas with logistic values greater than 0.6 as highly suitable habitats (Giliba and Yengoh, 2020).

3.2.2.5 Model validation and evaluation

The relationship between the Kongwa weed occurrence data and the environmental datasets in the model was established using bootstrap method with 70/30 partition. In order to the model, 70% of the Kongwa weed presence data was used to fit a model and the remaining 30% was used for the evaluation of the predictive ability of the model (Mwakapeje *et al*., 2019). Several methods exist for evaluation of model results. The following are examples of those methods; ROC curve and AUC value, Sensitivity, Accuracy, specificity and Precision-Recall curve (Tharwat, 2020). In this study ROC curve and AUC value method was used because it is one of the outputs from the Maxent model (Yackulic *et al.*, 2013). For the model results to be useful, the value of AUC for the training data and test data should be very close to one (Elith *et al*., 2006; Phillips *et al.*, 2006). The summary of all processes involved in the modelling are shown in Figure 3.

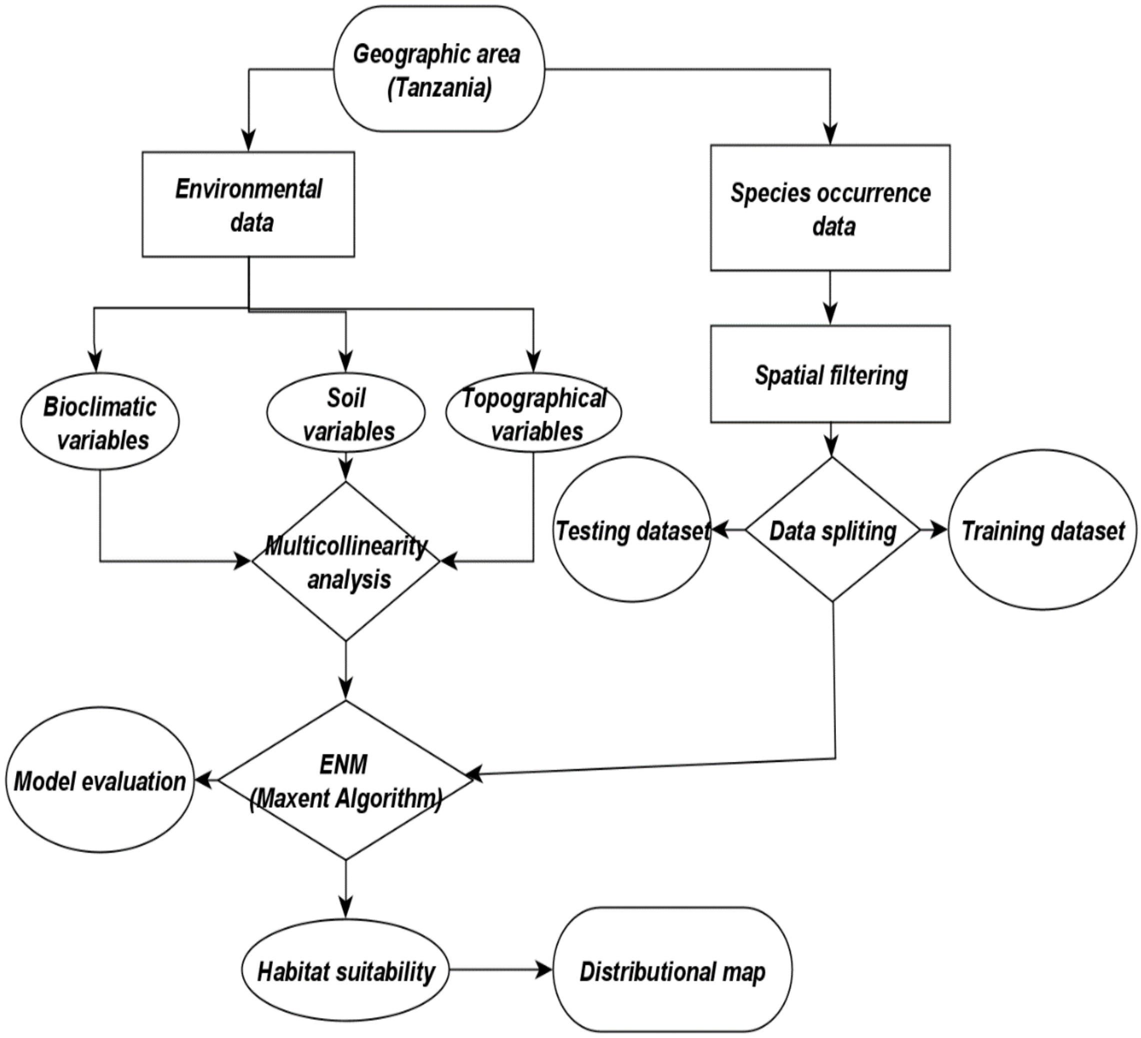


Figure 3: Flowchart of processes involved in modeling potential ecological niches of Kongwa weed

3.2.3 To assess pathways of spread of noxious Kongwa weed in Tanzania using pathway risk analysis method

To accomplish this objective, two sources of data/information were employed; the first one was a review of relevant local and international literatures to identify possible pathways for weed spread in Tanzania as it was indicated in the literature review section of this study. The second one was a household survey in Kongwa district using a semi structured questionnaire to collect information on the various land use practices for pathway risk assessment. During the survey, stratified random sampling method was used to select 120 respondents from 24 villages within Kongwa district. Respondents were stratified based on their land use category and were identified with the assistance of the Agricultural Extension Officers in their respective villages. The adopted land use categorization was agriculture, livestock and residential land because these are the main land use found over the area. Agricultural Extension Officers from Mtanana and Mbande villages and other 18 residents were purposely selected to act as key informants in this survey.

The identified possible pathways for weed spread in Tanzania from the literature reviews of studies by Hemp (2008); Elisante *et al*. (2013); Hulme *et al.* (2013); Wabuyele *et al*. (2014); Kilawe *et al*. (2017); Witt *et al.* (2017); Mtenga (2019) and Mtenga *et al*. (2019) were shown in Table 1 in the literature review section.

Step 1: Pathway risk analysis: A quantifiable risk assessment framework was developed and then applied to all the 10 pathways and after analysis, filtering of the pathways which were found to pose no, or little threat based on their risk score was done.

This method of ranking pathways basing on their risk score was adapted and modified from the work done by (King *et al.*, 2008). In this method 6 main criteria were developed in order to formulate the risk assessment framework. The 6 main criteria together with their sub criteria are shown in the Table 2 below;

Table 2: List of Assessment Criteria

Criterion	**Description**
Weed importance	The extent of the impact (social, agricultural and environmental impacts) of the weeds distributed by the pathway.
Distance (Rapidity)	The extent of the pathway
Introduction	The approximately amount of the viable weed's propagules that can be moved by the pathway
Frequency of the pathway	Frequency of the operation of the pathway in a year.
Establishment a. Probability of the pathway to spread viable propagules to suitable habitats; b. How often does the pathway could spread the viable weed propagule? c. Does the land use type promote deliberate establishment through this pathway? d. Tolerance of the land use type to weed entry or spread via the pathway;	Potential of the pathway in establishing the weed accidentally or deliberately.
Management	Are there any management practices established to reduce the weed spread by this pathway

Step 2: Criteria weighting: A criteria weighting process is done by using analytical hierarchical process whereby criteria are assigned weights (it can be in percentages or otherwise) based on their importance to the specific situation based on the values of their arithmetic mean in the pathway matrix of the analytical hierarchical process. As per (King

et al., 2008) method, the already mentioned criteria were assigned the following weights as shown in the Table 3 below;

Table 3: Weights of Selected C*riteria*

Criteria	**Weight (Percentage)**
Weed importance	4
Distance (Rapidity)	8
Introduction	8
Frequency of activity	13
Establishment	40
Management	27

In order to assess each criterion for every pathway, information about each criterion was collected from a household survey using semi structured interview questionnaire in Kongwa district. During the survey stratified random sampling method was used to select 120 respondents from 24 villages within Kongwa district. Respondents were stratified based on their land use category and were identified from the assistance of agricultural extension officers in their respective villages. The used land use categorization was agriculture, livestock and land user from built-up areas because these are main land users found over the area. Agriculture extension officers from Mtanana and Mbande village and other 18 residents were purposely selected to act as key informants in this survey.

However not all the times the information needed to assess each criterion with respect to a certain pathway was always available. In that regard the assessment was treated as missing data. Land management practices from the different land uses within Kongwa district were analyzed by using Statistical Package for Social Sciences (SPSS. i.e., IBM SPSS version 26). Since the information collected from the survey was categorical data, descriptive statistical analysis using percentages and frequency counts displayed in pie charts and bar graphs were used to evaluate intensity scores in each criterion in the risk assessment framework.

Step 3: Assigning intensity ratings and calculation of final pathway risk score for each pathway: Each pathway was evaluated for every criterion using the following intensity ratings: Low = 0, Medium-Low = 0.25, Medium = 0.5, Medium-High = 0.75, High = 1.0. Whereby the High rate indicates highest risk of the pathway in spreading the weed and the Low rate indicates lowest risk of the pathway in spreading the weed. In the moments of missing information, the criterion was removed from the analysis.

To obtain the final pathway risk score for each pathway, the following formula was applied;

$$Pathway\ Risk\ score = \sum\big((average\ intensity\ rate) \times (criterion\ weight)\big) \quad \ldots\ldots (1)$$

Whereby;

Average Intensity rate is obtained by taking the mean of intensity rating of all sub-criterion within main criterion.

Intensity rates can be chosen from intensity rating score i.e. (from H=1 to L=0).

Criterion weight can be chosen from highest criterion weight which is 0.4 to lowest criterion weight which is 0.04 as shown previously in the table of criterion weights.

Furthermore, the pathways were further classified into three groups depending on their risk percentage score as shown in Table 4.

Table 4: Classification of Risk Score

Group	**Risk score**
High	>75%
Medium	54%-75%
Low	< 54%

Whereby high-risk score (>75%) implies the pathway to pose high risk in spreading the weed and low risk score (<54%) implies the pathway pose low risk in spreading the weed.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Map of Existing Land Cover in Realized Ecological Niches of Noxious Kongwa Weed

The produced land cover map in the realized ecological niches of Kongwa weed contain seven classes which are cropland, bushland, woodland, grassland, built-up-land, open (bare-land) and water bodies. The results show that in the realised niches of Kongwa weed, cropland is the dominant land cover which suggests that the Kongwa weed, prefer cultivated land than uncultivated land as it can be seen in Figure 4.

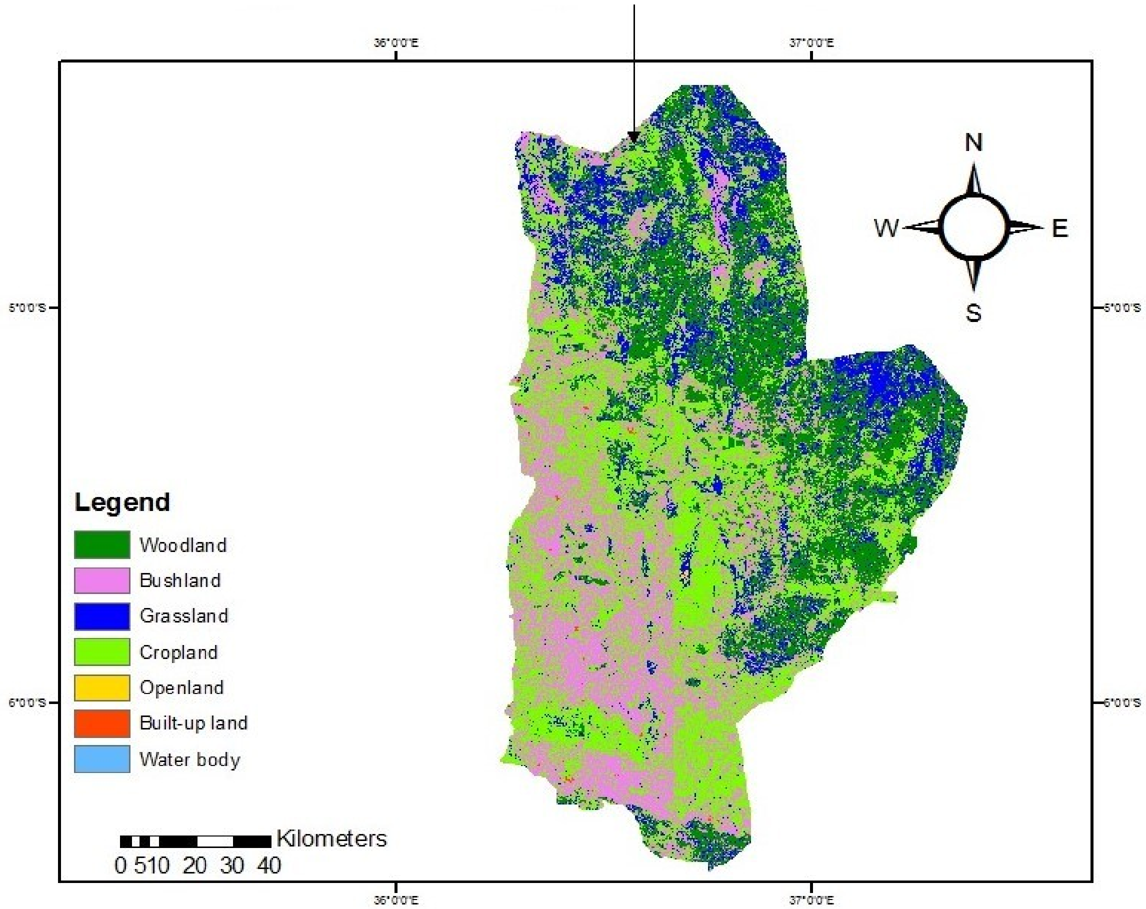


Figure 4: Map of land cover classification in realized ecological niches of noxious Kongwa weed in Kongwa and Kiteto Districts.

