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Modelling the Potential Distribution of *Vitellaria paradoxa* subsp. *nilotica* (C.F. Gaertn) across the Kidepo Landscape of Uganda in the Face of Climate Change

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Abstract

Climate change and human activities are increasingly linked with the extinction of species globally. In semi-arid regions, these pressures threaten the natural distribution and ecology of species. The threat that the shea butter tree (*Vitellaria paradoxa* subsp. *nilotica*) faces from human activity is well researched yet the sensitivity of its distribution to climate change remains barely known. We set out to assess the potential distribution of *Vitellaria* under different climate change scenarios using a MaxEnt. A current distribution model was first developed using only biophysical variables of soil type, temperature, precipitation, land use type, and elevation. This model was then projected onto two global warming scenarios (RCP 4.5 & RCP 8.5) for 2050 and 2070 using multi-model averages (BCC-CSM, CSM4, and MIROC5) derived from three general circulation models. Reductions are seen in distribution area across the landscape with soil type being the most important variable. These results draw useful implications for conservation of *Vitellaria* in that they show how it is vulnerable is to a changing climate as its natural range is mostly reduced. Since climate change is important in the distribution of the shea butter tree, the areas with highest suitability in this study can be used in establishing the Shea butter tree sustainable use zones/area within the Kidepo Critical Landscape (KCL), Uganda.

Keywords

Mapping, Biophysical Variables, General Circulation Models, Dry Land, MaxEnt

1. Introduction

Climate change has affected many species globally, causing them to migrate or redistribute to more habitable regions and thereby exposing them to the risk of extinction as their natural range is generally reduced (Kelly & Goulden, 2008; Thomas et al., 2004; Thuiller, 2004). This reinforces suggestions by the Intergovernmental Panel on Climate Change (IPCC) that 20% - 30% and 40% - 70% of species globally are likely to face extinction under the moderate and extreme case scenarios of global warming respectively (IPCC, 2007). The increasing risk of extinction is owed to prolonged and hard-to-predict variations in climate which cause unprecedented changes in natural limits of environmental cues like rainfall and temperature. Therefore, understanding species distributions is essential for safeguarding vulnerable and endangered species from further ecological and environmental stresses.

Species Distribution Models (SDMs) are essential in understanding species distributions in geographic and environmental space (Elith & Leathwick, 2009; Peterson et al., 2012). They have been applied in ecological reserve design and conservation planning (Araújo et al., 2004; Ferrier et al., 2002; Kremen et al., 2008; Thorn et al., 2009), as well as assessing effects of climate change on species distributions (Qin et al., 2017; Thomas et al., 2004; Thuiller, 2004). MaxEnt (Phillips et al., 2004) is one of the many SDMs that use a combination of species presence points and environmental conditions to predict species distributions. The algorithm is often preferred to others because of its precise mathematical foundation, low sample size threshold, and simplicity in model output interpretation (Elith et al., 2011; Radosavljevic & Anderson, 2014).

In this study, we focused on *Vitellaria paradoxa* (hereafter *Vitellaria*), a semi-arid tree species that occurs only in Africa, stretching its range from Senegal to Uganda, where it is only present in the Northern part of the country (Allal et al., 2011; Hall et al., 1996). It has several human and ecological values (Ferris et al., 2001; Okullo et al., 2012). Shea butter trees grow on a variety of soils with high humus content and their natural stands are often found at an elevation between 650 - 1600 metres. The best temperature range for the species is between annual means of 25˚C and 29˚C. Precipitation ranges from 600 - 1400 mm/year (Hall et al., 1996).

Anthropogenic activity also bears impact on the distribution of the shea butter tree (Buyinza & Okullo, 2015). Since agriculture is the main human activity in the communities where the tree is common, it can be used as a measure of anthropogenic impact on the distribution of the tree (Platts et al., 2010). Although the impact of anthropogenic activities on its distribution is well documented, the climate change threat remains scarcely known (Buyinza & Okullo, 2015; Okullo et al., 2012). If the climate change risk is left unaddressed, conservation efforts centred on offsetting human impact alone may not be sufficient in future conservation planning as global climate is expected to continually change. This study, thus, focussed on assessing the impact of climate change on distribution of *Vitellaria paradoxa* subsp. *Nilotica* (the shea butter tree) in the Kidepo Critical Landscape of Uganda.