From the obtained land cover map area for each land cover class was calculated in order to determine which land cover would need more sampling efforts as per proportional stratified sampling procedure. Area calculation results shows that the sampling area was largely occupied by cropland followed by bushland. The stratum which received little sampling efforts was water bodies because of its small total area coverage as shown in Table 5.

Table 5: Area for each Land Cover Class in the Produced Land Cover Map

Land cover	Total area (ha)
Cropland	637 637
Bushland	456 750
Woodland	378 469
Grassland	233 057
Built-up-land	2 244
Open land	696
Water bodies	41

The results for producer and user accuracy for each class are as shown in the error matrix Table 6.

Table 6: Error Matrix for Accuracy Assessment

Classified Data	Ground Truth Data						
	Woodland	**Bushland**	**Grassland**	**Cropland**	**Built-up**	**Water body**	**Total**
Woodland	13	4	0	0	0	0	17
Bushland	2	49	0	9	0	0	60
Grassland	0	0	15	4	0	0	19
Cropland	0	2	3	72	4	0	81
Built-up	0	2	0	0	21	0	23
Water body	0	0	0	0	0	10	10
Total	**15**	**57**	**18**	**85**	**25**	**10**	**210**
Producer's accuracy (%)	**86.67**	**85.96**	**83.33**	**84.71**	**84**	**100**	
User's accuracy (%)	**76.47**	**81.67**	**78.95**	**88.89**	**91.30**	**100**	

From the error matrix table, the overall accuracy for the classified map is calculated as follows;

Correctly classified values: 13 + 49 + 15 + 72 + 21+10 = 180

Total number of values: 210

Overall accuracy: 180 / 210= 0.8571= 85.71% which is good compared with the required minimum standard accuracy of 85% for land cover classification from satellites images (Foody, 2008).

4.2 Modelling the Current and Future Potential Ecological Niches of Kongwa Weed

4.2.1 Results of soil parameters

4.2.1.1 Soil drainage

According to FAO (2006) soil description guidelines, Tanzania soil drainage condition can be classified into seven classes, which are; excessive, somewhat excessive, well, moderate, imperfect, poor and very poor drained soils as it can be seen in Figure 5. Tanzania soil is mostly well drained which presents favorable conditions for most of the plants to establish especially weeds because well drained soils allow steady passage of water through and across the soil making water to be easily available for plants (Schaffrath *et al*., 2015).

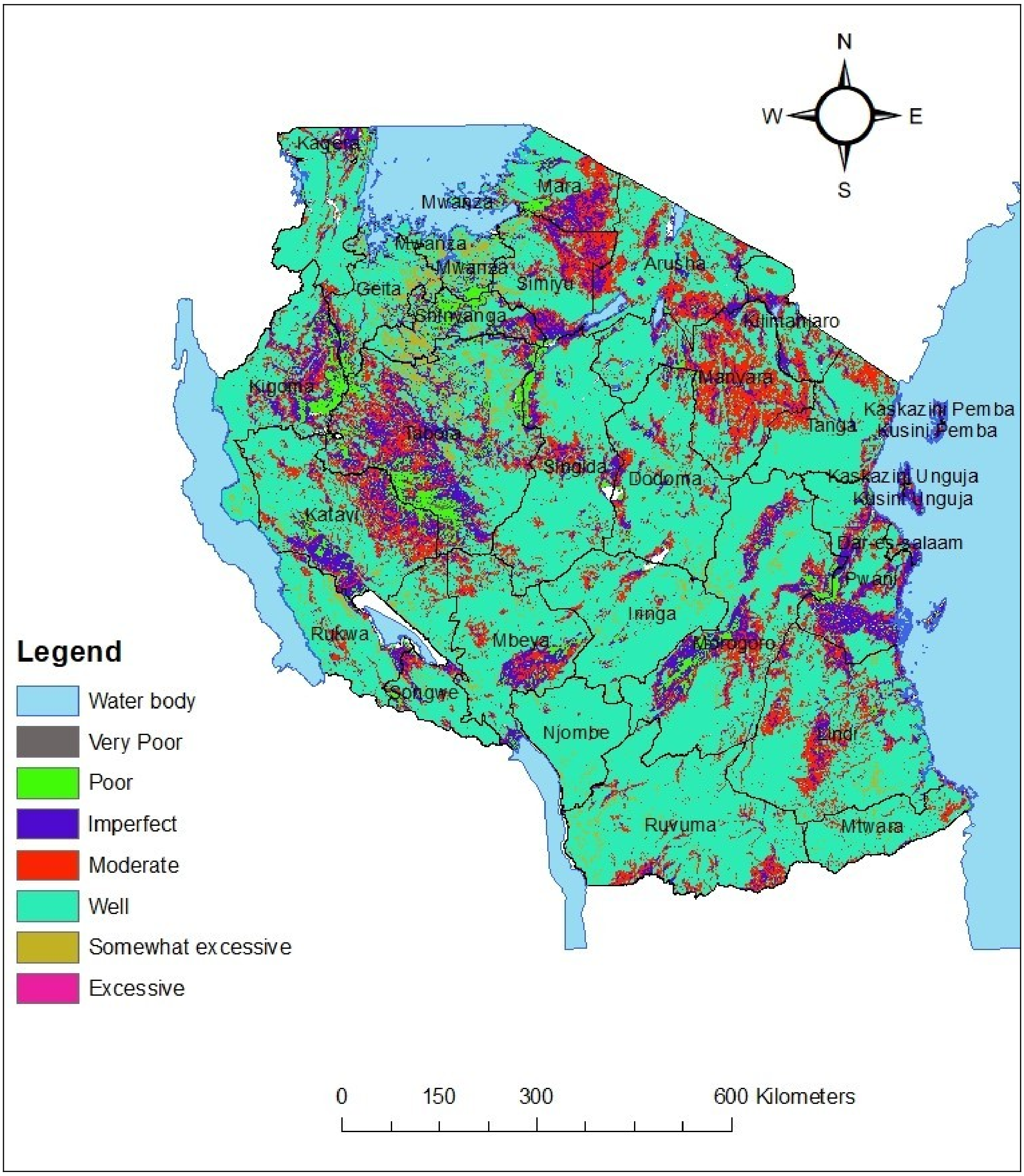


Figure 5: Map of soil drainage classes in Tanzania (Modified: Hengl *et al*., 2015)

4.2.1.2 Soil texture

According to United States Department of Agriculture (USDA, 2008) soil texture classification system, Tanzania's soil texture is grouped into seven classes which are; clay, sandy clay, clay loam, sandy clay loam, loam, sandy loam and loamy sand soil as it can be seen in Figure 6. From Figure 6, it can be seen that most of Tanzania soil is sandy clay loam which is a kind of soil containing 45% or more of sand, less than 28% of silt and 20% -35% clay (USDA, 2008).

This type of soil texture is considered to be the fairly fertile soil because of its ability in holding nutrients and water, however its main disadvantage is that in some areas the soil can contain a lot of stones (Rosolem and Steiner, 2017). The potential for fairly fertility associated with most of the sandy clay loam soils leaves Tanzania's soils to be vulnerable to weed invasion as most of the weeds like other plants prefer fertile soils than infertile soils.

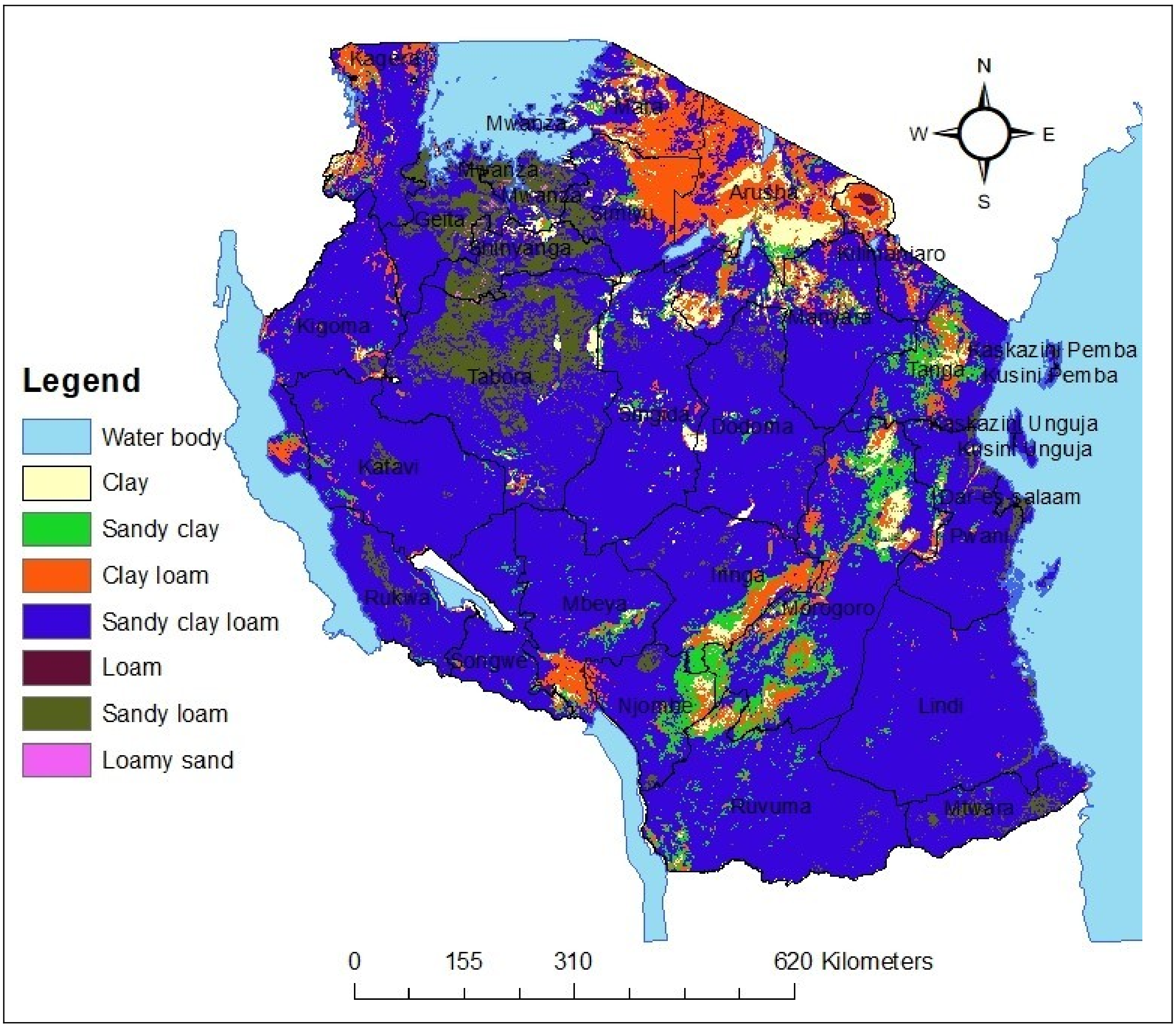


Figure 6: Map of soil textural classes in Tanzania (Modified: Hengl *et al*., 2015)

4.2.2.3 Soil pH

According to FAO (2021) soil pH categorization, Tanzania soil pH can be categorized into the following categories which are extremely acid (for pH 3.5 - 4.4), very strongly acid (for pH 4.5 – 5.0), strongly acid (for pH 5.1 – 5.5), moderately acid (for pH 5.6 – 6.0), slightly acid (for pH 6.1 - 6.5), neutral (for pH 6.6 – 7.3), slightly alkaline (for pH 7.4 – 7.8), moderately alkaline (for pH 7.9 – 8.4) and strongly alkaline (for pH 8.5-9.0) as it can be seen in Figure 7.