2. Data and Methods

2.1. Description of the Study Area

This study was conducted in Uganda within the Kidepo Landscape located between latitudes 1.71˚N and 4.23˚N, and longitudes 33.81˚E and 34˚E (**Figure 1**). The landscape stretches over 25,000 km^2 with 22% (1447.45 km^2) of this area forming the Kidepo Valley National Park (NEMA, 2011). It is bordered by South Sudan in the North and the whole of its Eastern borderline is shared with the Republic of Kenya.

The study area falls in the Karamoja climatic zone of Uganda which is characterized by a long dry season from October to March, with a single wet season from April to September. Average precipitation is between 300 mm and 600 mm

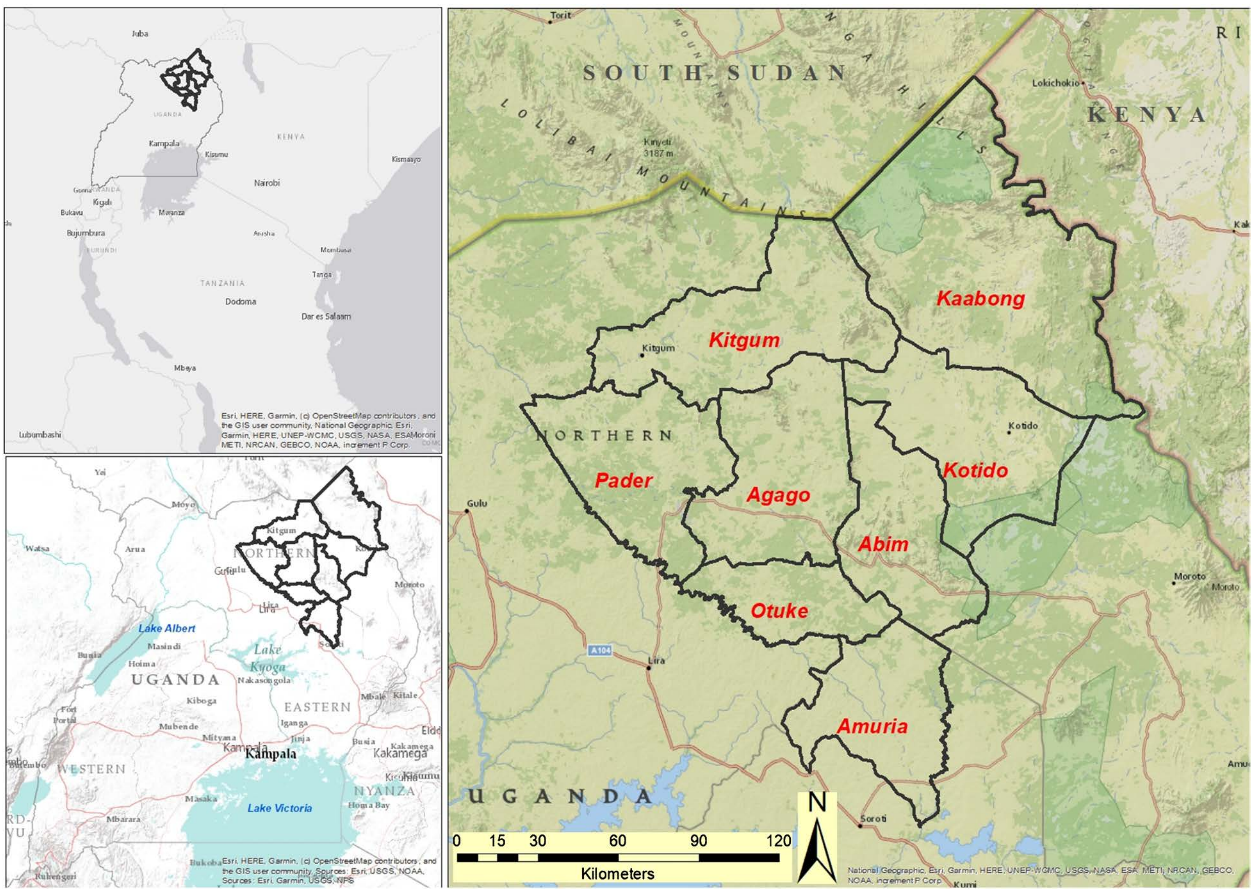

Figure 1. A map showing the Kidepo Critical Landscape.

declining from west to east of the landscape. The region is distinctively the driest and hottest part of the country. The dominant soils of the study area are ferralsols. The area is generally low lying and marshy with a few seasonal rivers. The common vegetation types within this area are *Vitellaria, Acacia* savannas, forest-savanna and open grasslands (NEMA, 2011).