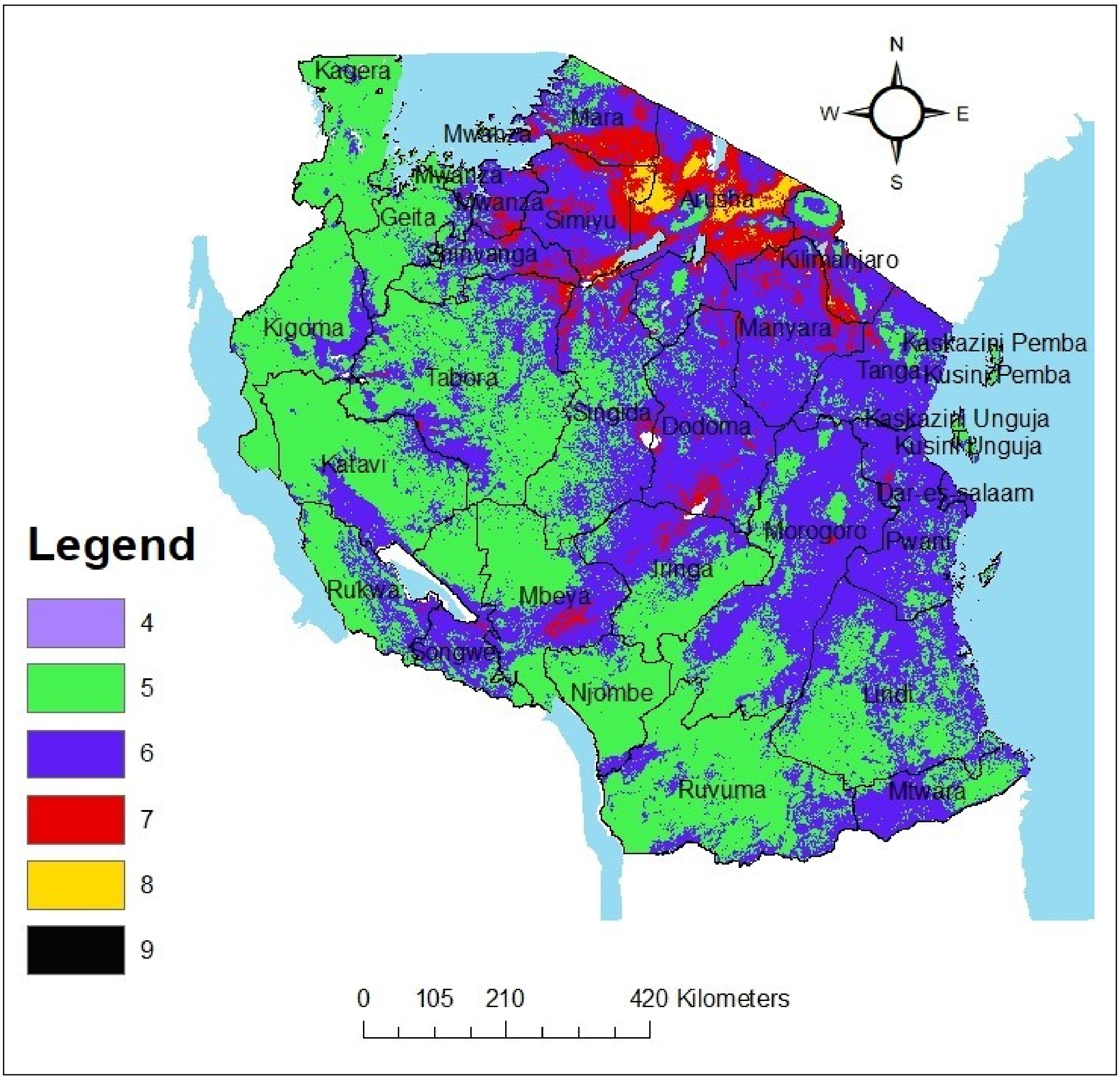


Figure 7: Map of Tanzania's soil pH characteristics (Modified: Hengl *et al*., 2015)

From Figure 7, it can be seen that most of Tanzania soils range from pH 4 to 5 which are extremely acid to very strongly acid.

4.2.2.4 Soil organic carbon content (in g/kg)

Soil organic carbon content is one way of measuring organic matter content in the soil. Figure 8, shows the distribution of soil carbon content in Tanzania, whereby it can be seen that areas at the central part of Tanzania which largely fall under the semi-arid climate zone is having the lowest amount of soil organic carbon content compared to other parts particularly areas near the lakes which have moderate to high amount of soil organic carbon content.

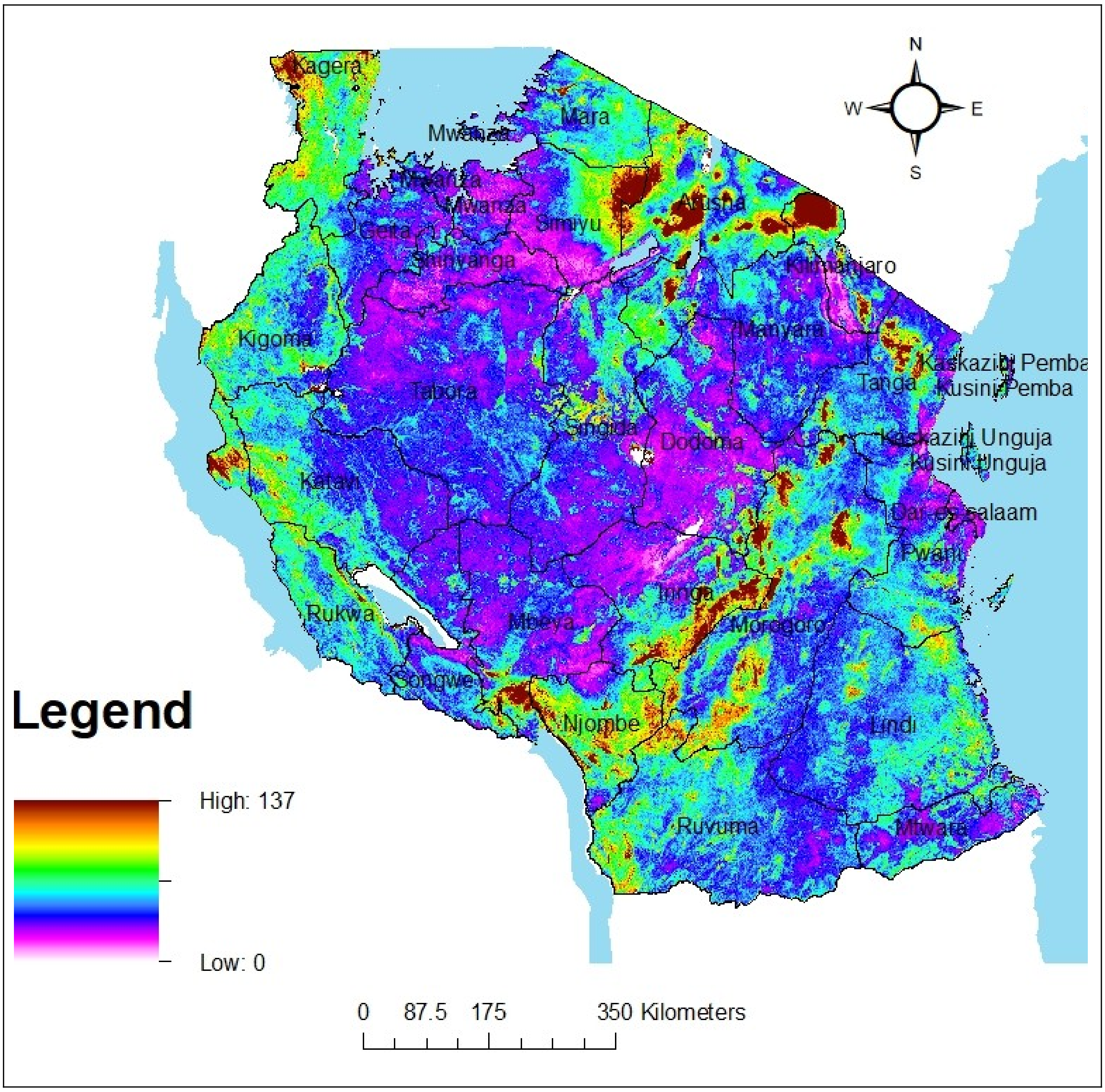


Figure 8: Map of Tanzania soil organic carbon content (g/kg) (Modified: Hengl *et al.*, 2015)

4.2.2.4 Cation Exchange Capacity (CEC)

Cation Exchange Capacity (CEC) is a quantity that is used to determine the capacity of the soil in supplying, holding and attracting exchangeable cations (magnesium, calcium, potassium and ammonium). In other words, CEC can be used as an indicator for soil fertility. From the figure 9, it can be seen that most of Tanzania soils has CEC ranging from low to medium with exception of some areas in Arusha and Kilimanjaro regions which have higher CEC because of the higher soil organic matter found in those areas as it was shown in Figure 8.

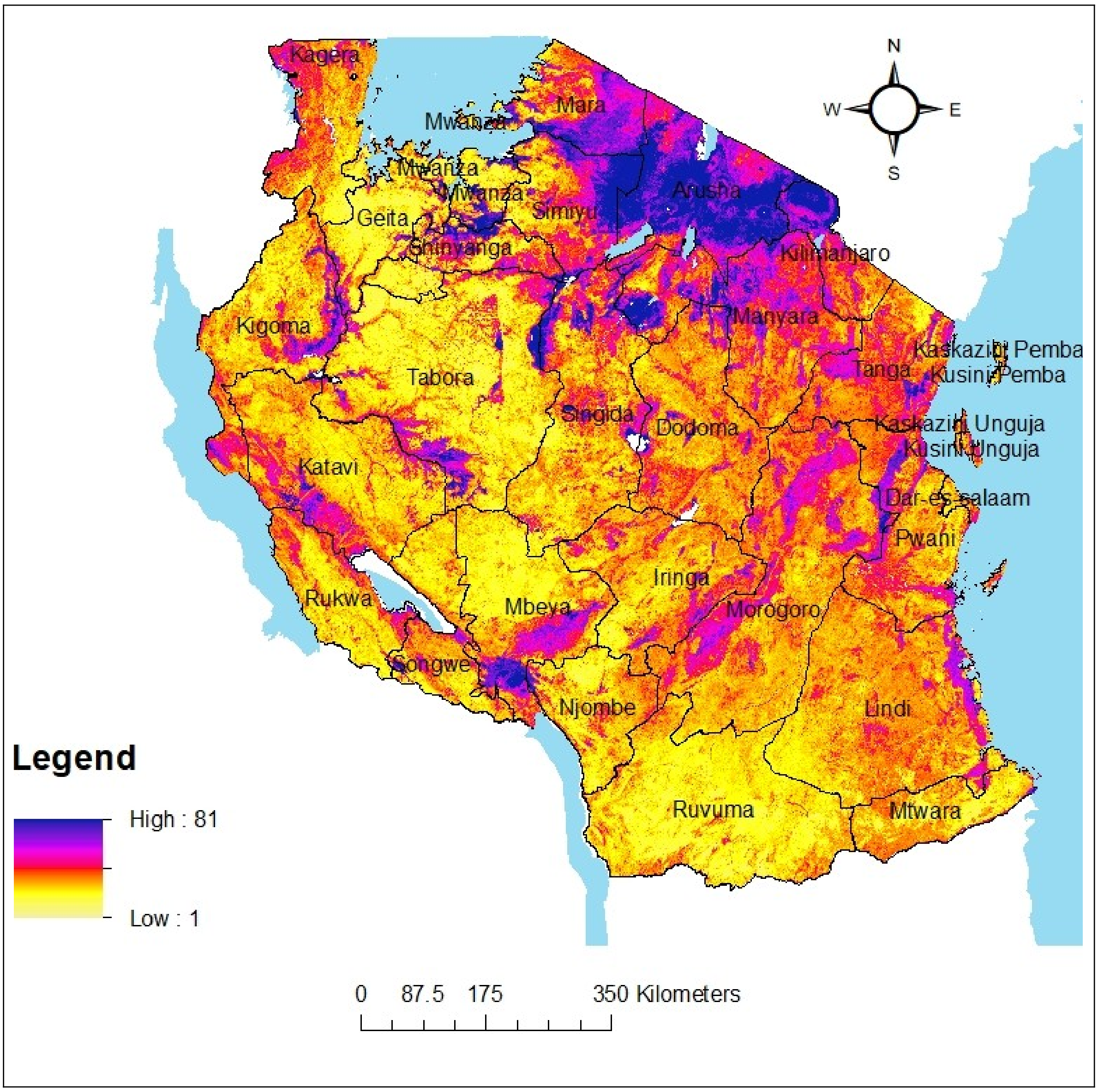


Figure 9: Map of Tanzania Cation Exchange Capacity (CEC) in (cmolc/kg) (Modified: Hengl *et al*., 2015)

4.2.2.5 Elevation parameter

Tanzania has got variable topography composed of valleys, hills, plateaus, coasts and mountainous zones. Figure 10 shows that the lowest point is found on the eastern side of the country where there is a costal of Indian Ocean, and the largest part of the country is composed of plateaus with elevation ranging from 1000 m to 2000 m. The highest point of the country is found on the north-eastern zone where Mount Kilimanjaro is found. Species distribution and composition is greatly affected by differences in altitude between one point and another.

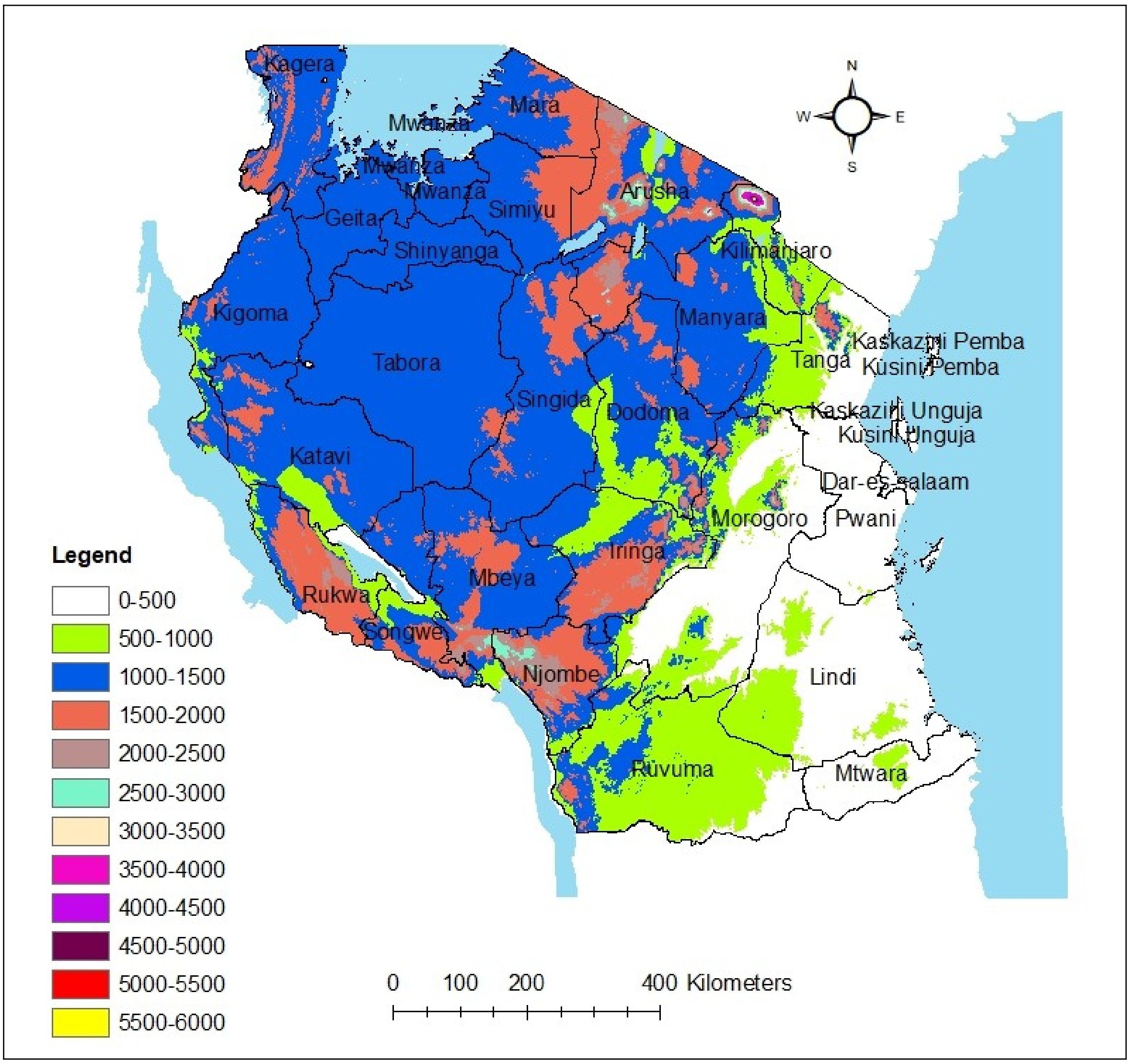


Figure 10: Elevation (in meters) Map of Tanzania (Modified: Hengl *et al*., 2015)

4.2.2 Jackknife test results

The environmental variables (19-bioclimatic variables, soil variables and elevation were assed for correlation between each other in the software Active Perl. The variables with correlation coefficient greater than +0.75 or -0.75 were removed and the remaining variables with their description are shown in Table 7.

Table 7: Final environmental variables after correlation assessment

Variable symbol	**Description**
bio12	Annual Precipitation
bio13	Precipitation of Wettest Month
bio15	Precipitation Seasonality
bio17	Precipitation of Driest Quarter
bio18	Precipitation of Warmest Quarter
bio19	Precipitation of Coldest Quarter
bio4	Temperature Seasonality
ele22	Elevation
org23	Soil Organic Carbon
tex25	Soil Texture

The final environmental variables in Table 7, were then subjected to Jackknife test in order to determine which environmental variable (s) have strong influence on the spatial distribution of the Kongwa weed. Figure 11 shows the results of the Jackknife test (environmental variable significance test) for each environmental variable (blue bar) relative to all other environmental variables (red bar).

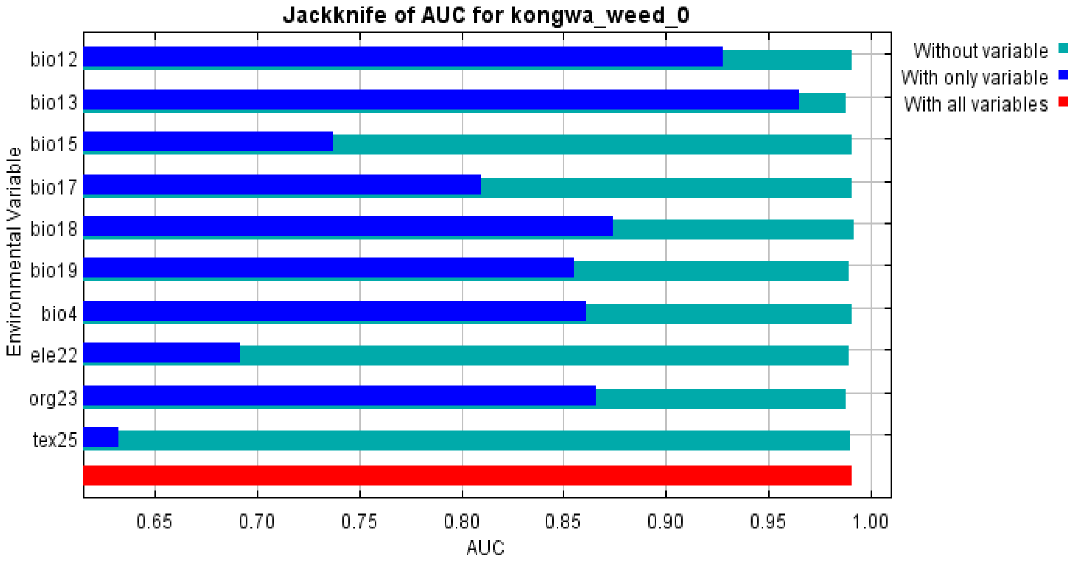


Figure 11: Jackknife results showing the significance of each variable on the distribution of Kongwa weed

From Figure 11, results show that bio13 (Precipitation of Wettest Month), bio12 (Annual Precipitation) and soil organic carbon content (org23) are the most significant bioclimatic variables in influencing the distribution of the weed.

4.2.3 Model predictive performance

Figure 13 shows the results of the Receiver Operating Curve (ROC) curve which provides evaluation of the model performance. Y- axis represent the ability (probabilities) of the model in detecting true presence of the weed (i.e. sensitivity) and the X- axis represent the ability (probabilities) of the model in detecting false presences of the weed (i.e. 1-specificity). The straight line from the origin to the top left corner is the baseline which separates the ROC into two parts, the top part is for the model with good performance levels and the bottom part is for model with poor performance levels. The results show that the model was having excellent predictive performance of 98.4% for the training data and 99.1% for the test data.

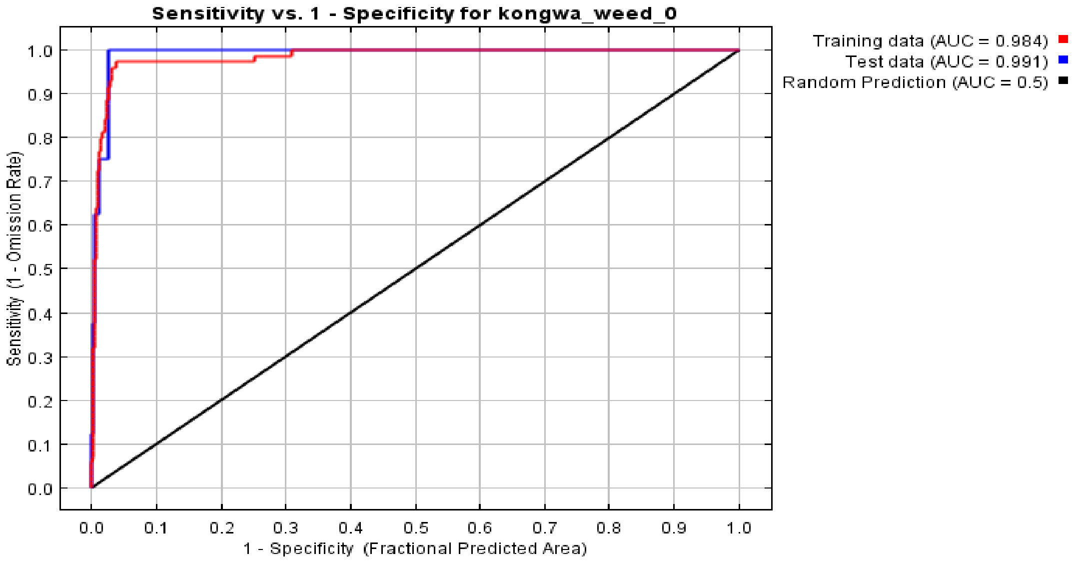


Figure 12: Receiver Operating Characteristic (ROC) curve showing the predictive ability of the model

For the model results to be useful, the results need to be validated. There exist several methods for validating results from ecological niche models. The findings from this study should thus be judged as being useful because results in Figure 13 show that, the model performance for training and test data was 0.984 (98.4%) and 0.991 (99.1%) respectively which is very excellent performance (Zhu *et al.*, 2010).

4.2.4 Map of potential ecological niches of the noxious Kongwa weed in Tanzania under present climate scenarios

Figure 13 shows the results of the modelling of the distribution of potential ecological niches of noxious Kongwa weed in Tanzania under present climatic scenarios. The potential ecological niches of Kongwa weed have been categorized into three groups, i.e., less suitable habitats, suitable habitats and highly suitable habitats.

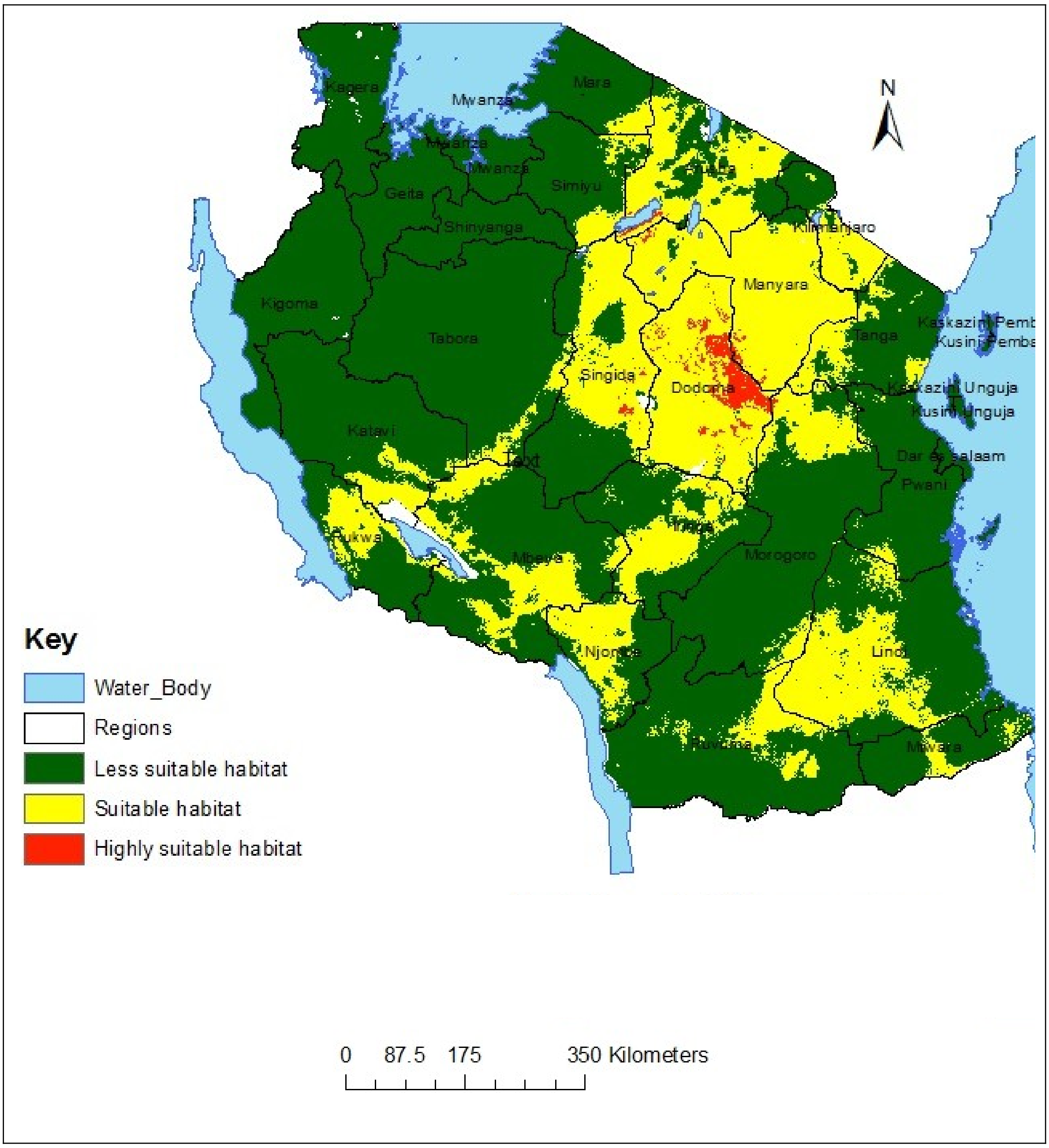


Figure 13: Modelled potential ecological niches of noxious Kongwa weed in Tanzania under present climate scenario.

From the map in Figure 13, areas which have been found to be highly suitable habitats for Kongwa weed, are found on the eastern parts of Dodoma and Singida regions and areas on the western part of Manyara region. The areas which fall under the group of suitable habitats include Arusha and Lindi regions and some parts of Tanga, Kilimanjaro, Mtwara, Njombe, Mbeya, Rukwa, Ruvuma and Morogoro regions.

Generally, the areas which have been found to be potential suitable habitat for Kongwa weed falls under the semi-arid agroclimatic zone of Tanzania as it can be seen in the agroclimatic classification map of Tanzania produced by Kihupi *et al.* (2007) in Appendix 6. These results suggest that Kongwa weeds have the ability to tolerate dry climatic conditions such as drought like most of the other noxious weeds (Ramesh *et al*., 2017).