2.2. Methodology and Analysis

2.2.1. Research Data

70 species presence points were used in the modelling process after a rigorous process of data cleaning and spatial filtering. Five environmental variables were selected based on knowledge of ecological requirements for the species (Hall et al., 1996; Naughton et al., 2015; Okullo et al., 2004; Orwa et al., 2009). As shown in **Table 1**, they included annual mean temperature (bio 1), annual precipitation (bio 12), elevation (dem), soil type (soil), and agricultural land use (land). Downscaled global climate data was obtained from Global Circulation Model (GCM) projections with resolution of 30 arc seconds (≈0.86 km^2 at the equator) and corrected for bias. Climate data for the baseline period of 1950-2000 and two RCPs was used to create distribution maps for 2050 (average for 2041-2060) and 2070 (average for 2060-2080).

2.2.2. Data Processing and Analysis

Model validation and evaluation

Data was partitioned in a 70 - 30 ratio for training and testing respectively. Default MaxEnt calibration settings were used in running the model. Suitability was classified as; Highly suitable (>0.6); Suitable (0.4 - 0.6); Marginally suitable (0.2 - 0.4); Least suitable (0 - 0.2). The resulting model was evaluated using the Area Under the Receiver Operating Curve. AUC values were interpreted as AUC > 0.90 (Excellent); 0.80 > AUC ≤ 0.90 (Good); 0.70 > AUC ≤ 0.80 (Acceptable); 0.60 > AUC ≤ 0.70 (Bad); and 0.50 > AUC ≤ 0.60 (Invalid) (Araújo et al., 2005).

Modelling the distribution under climate change

Distribution models were created for 2050 and 2070 under two emission scenarios RCP 4.5 (moderate case) and RCP 8.5 (extreme case), and three different GCMs; BCC-CSM, CCSM4, and MIROC5. The GCMs used were selected because they had harmonized temporal resolutions. Distribution maps under climate change were developed after differencing current and future distribution

Table 1. Environmental variables used in the model.

Variable code	Variable name	Data format	Data source
BIO 1	Annual Mean Temperature	ESRI Grid	WORLDCLIM
BIO 12	Annual Precipitation	ESRI Grid	WORLDCLIM
Soil	Soil type	Shapefile	FAO
Dem	Elevation	GeoTiff	USGS/NASA
Land	Land use type	Shapefile	FAO

models. Climate change impact was characterized as; High impact areas (where *Vitellaria* potentially occurs in the present climate but which will not be suitable anymore in the future); Low impact areas (where *Vitellaria* can potentially occur in both present and future climates); New suitable areas (where *Vitellaria* could potentially occur in the future, but which are not suitable for natural occurrence under present conditions). The areas for each suitability class were subsequently calculated in a GIS environment.

Analysis for variable importance

The jackknife test for variable importance was used to determine the most important variable in the modeling process. A model was first created by excluding each variable in turn while using the remaining variables, then using each variable in isolation, and lastly using all variables. Three plots were consequently generated. In addition to the jackknife analysis, two other tests were used to check for variable contribution in the modeling process, as well as analyze the sensitivity of the distribution to changes in environmental cues.

2.3. Results

Current Vitellaria distribution

The model for current distribution of *Vitellaria* showed variation in suitability across the landscape (**Figure 2**). Otuke and Kitgum visibly had the largest portion of highly suitable area (935.07 km^2 and 632.32 km^2 respectively. These were followed by Agago, Amuria, Abim and Pader (516.40 km^2, 207.60 km^2, 196.36 km^2, and 135.81 km^2 respectively). Kotido and Kaabong districts were the least suitable (**Table 2**). The average test AUC for the replicate runs was 0.923 (std. dev = 0.019).