The tolerance of the Kongwa weed under dry climatic conditions can further be explained by referring to the Jackknife test results in Figure 11. In order to determine the significance or contribution of each of the applied environmental variables (predictors) in the distribution of the species, Maxent model performs the Jackknife test (Phillips and Dudik, 2008).

By associating the results in Figure 8 and the suitable habitats shown in Figure 13 it can be inferred that Kongwa weed prefers soils with lower organic carbon content than those with higher content. However, a study by (Patzald *et al*., 2019) indicated that Soil Organic Carbon (SOC) to have complex non- directional relationship with distribution of most weeds. The reason for low SOC in the potential habitats could be due to the fact that most of the potential suitable habitats falls in semi-arid areas where there is less vegetation cover, more soil erosion and much deep leaching (Hontoria *et al*., 2005; Blanco *et al*., 2013).

Moreover, by relating result in Figure 10 with potential suitable habitats in Figure 13, Kongwa weed can grow in areas with altitude ranging from 500 m to 1500 m. This result support findings by (Gonçalves, 1987) which identified the elevation preferable for the *Astropomoea hyoscyamoides* as 900 m to 1280 m.

Other important soil variable is pH which has an influence on the availability of essential plant's nutrients. Referring to result in Figure 7 and Figure 13, it can well be established that Kongwa weed prefers soils with pH ranging between 5 to 7 which indicates the weed to prefer strongly acidic to neutral soils as per FAO (2021) soil pH classification.

4.2.5 Map of potential ecological niches of the noxious Kongwa weed in Tanzania under present future scenarios

Figure 14 shows the results of the modelling of the distribution of potential ecological niches of noxious Kongwa weed in Tanzania under future climatic scenarios. The potential ecological niches of Kongwa weed have been categorized into three groups, i.e., less suitable habitats, suitable habitats and highly suitable habitats.

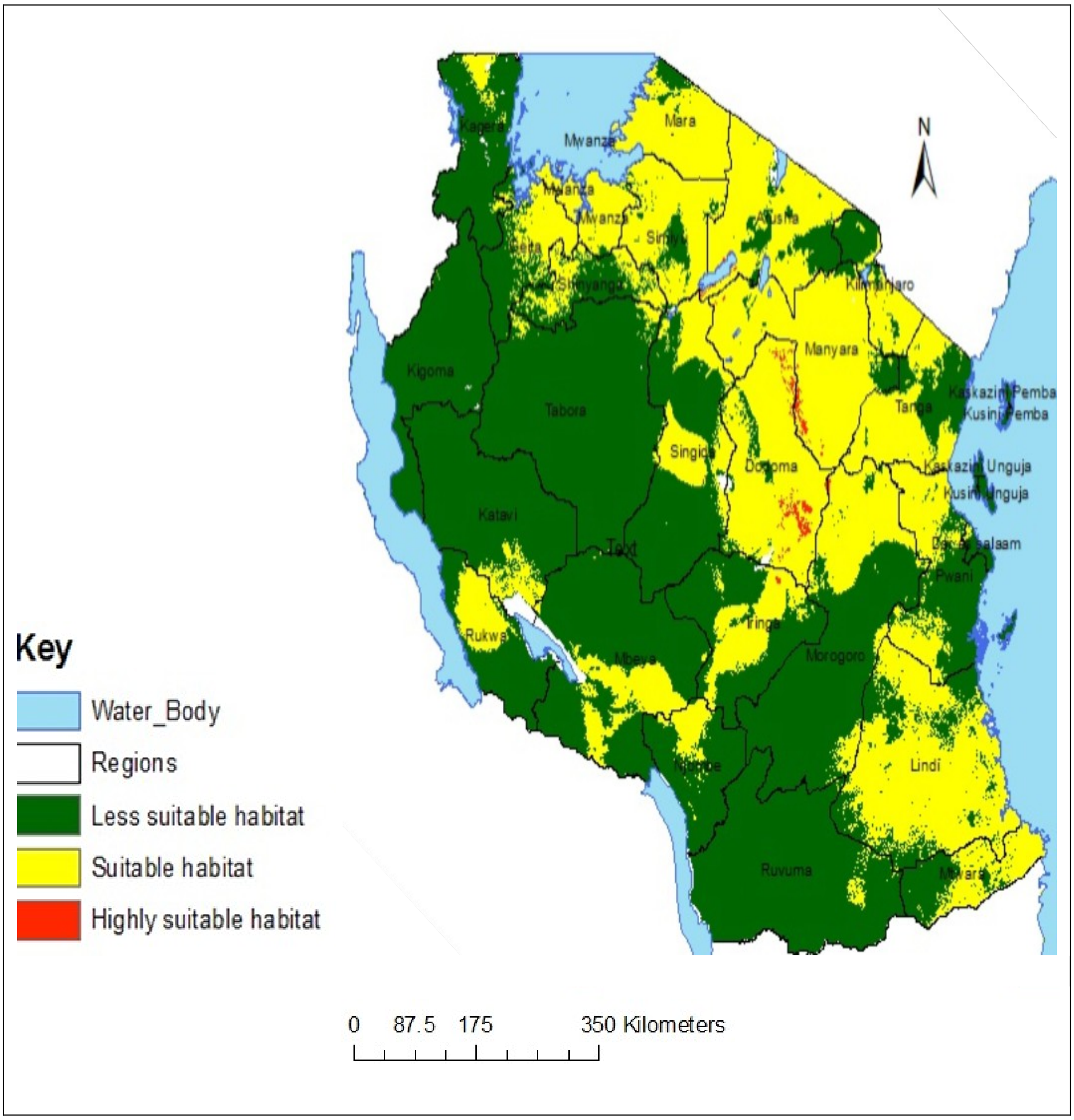


Figure 14: Modelled potential ecological niches of noxious Kongwa weed in Tanzania under future climate scenarios

Under future climate scenarios (2050), model results, show that, the weed will be spreading to areas around Lake Victoria. The new regions which are likely to be invaded by the Kongwa weed in the future are; Mara, Simiyu, Shinyanga and some parts of Kagera region as shown in Figure 14. Results in Figure 14 suggest that the eastern side of the country is likely to be affected more than the western side of the country. This observation suggests the need for more research to study the influence of proximity to Indian Ocean on the future climate in Tanzania.

The predicted change of suitability of Lake Victoria zone can be explained by the predicted land use changes around the Lake which are caused by the increased human demand (i.e., food through fisheries, hydropower, water supply, agriculture, etc.) on the Lake (Odada *et al*., 2009). The increased trend in land use changes near the Lake is predicted to exacerbate the impacts of climate change for areas around the Lake. Several studies have highlighted the impacts of local land use changes in local climate. Ge (2010) studied the consequences of wheat cultivation at Southern Great plains in USA to the land surface climatic conditions. Petchprayoon *et al*. (2010) showed the impacts of urbanization on the increased frequency of flooding in the Yom river of Thailand. Changes on the future climate as a result of present land use activities on the Lake zone could lead to the introduction of new invasive weed species (Sayer *et al.,* 2018; Olaka *et al*., 2019; Luhunga and Songoro, 2020).

4.3 Risk Assessment Results of Spread Pathways of Noxious Kongwa Weed in Tanzania

The results for the formulated risk assessment framework for the pathways and their assigned intensity rating score with respect to each established criterion are shown in Appendix 4. The results for the pathway risk score for each pathway are shown in Appendix 5. The results were obtained by multiplying the intensity scores in Appendix 4 and the weight values of each criterion. Table 8 shows the results of the final risk score for each pathway.

Table 8: Final Risk Score of Different P*athways*

Pathway	**Risk score (%)**
Livestock movements and stock fodder transportation	81
Agricultural produce and inputs	77
Farming tools, equipment, machines, footwear, and clothing	75
Water dispersal	56
Wind dispersal	44
Landscaping/Construction activities	43
Escape from research sites	30
Ornamental plant trade	28
Introduction via tourism	25
Introduction via exotic plant species	20

Based on the grouping as per Table 4, the pathways in Table 8 were further grouped as shown in Table 9.

Table 9*: Classification of Risk Score*

Pathway	**Group**
Livestock movements and stock fodder transportation	High Risk
Agricultural produce and inputs	High Risk
Farming tools, equipment, machines, footwear and clothing	Medium Risk
Water dispersal	Medium Risk
Wind dispersal	Low Risk
Landscaping/construction activities	Low Risk
Escape from research sites	Low Risk
Ornamental plant trade	Low Risk
Introduction via tourism	Low Risk
Introduction via exotic plant species	Low Risk

The introduction of noxious weeds in an area can be a result of the changes in environmental conditions of an area, accidental or intentional introduction through human activities and/or natural means such as water and wind dispersal (Bhowmik, 2014). In this study, the focus was on weed introduction via human activities and natural means.

Among the various investigated potential pathways, livestock movements and stock fodder transportation were found to be the pathway which posed the highest risk (81%) for the spread of the Kongwa weed as shown in Table 6. This result can be explained first by the nature of the major land use practice in Kongwa district which is largely mixed agriculture (URT, 2016) and second by the data collected during the interviewing of the land users in the infested land particularly, Kongwa district. The interview results showed that 74.6% of livestock keepers practice agro-pastoralism, with 96.6% of them not taking any precaution to quarantine new arriving livestock and 100% of them not taking any hygienic measures to livestock before leaving infested pasture land or before arriving in weed free areas. Livestock mobility and crop residue feeding have been used by pastoralists as drought coping strategies where animals get access to high quality forage resources and water (Vetter, 2005). Livestock movement and stock fodder transportation have been reported to be the major pathway for the spread of weeds in agro-pastoral societies (Hogan and Phillips, 2011; Zhu *et al*., 2019).

The other pathway which posed high risk for the spread of the Kongwa weed was agricultural produce and inputs. Usually, Kongwa weed reaches maturity stage at the same time with most of the crops like maize, sorghum, millet and sunflower (i.e., around April-June). Because of that, there is a greater risk of harvesting contaminated crops. This is supported by the results from the interviews which indicate that 70.9% of the farmers do not take any measures to control Kongwa weeds on their crop farms. Moreover, the results from the interviews indicate that 73.3% of the farmers use uncertified crop seeds. This may pose greater risk of planting seeds contaminated with Kongwa weed seeds because 79% of the farmers keep seeds from the previous harvest for the next growing season. Agricultural produce and inputs have been reported to pose greater risk for spreading weed seeds in several other studies (Gbehounou, 2013; Dual, 2014; Rao *et al*., 2017).

Water dispersal (Hydrochory) has been reported to be an important pathway for spreading weed seeds and propagules (De Rouw *et al*., 2006; Benvenuti, 2007). However, results from this study indicate that water dispersal pathway poses medium risk in the spread of Kongwa weed. This can be explained in part by the nature of the Kongwa weed seeds which have been observed (through field observations) to lack buoyancy, a property essential for seeds to float in water over long distances. Weed seeds need to have buoyancy characteristics to enable them to float in water over long periods of time and be transported over long distances (Fernandez, 2019 and Shi *et al*., 2020).

Farming tools, equipment, machines, footwear, and clothing have been assessed to pose medium risk for spreading Kongwa weed. This is apparent from the interview results which show that about 95.8% of all the land users in Kongwa district do not take hygienic measures on themselves and tools when entering or leaving infested lands. Kongwa weed seeds can attach themselves to clothing, or stick to footwear, farming tools, tractor tires or harvesting machines where they can be transported to other weed free areas and thereby start new infestation.

On the other hand, the wind dispersal pathway was assessed to pose low risk in spreading the Kongwa weed. This can be explained by the biological characteristics of the Kongwa weed seeds. Weed seeds need to have special features such as lateral wings or pappus, hairs of feather and very light seed weight for them to be able to be transported by winds over long distances (Bryson and Carter, 2004). Kongwa weed seeds are devoid of such characteristics. Furthermore, Kongwa weed seeds have been observed to fall very near to their plant stems and therefore very unlikely to be carried over long distances by wind (Nkombe *et al*., 2018).

Other pathways that fell under the group of low-risk pathway are; landscaping/ construction activities, escape from research sites, ornamental plant trade, introduction via tourism and introduction via exotic plant species. The major reason for these pathways to pose low risk was the low frequency of operation per year of these pathways (Randall, 2014).

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study has demonstrated the potential of Kongwa weed to establish itself in many parts of the country from the existing habitats in and around Kongwa district. The potential habitats are mostly, areas in the semi-arid climatic zone of Tanzania which include Singida, Manyara, Arusha, Lindi and some parts of Kilimanjaro, Tanga, Morogoro, Rukwa, Mbeya, Njombe Ruvuma and Mtwara regions.

Among many of the environmental variables which can drive the distribution of noxious Kongwa weed include total annual rainfall, amount of rainfall in the wettest month in a given area and soil organic carbon content, have been found to be the most significant in the case of the noxious Kongwa weed spatial distribution.

Moreover, the extent of the spread of the weed is predicted to increase, with the addition of other regions especially areas around Lake Victoria which currently provide less suitable habitats for the Kongwa weed. The predicted new areas which are at higher risk of being invaded by the noxious Kongwa weed in the future climate scenarios (2050) are Mara, Mwanza, Simiyu, Shinyanga regions and northern part of Kagera region.

Apart from changes in environmental factors such as climate or soil characteristics which may trigger establishment of weeds in weed free areas, risk assessment results of spread pathways, has shown that livestock movements and transportation of fodder and agriculture inputs and produce can be the major cause for the entry and spread of the noxious Kongwa weed in Tanzania.

5.2 Recommendations

In an effort to prevent or reduce the spread of weeds, the first step invariably involves awareness of the various pathways at play in the spread of the weeds. In this study, spread risk of various pathways has been assessed and the results indicate the need for preventive measures such as inspection of agricultural inputs and produce before transportation, initiation of livestock quarantine centers and observance of general hygienic measures in various land uses to be initiated both at national and individual level (i.e., every person) because as always prevention is cheaper and much better than eradicating weeds after they have long established.