Vitellaria distribution under different climate change scenarios

Figure 3 shows the distribution of *Vitellaria paradoxa* in future for the three GCMs. There was no major variation in *Vitellaria* distribution across the different GCMs and emission scenarios for 2050 and 2070. Majority of the highly suitable habitat was constrained to Otuke, Kitgum and Agago districts across all GCMs.

Impact of climate change on Vitellaria distribution

Maps showing how the distribution of *Vitellaria* is impacted by climate change are shown in **Figure 4**. There is an increase in the amount of habitat lost as a

Table 2. General suitability in the Kidepo Landscape.

Suitability class	Area in km^2	Percentage
Highly suitable	2675	9.2%
Suitable	3449	11.8%
Marginally suitable	3600	12.3%
Least suitable	19,444	66.7%
Total	**29,168**	**100%**

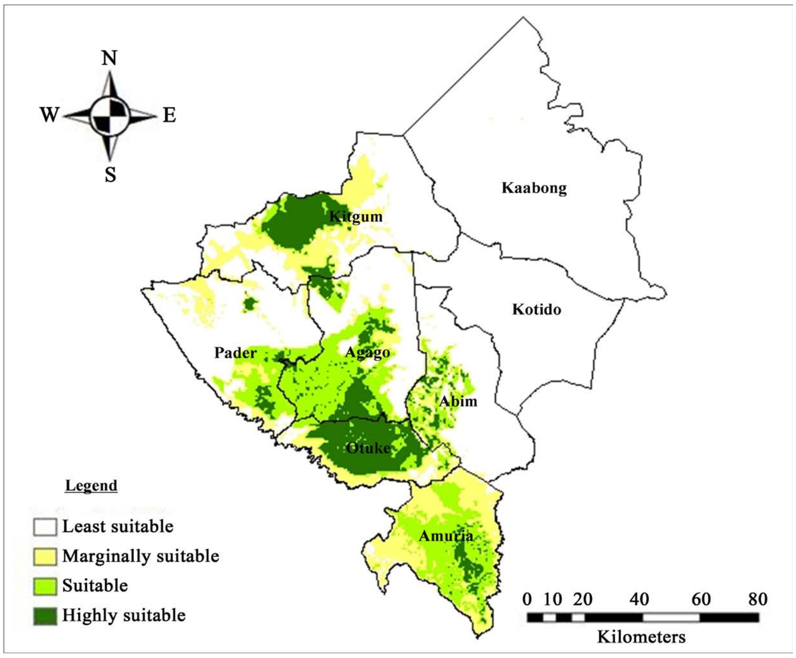

Figure 2. Current potential distribution of *Vitellaria* in the Kidepo Landscape. Dark green = highly suitable; Light green = Suitable; Cream = marginally suitable; White = least suitable.