At national level, there is a need for formulation of a national weed strategy. The aim of this national strategy should be to increase awareness to the public on various pathway of weed spread in the country and the habitats suitable for weed establishment. Moreover, the strategy should be able to establish a mechanism where information concerning early warnings on introduction of noxious weeds can be efficiently shared. The strategy should also ensure proper cooperation and participation among government officials, farmers and other stakeholders in managing weeds across Tanzania’s landscape.

At individual level, private and public land owners can take several prevention measures to avoid the entry of noxious weeds into their property for example through continuous monitoring and inspection of their land (and even neighbor’s land), so as not to be caught with the invasion of new weeds. Moreover, since the most risk pathway is livestock movement, it is recommended for livestock keepers to reduce livestock movements through improved forage resources via pasture establishment or enclosure management.

For areas which are at risk of invasion under future climate scenarios, especially Lake zone, it is recommended that people should be aware of the high-risk pathways such as uncontrolled livestock movements and uninspected introduction of agricultural goods and produce and adopt climate mitigation measures such as the use of environmentally friendly energy sources and afforestation measures.

In order to reach the goal set in Tanzania's national development blueprint, Vision 2025, the findings from this study can be incorporated in the implementation of national climate strategy especially on the management of weed spread pathways as a way of reducing one of the impacts of climate change which is introduction of weeds in weed free areas.

REFERENCES

Aiello-Lammens, M. E., Boria, R. A., Radosavljevic, A., Vilela, B. and Anderson, R. P. (2015). spThin: An R package for spatial thinning of species occurrence records for use in ecological niche models. *Ecography* 38(5): 541-545.

Al-Huqail, A., El-Dakak, R. M., Sanad, M. N., Badr, R. H., Ibrahim, M. M., Soliman, D., and Khan, F. (2020). Effects of climate temperature and water stress on plant Growth and accumulation of antioxidant compounds in Sweet Basil (*Ocimum basilicum* L.) leafy vegetable. *Scientifica* 2020(3808909): 1-12.

Arnold, J. D., Brewer, S. C. and Dennison, P. E. (2014). Modeling climate-fire connections within the great basin and upper Colorado river basin, western united states. *Fire Ecology* 10(2): 64 – 75.

Bajwa, A. A., Wang, H., Chauhan, B. S. and Adkins, S. W. (2019). Effect of elevated carbon Dioxide concentration on growth, productivity and glyphosate response of parthenium weed (*Parthenium hysterophorus* L.). *Pest Management Science* 75(11): 2934 – 2941.

Benvenuti, S. (2007). Weed seed movement and dispersal strategies in the agricultural environment. *Weed Biology and Management* 7(3): 141 – 157.

Bhowmik, P. C. (2014). Invasive weeds and climate change: Past, present and future. *Journal of Crop and Weed* 10(2): 345 – 349.

Blanco-Canqui, H., Shapiro, C. A., Wortmann, C. S., Drijber, R. A., Mamo, M., Shaver, T. M. and Ferguson, R. B. (2013). Soil organic carbon: The value to soil properties. *Journal of Soil and Water Conservation* 68(5): 129A-134A.

Bryson, C. T. and Carter, R. (2004). Biology of pathways for invasive weeds1. *Weed Technology* 18(1): 1216 – 1220.

Burgess, N. D., Hales, J., Underwood, E., Dinerstein, E., Olson, D., Itoua, I., Schipper, J., Ricketts, T. and Newman, K. (2004). *Terrestrial Ecoregions of Africa and Madagascar: A Continental Assessment*. Island Press, Washington DC. 150pp.

Camberlin, P. and Okoola, R. E. (2003). The onset and cessation of the “long rains” in eastern Africa and their internal variability. *Theoretical and Applied Climatology* 75(1-2): 43 – 54.

Chang’a, L. B. and Nduganda, A. R. (2008). Drought analysis in Tanzania. *Tanzania Meteorological Agency Research Journal* 2008: 40-53.

Chauhan, B. S. (2020). Grand Challenges in Weed Management. *Front Agronomy* 1: 1-3.

De Rouw, A., Douillet, M., Tjiantahosong, H., Ribolzi, O. and Thiébaux, J. P. (2006). Dispersal of weed seeds by erosion and flow processes in upland fields. In: *International Conference on Sustainable Sloping Lands and Watershed Management: Linking Research to Strengthen Upland Policies and Practices (edited by National Advanced Fire and Resource Institute (NAFRI)),* Luang Prabang, Laos. pp. 156 – 166.

Duary, B. (2014). Weed prevention for quality seed production of crops. *SATSA Mukhopatra Annual Technical Issue* 18: 48 – 57.

Elisante, F., Tarimo, M. T. and Ndakidemi, P. A. (2013). Distribution and abundance of Datura stramonium in Ngorongoro Conservation Area. *American Journal of Research Communication* 1(12): 182 – 196.

Elith, J., H. Graham, C., P. Anderson, R., Dudík, M., Ferrier, S., Guisan, A. and Li, J. (2006). Novel methods improve prediction of species' distributions from occurrence data. *Ecography* 29(2): 129 – 151.

Elith, J., Phillips, S. J., Hastie, T., Dudík, M., Chee, Y. E. and Yates, C. J. (2011). A statistical explanation of MaxEnt for ecologists. *Diversity and Distributions* 17(1): 43 – 57.

Esfanjani, J., Ghorbani, A. and Chahouki, M. A. Z. (2018). MaxEnt Modeling for Predicting Impacts of Environmental Factors on the Potential Distribution of Artemisia aucheri and Bromus tomentellus-Festuca ovina in Iran. *Polis Journal of Environmental Studies* 27(3).

FAO (2006). *Guidelines for Soil Description (4th ed)*. Food and Agriculture Organization (FAO) of the United Nations, Rome. 110pp.

FAO (2011). *Procedures for Post-Border Weed Risk Management: Plant Production and Protection Division*. Food and Agriculture Organization, Rome. 34pp.

FAO (2016). *Land Degradation Assessment in Dry lands: Part 2-Field Methodology and Tools*. Food and Agriculture Organization, Rome. 20pp.

FAO (2021). FAO SOILS PORTAL. [http://www.fao.org/soils-portal/soil-management/management-of-some-problem-soils/salt-affected-soils/more-information-on-salt-affected-soils/technical-issues/en/] site visited on 19/01/2021.

Fernández, F. F., Schneider, B. and Zilli, F. (2019). Factors driving seed dispersal in a Neotropical river-floodplain system. *Acta Botanica Brasilica* 33(3): 465 - 473.

Fick, S. E. and Hijmans, R. J. (2017). WorldClim 2: new 1km spatial resolution climate surfaces for global land areas. *International Journal of Climatology* 37(12): 4302-4315. https://doi.org/10.1002/joc.5086.

Foody, G. M. (2008). Harshness in image classification accuracy assessment. *International Journal of Remote Sensing* 29(11): 3137 – 3158.

Franklin, J. (2010). *Mapping Species Distributions: Spatial Inference and Prediction*. Cambridge University Press, Cambrige. 319pp.

Garcia, K., Lasco, R., Ines, A., Lyon, B. and Pulhin, F. (2013). Predicting geographic distribution and habitat suitability due to climate change of selected threatened forest tree species in the Philippines. *Applied Geography* 44: 12 - 22.

Gbèhounou, G. (2013). *Guidance on Weed Issues and Assessment of Noxious Weeds in a Context of Harmonized Legislation for Production of Certified Seeds*. Plant Production and Protection Division, Food and Agriculture Organization of the United Nations, Rome. 38pp.

Ge, J. (2010). MODIS observed impacts of intensive agriculture on surface temperature in the southern Great Plains. *International Journal of Climatology* 30(13): 1994-2003.

Gharde, Y., Singh, P. K., Dubey, R. P. and Gupta, P. K. (2018). Assessment of yield and economic losses in agriculture due to weeds in India. *Crop Protection* 107: 12-18.

Gianessi, L. P. (2009). *Solving Africa's Weed Problem: Increasing Crop Production and Improving the Lives of Women*. Crop Protection Research Institute, Washington. 37pp.

Giliba, R. A. and Yengoh, G. T. (2020). Predicting suitable habitats of the African cherry (Prunus Africana) under climate change in Tanzania. *Atmosphere* 11(9): 988-992.

Goncalves, M. L. (1987). *Flora Zambesiaca (Vol.8).* Royal Botanic Gardens, Kew, London. 142pp.

Gregrio, A. and Jansen, J. (2000). *Land cover classification system. Classification Concepts and User Manual for Software.* Food and Agriculture Organization, Rome. 92pp.

Guisan, A. and Zimmermann, N. E. (2000). Predictive habitat distribution models in ecology. *Ecological Modelling* 135(3): 147 – 186.

Guisan, A., Tingley, R., Baumgartner, J. B., Naujokaitis-Lewis, I., Sutcliffe, P. R., Tulloch, A. I. and Martin, T. G. (2013). Predicting species distributions for conservation decisions. *Ecology Letters* 16(12): 1424 – 1435.

Hemp, A. (2008). Introduced plants on Kilimanjaro: tourism and its impact. *Plant Ecology* 197(1): 17 – 29.

Hengl, T., Heuvelink, G. B., Kempen, B., Leenaars, J. G., Walsh, M. G., Shepherd, K. D., and Tondoh, J. E. (2015). Mapping soil properties of Africa at 250 m resolution: Random forests significantly improve current predictions. *PloS One* 10(6): e0125814.

Hernandez, P. A., Franke, I., Herzog, S. K., Pacheco, V., Paniagua, L., Quintana, H. L., Soto, A., Swenson, J. J., Tovar, C., Valqui, T. H., Vargas, J. A. and Young, B. E. (2008). Predicting species distributions in poorly studied landscapes. *Biodiversity and Conservation* 17: 1353 – 1366.

Hogan, J. P. and Phillips, C. J. C. (2011). Transmission of weed seed by livestock: A review. *Animal Production Science* 51(5): 391 – 398.

Hontoria, C., Rodríguez-Murillo, J. C. and Saa, A. (2005). Soil organic carbon contents in arid and semiarid regions of Peninsular in Spain: *Sustainable Use and Management of Soils–Arid and Semiarid Regions* (*edited by: Faz Cano, A., Ortiz silla, R. and Mermut AR, Catena Verlag, Reiskirchen*), Schweizerbert Science, Stuttgart, Germany. pp. 275-280.

Hulme, P. E., Burslem, D. F., Dawson, W., Edward, E., Richard, J. and Trevelyan, R. (2013). Aliens in the Arc: Are invasive trees a threat to the montane forests of East Africa? In: *Plant Invasions in Protected Areas: Patterns, Problems and Challenges.* (Edited by Foxcroft L. C., Pysek P., Richardson D. M. and Genovesi P.), Springer, Dordrecht, pp. 145 – 165.

Hyde, M.A., Wursten, B.T., Ballings, P. and Coates Palgrave, M. (2021). *Flora of Zimbabwe: Species information: Astripomoea hyoscyamoides.* [https://www.zimbabweflora.co.zw/speciesdata/species.php?species_id=203800] site visited on 12/05/2021.

Ian Popay. (2008). Weeds of agriculture - Introduction of weeds, Te Ara - the Encyclopedia of New Zealand, [http://www.TeAra.govt.nz/en/weeds-of-agriculture/page-1] site visited on 09/05/2021.

IPPC (2017). *International Plant Protection Convention – International Standards for Phytosanitary Measures, ISPM 5: Glossary of Phytosanitary Terms*. Food and Agriculture Organization, Rome. 34pp.

Jiménez-Valverde, A., Peterson, A. T., Soberón, J., Overton, J. M., Aragón, P. and Lobo, J. M. (2011). Use of niche models in invasive species risk assessments. *Biological Invasions* 13(12): 2785 – 2797.

Joyner, T. A. (2010). Ecological niche modeling of a zoonosis: A case study using anthrax outbreaks and climate Change in Kazakhstan. MSc Thesis for Award Degree at University of Florida, USA. 150pp.

Kearney, M. and Porter, W. (2009). Mechanistic niche modelling: combining physiological and spatial data to predict species' ranges. *Ecology Letters* 12(4): 334 – 350.

Kihupi, N. I., Tarimo, A. K. P. R. and Dihenga, H. O. (2007). Spatial and temporal variability of growing season characteristics in Tanzania. *Journal of the Geographical Association of Tanzania* 32: 33 – 49.

Kilawe, C. J., Mbwambo, J. R., Kajembe, G. C., Mwakalukwa, E. E., Amri, A. M., Mushi, G. V., Athumani, A. M., Eckert, S. and Eschen, R. (2017). Mrashia: Prosopis invading pastures and agricultural lands in Tanzania. *The Woody Weeds Project. INSIGHTS Report* 1(1): 1-3.

King, C., Thomas, N., Steel, J., Hunt, T. and Weiss, J. (2008). Weed spread pathways risk assessment in Victoria. In: *Proceedings of the 16th Australian Weeds Conference* (*edited by RD van Klinken, VA Osten, FD Panetta and JC Scanlan*). pp. 50-52.

Kyei-Mensah, C., Kyerematen, R. and Adu-Acheampong, S. (2019). Impact of rainfall variability on crop production within the Worobong Ecological Area of Fanteakwa District, Ghana. *Advances in Agriculture* 2019(123): 1-7.

Leenaars, J. G. B., Van Oostrum, A. J. M. and Ruiperez, G. M. (2014). *Africa Soil Profiles Database, Version 1.2. A compilation of georeferenced and standardized legacy soil profile data for Sub-Saharan Africa (with dataset). ISRIC Report 2014/01*. Africa Soil Information Service (AfSIS) project and ISRIC - World Soil Information, Wageningen, the Netherlands. 162pp.

Liu, C., White, M. and Newell, G. (2013). Selecting thresholds for the prediction of species occurrence with presence-only data. *Journal of Biogeography* 40: 778 – 789.

Luhunga, P. M. and Songoro, A. E. (2020). The analysis of climate change, and extreme climatic events in the Lake Victoria region of Tanzania. *Frontiers in Climate* 2: 1-27.

Maleko, D., Sangeda, A. and Mtengeti, E. (2015). A prospective method for overcoming challenges of rehabilitating degraded semi-arid rangelands of Tanzania: A case of Gairo district. *Journal of Continuing Education and Extension* 5(2): 1 – 10.

Marcer, A., Sáez, L., Molowny-Horas, R., Pons, X. and Pino, J. (2013). Using species distribution modelling to disentangle realised versus potential distributions for rare species conservation. *Biological Conservation* 166: 221 – 230.

Mbonde, F. J. (2015). Assessment of land use conflicts in Tanzania: A Case Study of Songambele and Mkoka Villages in Kongwa District, Dodoma region. MSc Thesis for Award Degree at Mzumbe University, Morogoro, Tanzania. 87pp.

Melo-Merino, S. M., Reyes-Bonilla, H. and Lira-Noriega, A. (2020). Ecological niche models and species distribution models in marine environments: A literature review and spatial analysis of evidence. *Ecological Modeling* 415: 108837.

Molloy, S. W., Davis, R. A. and Van Etten, E. J. (2014). Species distribution modelling using bioclimatic variables to determine the impacts of a changing climate on the western ringtail possum (*Pseudocheirus occidentals*; *Pseudocheiridae*). *Environmental Conservation* 41(2): 176 – 186.

MOWI (2014). Ministry of Water and Irrigation. [http://www.maji.go.tz/basins/nine.php] site visited on 12/11/2019.

Mtenga, N. C. (2019). Developing an eco-friendly and bio-management strategy against Parthenium hysterophorus (I.) in Arusha, Tanzania. Dissertation for Award of MSc. Thesis for Award Degree at the Nelson Mandela African Institution of Science and Technology, Arusha, Tanzania. 85pp.

Mtenga, N. C., Tarimo, T. M., Ndakidemi, P. A. and Mbega, E. R. (2019). Carrot-Weed: A Noxious Plant That Threatens Biodiversity in Africa. *American Journal of Plant Sciences* 10(03): 433-448.

Mwakapeje, E. R., Ndimuligo, S. A., Mosomtai, G., Ayebare, S., Nyakarahuka, L., Nonga, H. E. and Skjerve, E. (2019). Ecological niche modeling as a tool for prediction of the potential geographic distribution of Bacillus anthracis spores in Tanzania. *International Journal of Infectious Diseases* 79: 142 – 151.

Mwalongo, N. A., Selemani, I. S., Sibuga, K. P., Rweyemamu, C. L. and Fupi, G. F. (2020). Effectiveness of Selected Cultural, Biological and Chemical Methods Singly or in Integration as Management Options against Kongwa Weed (Astripomoea hyoscyamoides Vatke Verdc.). *Journal of Plant Sciences and Agricultural Research* 4: 3-41.

NAFORMA (2015). *National Forest Resources Monitoring and Assessment of Tanzania Mainland: Main Results.* Ministry of Natural resources and Tourism, Dar es Salaam. 124pp.

Nandi, S. (2019). Maximum Likelihood Estimation from Bayes's Theorem. [https://towardsdatascience.com/maximum-likelihood-estimation-from-baytheorem-6cc7f0 db 9adb] site visited on 10/09/2020.

National Bureau of Statistics (NBS) [Tanzania] (2017). National Environment Statistics Report, 2017 (NESR, 2017), Dar es Salaam, Tanzania Mainland. 231pp.

Nenzén, H. K. and Araújo, M. (2011). Choice of threshold alters projections of species range shifts under climate change. *Ecological Modeling* 222: 3346 – 3354.

Nkombe, B., Sangeda, A., Sibuga, K. and Hermansen, J. (2018). Assessment of farmers perceptions on the status of *Astripomoea Hyscamoides* (Kongwa Weed)

Invasiveness in Central Tanzania. *Journal Plant Science Agriculture Research* *2*(1): 1 – 11.

Norris, D. (2014). Model thresholds are more important than presence location type: Understanding the distribution of lowland tapir (*Tapirus terrestris*) in a continuous Atlantic forest of southeast Brazil. *Tropical Conservation Science* 7(3): 529 – 547.

Odada, E. O., Ochola, W. O. and Olago, D. O. (2009). Drivers of ecosystem change and their impacts on human well-being in Lake Victoria basin. *African Journal of Ecology* 47: 46 – 54.

Oerke, E. C. (2006). Crop losses to pests. *The Journal of Agricultural Science* 144(1): 31 – 43.

Olaka, L. A., Ogutu, J. O., Said, M. Y. and Oludhe, C. (2019). Projected climatic and hydrologic changes to Lake Victoria Basin Rivers under three RCP emission scenarios for 2015–2100 and impacts on the water sector. *Water* 11(7): 1449-14502.

Omeny, P. A., Ogallo, L. A., Okoola, R., Hendon, H. A. and Wheeler, M. (2006). East African rainfall variability associated with the Madden-Julian Oscillation. *Journal of Kenya Meteorological Society* 2(2).

Palai, J. B. (2010). Weed Management [http://courseware.cutm.ac.in/wp-content/uploads/2020/05/weed-management-E-material.pdf] site visited on 20/10/2020.

Pätzold, S., Hbirkou, C., Dicke, D., Gerhards, R. and Welp, G. (2019). Linking weed patterns with soil properties: a long-term case study. *Precision Agriculture* 2019: 1-20.

Pearson, R. G. and Dawson, T. P. (2003). Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful? *Global Ecology and Biogeography* 12(5): 361 – 371.

Pearson, R. G., Raxworthy, C. J., Nakamura, M. and Townsend Peterson, A. (2007). Predicting Species distributions from small numbers of occurrence records: A test case using cryptic Geckos in Madagascar. *Journal of Biogeography* 34(1): 102 – 117.

Petchprayoon, P., Blanken, P. D., Ekkawatpanit, C. and Hussein, K. (2010). Hydrological impacts of land use/land cover change in a large river basin in central–northern Thailand. *International Journal of Climatology* 30(13): 1917-1930.

Peterson, A. T., Papeş, M. and Soberón, J. (2015). Mechanistic and correlative models of ecological niches. *European Journal of Ecology* 1(2): 28 – 38.

Phillips, S. J. and Dudík, M. (2008). Modeling of species distributions with Maxent: New extensions and a comprehensive evaluation. *Ecography* 31(2): 161 – 175.

Phillips, S. J. and Elith, J. (2013). On estimating probability of presence from use availability or presence–background data. *Ecology* 94(6): 1409 – 1419.

Phillips, S. J., Anderson, R. P. and Schapire, R. E. (2006). Maximum entropy modeling of species geographic distributions. *Ecological Modelling* 190(4): 231 – 259.

Pidwirny, M. (2006). Concept of ecological niche. Fundamentals of physical geography. [http://www.physicalgeography.net] site visited on 4/10/2019.

Platts, P. J., Omeny, P. A. and Marchant, R. (2015). Africlim high-resolution climate projections for ecological applications in Africa. *African Journal of Ecology* 2015: 103 – 108.

Polechová, J. and Storch, D. (2019). *Ecological Niche. Encyclopedia of Ecology*. Elsevier Publishers, USA. 2780pp.

Ramesh, K., Matloob, A., Aslam, F., Florentine, S. K. and Chauhan, B. S. (2017). Weeds in a changing climate: vulnerabilities, consequences, and implications for future weed management. *Frontiers in Plant Science* 8: 1 – 95.

Rana, S. S. and Rana, M. C. (2016). *Principles and practices of weed management.* Department of Agronomy, College of Agriculture, CSK Himachal Pradesh Krishi Vishvavidyalaya, Palampur. pp 138.

Randall, R. (2014). *Weed Threats to the Kimberley Region, Pathways and the Risk of Incursion*. Department of Agriculture and Food, Western Australia. 37pp.

Rao, A. N., Brainard, D. C., Kumar, V., Ladha, J. K. and Johnson, D. E. (2017). Preventive weed management in direct-seeded rice: targeting the weed seedbank. *Advances in Agronomy* 144: 45 – 142.

Rebelo, H. and Jones, G. (2010). Ground validation of presence-only modelling with rare species: A case study on barbastelles Barbastella barbastellus (Chiroptera: Vespertilionidae). *Journal of Applied Ecology* 47(2): 410 – 420.

Rosolem, C. A. and Steiner, F. (2017). Effects of soil texture and rates of K input on potassium balance in tropical soil. *European Journal of Soil Science* 68(5): 658-666.

Sayer, C. A., Máiz-Tomé, L. and Darwall, W. R. T. (2018). *Freshwater Biodiversity in the Lake Victoria Basin: Guidance for Species Conservation, Site Protection, Climate Resilience and Sustainable Livelihoods*. IUCN Gland, Switzerland. 226pp.

Schaffrath, V. R., Gonçalves, A. C. A., Sousa, A. J. and Tormena, C. A. (2015). Spatial correlation between physical properties of soil and weeds in two management systems. *Revista Brasileira de Ciência do Solo* 39(1): 279-288.

Scott, J. K., Murphy, H., Kriticos, D. J., Webber, B. L., Ota, N. and Loechel, B. (2014). *Weeds and Climate Change: Supporting Weed Management Adaptation*. Commonwealth Scientific and Industrial Research Organization, Australia. 74pp.

Shi, X., Li, R., Zhang, Z. and Qiang, S. (2020). Microstructure determines floating ability of weed seeds. *Pest Management Science* 4: 1-9.

Sisodia, P. S., Tiwari, V. and Kumar, A. (2014). Analysis of supervised maximum likelihood classification for remote sensing image. In: *International Conference on Recent Advances and Innovations in Engineering*. 4pp.

Tharwat, A. (2018). Classification assessment methods. *Applied Computing and Informatics* 17(1): 168-192.

Thorn, J. S., Nijman, V., Smith, D. and Nekaris, K. A. I. (2009). Ecological niche modelling as a technique for assessing threats and setting conservation priorities for Asian slow lorises (*Primates: Nycticebus*). *Diversity and Distributions* 15(2): 289 – 298.

Title, P. O. and Bemmels, J. B. (2018). ENVIREM: an expanded set of bioclimatic and topographic variables increases flexibility and improves performance of ecological niche modeling. *Echography* 41(2): 291 – 307.

URT (2012). *National Climate Change Strategy*. Vice President Office, Division of Environment, Dar es Salaam. 92pp.

URT (2016). *Kongwa District Socio-Economic Profile*. Regional Administration and Local Government's office, Dodoma. 44pp.

URT (2018). *National Population Projections*. National Bureau of Statistics, Dar es Salaam. 113pp.

USDA (2008). *Noxious Weed Treatment Project: Final Environmental Impact Assessment*. Modoc National Forest, California. 644pp.

Vetter, S. (2005). Rangelands at equilibrium and non-equilibrium: recent developments in the debate. *Journal of Arid Environments* 62(2): 321-341.

Wabuyele, E., Lusweti, A., Bisikwa, J., Kyenune, G., Clark, K., Lotter, W. D. and Wondi, M. (2014). A roadside survey of the invasive weed Parthenium hysterophorus (*Asteraceae*) in East Africa. *Journal of East African Natural History* 103(1): 49 – 57.

Walsh, M. J., Broster, J. C., Schwartz-Lazaro, L. M., Norsworthy, J. K., Davis, A. S., Tidemann, B. D. and Bagavathiannan, M. V. (2018). Opportunities and challenges for harvest weed seed control in global cropping systems. *Pest Management Science* 74(10): 2235-2245.

Warren, D. L. and Seifert, S. N. (2011). Ecological niche modeling in Maxent: The importance of model complexity and the performance of model selection criteria. *Ecological Applications* 21(2): 335 – 342.

Witt, A. B., Kiambi, S., Beale, T. and Van Wilgen, B. W. (2017). A preliminary assessment of the extent and potential impacts of alien plant invasions in the Serengeti-Mara ecosystem, East Africa. *Koedoe* 59(1): 1 – 16.

WSSA (2016). Do you have a weed, noxious weed, invasive weed or "super weed"? [http://wssa.net/wp-content/uploads/WSSA-Weed-Science-Definitions.pdf] site visited on 23/12/2019.

Yackulic, C. B., Chandler, R., Zipkin, E. F., Royle, J. A., Nichols, J. D., Campbell, G. E. H. and Veran, S. (2013). Presence-only modelling using Maxent: When can we trust the inferences? *Methods in Ecology and Evolution* 4(3): 236 – 243.

Yu, Z., Di, L., Yang, R., Tang, J., Lin, L., Zhang, C. and Sun, Z. (2019). Selection of Landsat 8 OLI Band Combinations for Land Use and Land Cover Classification. In: *8th International Conference on Agro-Geoinformatics* (*Agro-Geoinformatics*). pp. 1 – 5.

Zhu, W., Zeng, N. and Wang, N. (2010). Sensitivity, specificity, accuracy, associated confidence interval and ROC analysis with practical implementations. *NESUG*

Proceedings: Health Care and Life Sciences, Baltimore, Maryland. pp. 19 – 67.