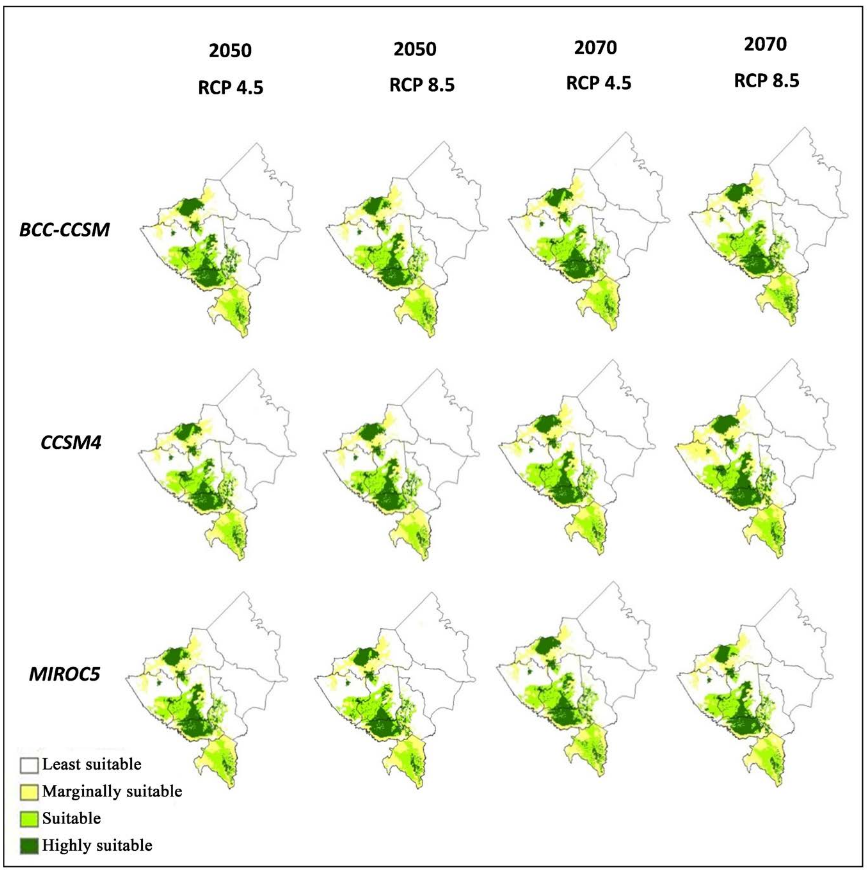

Figure 3. Future potential distribution of *Vitellaria* for 2050 and 2070 under different RCPs.

result of climate change. Under the moderate scenario (RCP 4.5), habitat averages of 786 km^2 and 730 km^2 become suitable. Similarly, for the extreme scenario (RCP 8.5), 1115 km^2 and 884 km^2 of previously suitable habitat became unsuitable in 2050 and 2070 (Table 3).

Environment response curves

Lower and upper limits for temperature, precipitation, and elevation are shown in Table 4. These limits were obtained from the response curves of *Vitellaria* distribution for changes in these parameters generated by MaxEnt. In 2050 the lower limit average for bio 1 (annual mean temperature) under both RCP 4.5 and RCP 8 was 21.50˚C, while the highest limit was 25.3˚C. Both the lower and upper limits were consistent across all future models (21.50˚C and 25.3˚C respectively). For RCP 4.5, the upper limit average was 1459 mm while that for RCP 8.5 was 1458.7 mm. With regard to elevation, the lowest limit varied across all future models, with an average of 726.83 m. The averaged upper limit on the other hand was 2485.67 m.

2.4. Discussion

Model projections under climate change show that while the suitability reduces

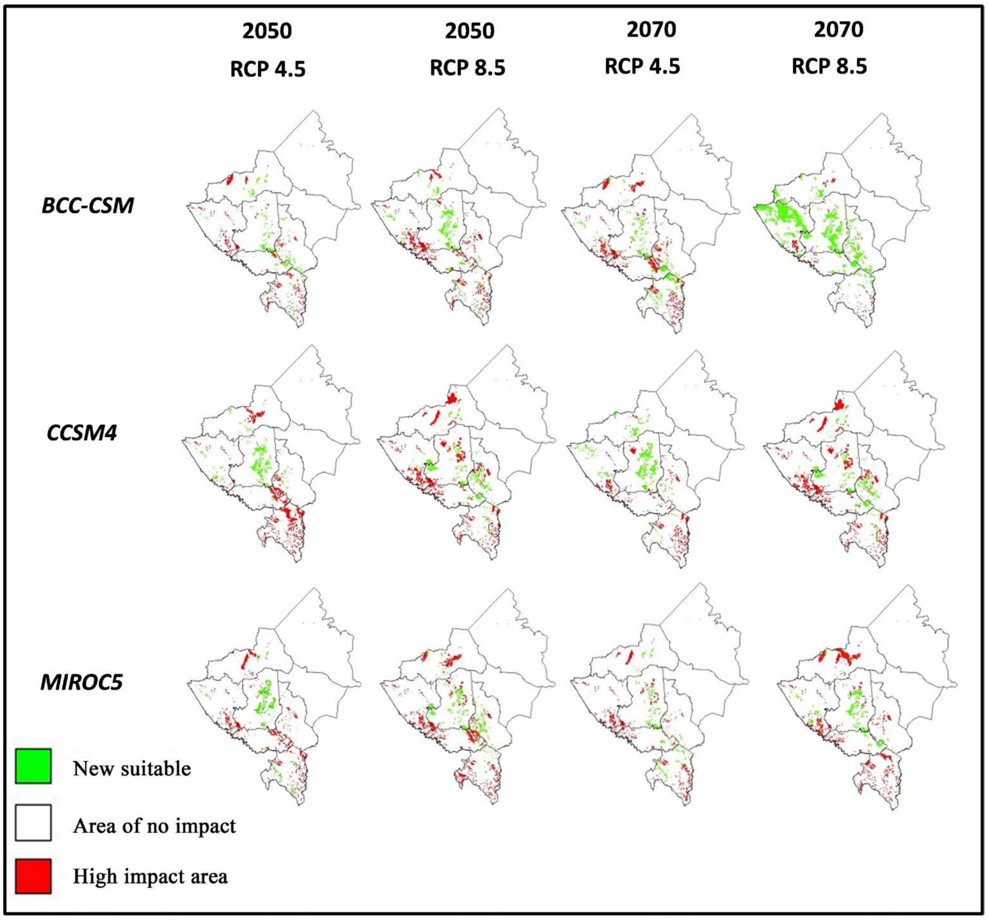

Figure 4. Spatial variation of climate change impact on future potential distribution of *Vitellaria* for 2050 and 2070.

Table 3. Quantified loss in suitability for Vitellaria across all GCMs.

	2050		2070	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5
BCC	606	954	895	265
CCSM4	978	1,227	587	1,254
MIROC5	774	1,165	707	1,132
Average	**786**	**1,115**	**730**	**884**

Table 4. Multi-model averages for environmental limits for *Vitellaria*.

	Temperature (˚C)		Precipitation (mm)		Elevation (m)	
	Lower	Upper	Lower	Upper	Lower	Upper
2050/RCP4.5 average	21.5	25.3	700	1459.0	726.0	2518.3
2050/RCP8.5 average	21.5	25.3	700	1458.6	727.6	2453.0
2070/RCP4.5 average	21.5	25.3	700	1463.0	724.6	2551.3
2070/RCP8.5 average	21.5	25.3	700	1461.6	729.0	2477.6

in some areas of the landscape, it increases in other areas. The increase in the upper limit for precipitation for both the moderate and the extreme case scenarios in 2070 is an indication that *Vitellaria* is likely to adapt to higher precipitation. On the other hand, the substantial drop in the limits for elevation for both RCP 4.5 and RCP 8.5 of 2050 and 2070 suggests that the range of *Vitellaria* may shrink as these upper limits for these future years are above the idealized range for elevation of such a species. Such shifts are expected for most species globally (Ayebare et al., 2013; Kelly & Goulden, 2008; McClean et al., 2005; Pearson et al., 2003; Thuiller, 2004). In their study on the diversity of several African plant species with regard to climate change, McClean et al. (2005) found considerable shifts in suitable areas for most species and predicted decreases in patches along with range shifts for 81% - 97% of plant species.

All models predicted soil type as the most important variable in the modeling process for both current and future time periods. It is possible that differences in soil type between districts could have led to differences in suitability across the landscape as shown in the maps for current and future predicted distribution. This could be the case since the species is adapted to semi-arid conditions, where variations in temperatures and precipitation have been reported to have less influence in determining the species' distribution (Cahill et al., 2013). Similarly, the low importance attached to temperature could be explained by the ability of *Vitellaria* to live in hot areas, implying that temperature is not a very important limiting factor for the growth of *Vitellaria*. Indeed, temperature changes have been shown to have less of an effect on the suitability for the sheanut tree (Cahill et al., 2013; Grossiord et al., 2017).

2.5. Conclusion and Recommendation

Predicting the impact of climate change on species distributions is a key step in developing actions for conservation management. Evident suitability losses in the Kidepo landscape give reason to further assert suggestions that climate change is likely to push vulnerable species such as *Vitellaria* to the brink of extinction in the long term. It should be noted, however, that while greater portions that are suitable become unsuitable due to climate change, coincidentally, patches of new suitable areas also emerge. This affirms that climate change will have a dual impact. Therefore, existing on-farm tree conservation (Okiror et al., 2012) should be upheld where existent, and is highly recommended where it is not being practiced.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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