Zhu, X., Gopurenko, D., Serrano, M., Spencer, M. A., Pieterse, P. J., Skoneczny, D. and Weston, L. A. (2019). Genetic evidence for plural introducti pathways of the invasive weed Paterson’s curse (*Echium plantagineum* L.) to southern Australia. *PloS One* 14(9): 222 – 696.

APPENDICES

Appendix 1: Description of NAFORMA land cover classification system

Class	National Land Cover Description
Forest land	"An area of land with at least 0.5 ha, with a minimum tree crown cover of 10% or with the existing tree species planted or natural having the potential of attaining more than 10% crown cover, and with trees which have the potential or have reached a minimum height of 3 m at maturity in situ. It includes montane, lowland, mangrove and plantation forests, woodlands, thickets, cultivated land mixed crops and cultivated land with wooded crops".
Wood land	"Vegetation type in which the canopy coverage generally ranging between 20–80%, and height between 5–20 meters".
Bush land	Bushland predominantly comprises of wooded plants, which are multi-stemmed from a single root base. It includes dense and open bushland except thickets
Grass land	For the most part, grassland occurs in combination with either limited wooded or bushed component, or with scattered subsistence cultivation
Crop land	Land, which is actively used, and grows agriculture crops including agroforestry systems, herbaceous crops and grain crops
Open land	The land where vegetation cover is almost or entirely absent
Water body	Rivers, lakes, Oceans
Other land	Built-up land such as buildings, infrastructure (e.g., power line, railways, airfields etc.)

Appendix 2: Worldclim bioclimatic variables to be used for mapping the current ecological niches of noxious Kongwa weed in central Tanzania

BIO1 = Annual Mean Temperature

BIO2 = Mean Diurnal Range (Mean of monthly (max temp - min temp))

BIO3 = Isothermality (BIO2/BIO7) (* 100)

BIO4 = Temperature Seasonality (standard deviation *100)

BIO5 = Max Temperature of Warmest Month

BIO6 = Min Temperature of Coldest Month

BIO7 = Temperature Annual Range (BIO5-BIO6)

BIO8 = Mean Temperature of Wettest Quarter

BIO9 = Mean Temperature of Driest Quarter

BIO10 = Mean Temperature of Warmest Quarter

BIO11 = Mean Temperature of Coldest Quarter

BIO12 = Annual Precipitation

BIO13 = Precipitation of Wettest Month

BIO14 = Precipitation of Driest Month

BIO15 = Precipitation Seasonality (Coefficient of Variation)

BIO16 = Precipitation of Wettest Quarter

BIO17 = Precipitation of Driest Quarter

BIO18 = Precipitation of Warmest Quarter

BIO19 = Precipitation of Coldest Quarter

Appendix 3: Interview questions on land management practices

A. General Information

Respondent’s name..Date...

Region.............................. District.......................Village name.............................

Ward................................ Division......................

Interviewer’s name.......................................

B. Familiarity with noxious Kongwa weed

1. Are you familiar with noxious Kongwa weed?

Well known .... general........... Little...........

2. Have you ever observed any noxious Kongwa weed in your area?

Yes………………. No……………if Yes

where? ....

C. Crop cultivation land use

1. Farm details

Owner	Latitudes	Longitudes

2a. How do you prepare land before the start of the new growing season?

Burning	Bush slashing	Conventional Tillage	Zero tillage	Conservation Tillage

2b. Do you use certified weed free crop seeds? YES ☐/NO ☐

3a. Do you practice soil fumigation? YES ☐/NO ☐

3b. Do you use seeds from previous crop harvest? YES ☐/NO ☐

4. What kind of cropping system do you practice in your farm land?

Mono cropping	Crop rotation	Inter cropping	Overlapping cropping	Non-Overlapping	Others

5. How do you handle previous crop residue?

Burning/fire	Burying	Use it for mulching	Others

6a. Do you control Kongwa weeds in your farm land? If yes, how?

Mechanical Means	Chemical Means	Biological Means	Cultural Means	No Control

6b. At what stage of Kongwa weed growth do you start to control them?

Just after germination	Before it sets seeds	After it sets seeds

7. Do you take any measures to improve soil fertility in your farm? If yes, how? (e.g., Organic manure, inorganic fertilizers etc.)

8. Do you control floods in your land? If yes, how?

Terraces	Strip Cropping	Contour farming	Others

9. Do you take any measures to preserve and maintain soil moisture for crop growth in your farm? If yes, how? (e.g., mulching, irrigation etc.)

10. Do you protect your crops from strong winds in your farm land? If yes, how?

11. Do you observe hygienic measures to prevent yourself, tools, and machines from weed contamination? YES ☐/NO ☐

D. Livestock keeping land use

1. Rangeland/Grazing land details

Plot owner	**Latitudes**	**Longitudes**

2. Which kind of livestock keeping system do you practice?

Ranching	**Agro-pastoralism**	**Mixed-agriculture**	**Pastoralism**

3a. Do you control Kongwa weeds in your pasture land? If yes, how?

Mechanical Means	Chemical Means	Biological Means	Cultural Means	No Control

3b. At what stage of Kongwa weed growth do you start to control them?

Just after germination	Before it sets seeds	After it sets seeds

4. Do you clean your livestock especially on the hoofs and on the coats after they leave a pasture area?

5. Do you control floods in your Pasture land? If yes, how?

Terraces	Strip Cropping	Contour farming	Others

6. Do you quarantine new-arriving livestock? YES ☐/NO ☐

E. Residential land use

1. Plot details

Plot owner	Latitudes	Longitudes

2a. Do you control Kongwa weeds in your residential land? If yes, how?

Mechanical	Chemical	Biological	Cultural	No Control

2b. At what stage of Kongwa weed growth do you start to control them?

Just after germination	Before it sets seeds	After it sets seeds

3. Do you observe hygienic measures to weed contamination at your land? YES ☐/NO ☐

Appendix 4: Intensity rating score in each criterion

		Intensity rating score in each criterion										
		Mng	Frq	Est				Int	Dst		W/im	
S/N	**Pathway**			**A**	**b**	**C**	**d**		**a**	**b**	**a**	**b**
01	Contaminated agricultural produce and inputs	0.75	0.75	1	0.75	0.75	0.75	0.75	0.75	0.5	0.75	1
02	Contaminated Tools, Equipment, Machinery, Shoes, and Clothes	1	0.75	0.75	0.75	0.75	0.75	0.25	0.75	0.25	0.25	0.75
03	Escape from research sites	0.25	0.25	0.75	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
04	Livestock Movements	1	1	1	1	0.25	0.75	0.25	0.75	0.75	0.5	0.75
05	Landscaping/ Construction of infrastructure (Roads and Railways)	1	0	0	0	0.25	0.25	0.75	0.25	0.5	0.75	0.25
06	Ornamental plants trade	0.75	0	0.25	0	0.25	0.25	0	0	0	0	0
07	Introduction via tourists	0.5	0	0	0	0.25	0.25	0.25	0.25	0.5	0.25	0.25
08	Introduction via exotic vegetable species	0.25	0	0.25	0	0.25	0.25	0.25	0.25	0.25	0.25	0.5
09	Water dispersal through irrigation or/and flooding.	0.75	0.25	0.75	0.25	0.25	0.75	0.75	0.25	0.5	0.75	0.75
10	Wind dispersal	0.75	0.75	0.25	0.25	0	0	0.25	0	0	0.25	0.75

The options for intensity rating score were either 0, 0.25, 0.5, 0.75 or 1 whereby the intensity score of 1 indicated high risk and 0 indicated no risk at all.

Whereby **Mng** stands for Management criterion, **Frq** stands for Frequency of activity criterion, **Est** stands for Establishment criterion, **Int** stands for Introduction criterion, **Dst** stands for Distance criterion and **W/im** stands for Weed importance criterion

*The alphabetical letters **a, b, c, d** represents sub-criteria from respective main criteria as described previously.

Appendix 5: Pathway risk score in each of the main criterion

S/N	Pathway	Pathway Risk Score in Each of the Main criterion= $((average\ intensity\ rate) \times (criterion\ weight))$						Final Risk Score for Each Pathway $\sum \overline{Ir} \times cw$
		Mng	Frq	Est	Int	Dst	W/im	
01	Contaminated agricultural produce and inputs	0.2025	0.0975	0.325	0.06	0.05	0.035	0.77
02	Contaminated Tools, Equipment, Machinery, Shoes, and Clothes	0.27	0.0975	0.30	0.02	0.04	0.02	0.75
03	Escape from research sites	0.0675	0.0325	0.15	0.02	0.02	0.01	0.30
04	Livestock Movements and stock feeds	0.27	0.13	0.30	0.02	0.06	0.025	0.81
05	Landscaping/ Construction of infrastructure (Roads and Railways)	0.27	0	0.05	0.06	0.03	0.02	0.43
06	Ornamental plants trade	0.2025	0	0.075	0	0	0	0.28
07	Introduction via tourism	0.135	0	0.05	0.02	0.03	0.01	0.25
08	Introduction via exotic vegetable species	0.0675	0	0.075	0.02	0.02	0.015	0.20
09	Water dispersal through irrigation or/and flooding.	0.2025	0.0325	0.20	0.06	0.03	0.03	0.56
10	Wind dispersal	0.2025	0.0975	0.1	0.02	0	0.02	0.44

The results in appendix 5, were obtained by multiplication of intensity scores in appendix 4 and the corresponding weight values of each criterion.

*Whereby **Mng** stands for Management criterion

Frq stands for Frequency of activity criterion

Est stands for Establishment criterion

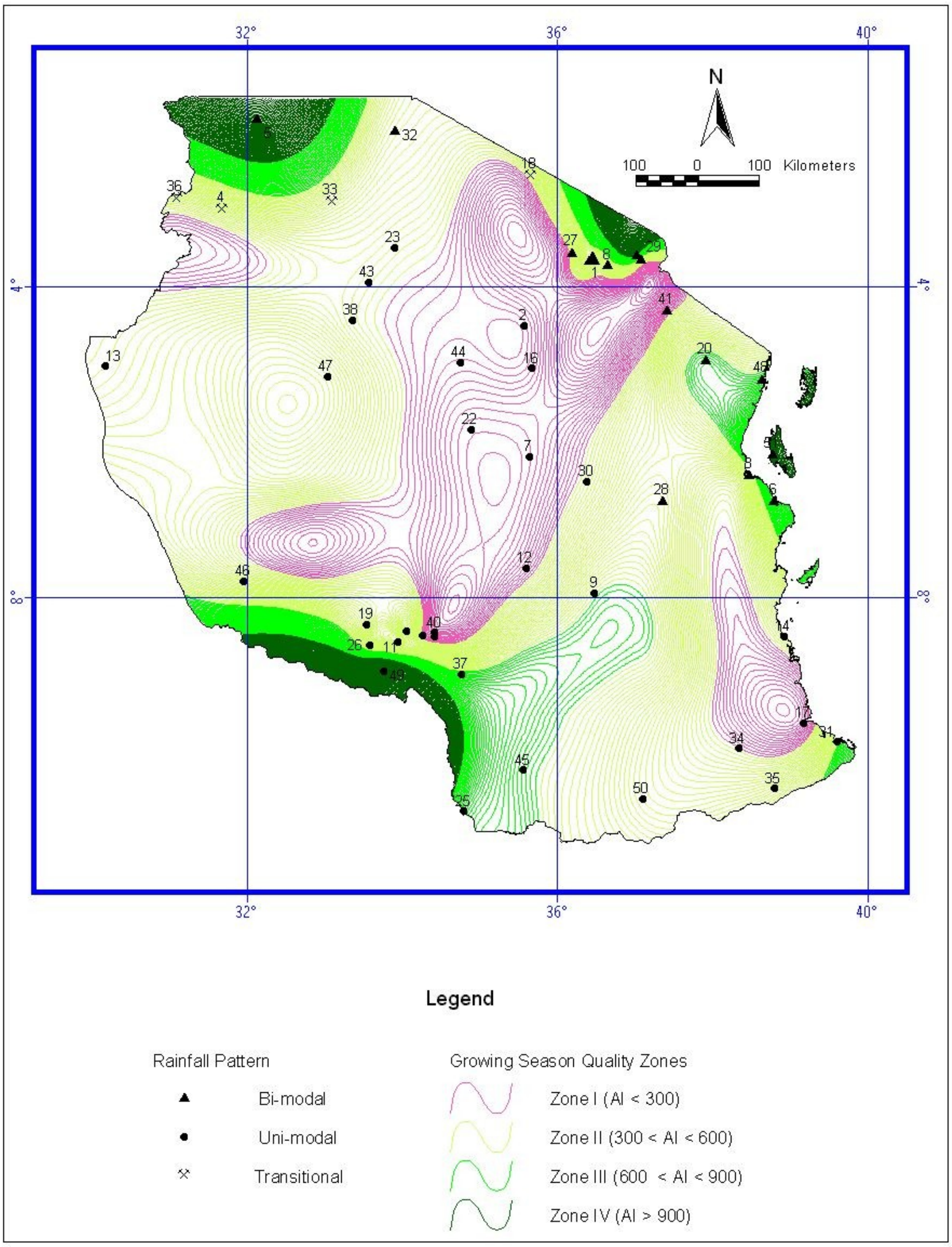
Int stands for Introduction criterion

Dst stands for Distance criterion

W/im stands for Weed importance criterion

$\overline{Ir}$ = average intensity rate and **cw**=criterion weight

Appendix 6: Tanzania agroclimatic zones based on aridity index



Agroclimatic zones based on Aridity Index (Source: Kihupi *et al*., 2007).