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Predicting the potential impact of environmental factors on the distribution of *Triplochiton scleroxylon* (Malvaceae): An economically important tree species in Nigeria

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ABSTRACT

Triplochiton scleroxylon is a lowland rainforest tree species distributed in Central and West Africa, with economic and medicinal importance. Given that its population is threatened by overexploitation for timber, poor seed production, and habitat destruction, it becomes important to project its distribution along environmental gradients to bolster our understanding of its conservation. This study thus examines the combined effect of over-exploitation and climate change on its distribution in Nigeria. We used MaxEnt algorithm and spatial analysis module of ArcGIS to model the current and future habitat suitability of *T. scleroxylon* in Nigeria. We utilized 95 unique occurrence points and eight environmental variables (Bio7, Bio8, Bio9, Bio13, Bio14 & Bio18, elevation, and slope) to understand the response of the species to changing climates during the time periods 1970–2000, and to project species responses to temperature and precipitation in the years 2050 and 2070, using two Global Climate Models. Results indicated that the prediction of the suitable habitat for *T. scleroxylon* under the model was very reliable ($AUC \geq 0.9$; $TSS \geq 0.6$). Annual temperature range (Bio7) was the most influential bioclimatic variable for predicting habitat suitability and distribution for the species in Nigeria. Highly suitable habitat has an optimum temperature of 28.5 °C, precipitation ≤ 600 mm, an elevation of ≤ 400 m, and a slope of 90°; it is currently estimated at 23.3% of the total land cover, and predicted to reduce to $<15\%$ by the year 2050. The methods of SDM have a great potential in understanding species richness, and also provide data for the support of conservation strategies at local scales. Hence, this study advocates for the conservation of the remaining habitats of *T. scleroxylon* through the implementation of strategic plans, especially in South-western Nigeria where there is a high potential for its regeneration owing to favourable environmental conditions.

1. Introduction

The exploitation of forest species such as *Entandrophragma angolense* (Welw.) C.DC., *Khaya ivorensis* A.Chev., *Khaya senegalensis* (Desr.) A. Juss., *Milicia excelsa* (Welw.) C.C.Berg, and *Triplochiton scleroxylon* K. Schum. as means of livelihood is a common practice [1–6], and

consequently puts the West African and Nigerian ecosystem at the risk of species disappearance. Nevertheless, of all West African timber species, *T. scleroxylon* (commonly called Obeche) is exploited at the highest volume [7,8]. It is an emergent long-lived tropical tree species found in the lowland rainforest of West and Central Africa. In Nigeria, the species is confined to the forest zones of the South, with a few records from the

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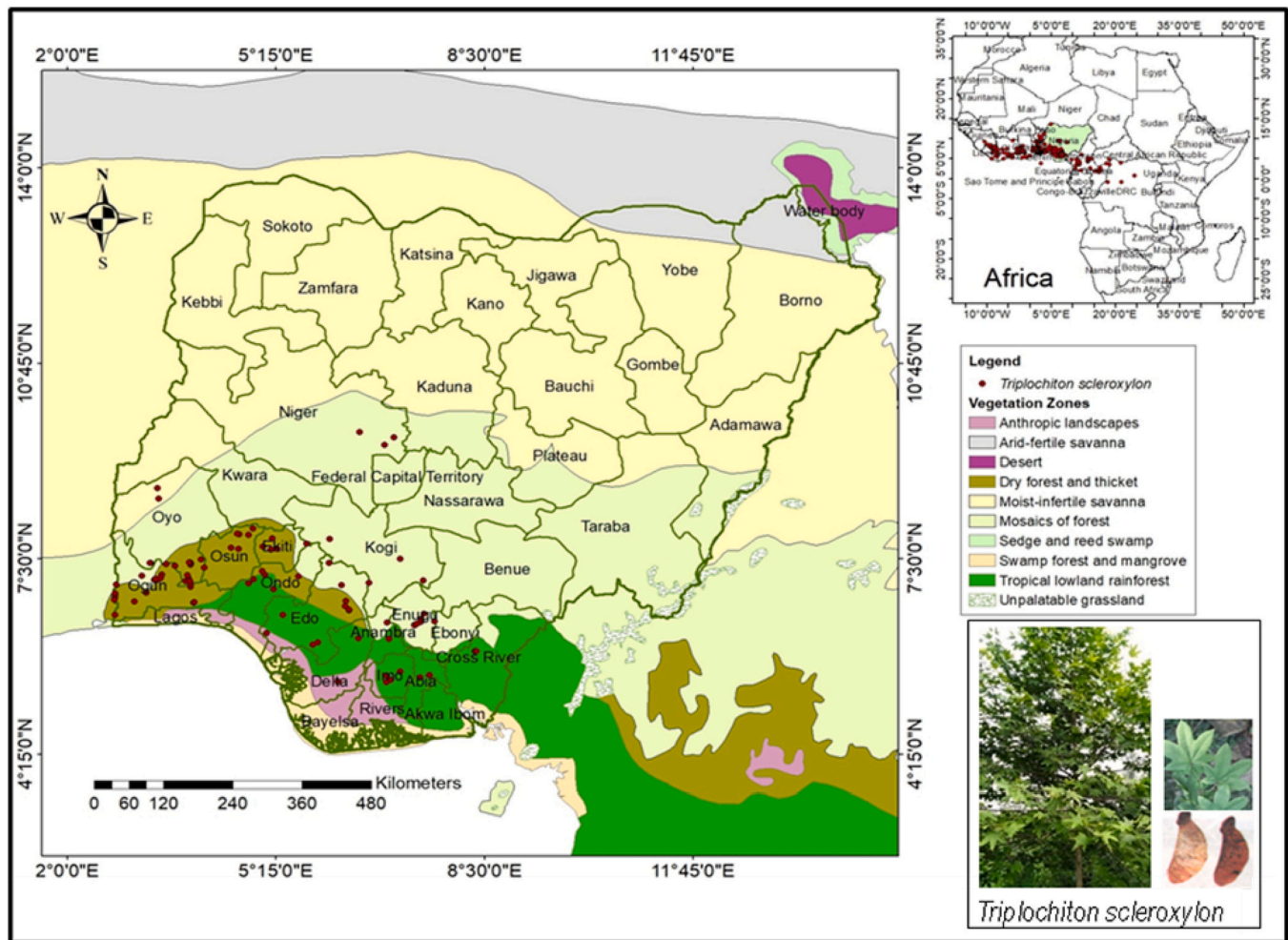


Fig. 1. Occurrence distribution map of *T. scleroxylon* in Nigeria.

North [9,10]. Morphologically, it attains ca. 65 m in height with large buttressed (ca. 7 m in girth) cylindrical bole [11,12]. It is cultivated through seeds, and germinates 1–2 weeks after sowing but with low germination rate. However, germination rate is improved when the seeds are pre-treated by moistening between layers of damp cotton wool [13]. Authors have noted that the poor seed regeneration rate is a major setback for the establishment of plantations, although methods of relatively cheap vegetative propagation are possible and could offer great opportunities when superior germplasm becomes available [14,15]. Apart from the known threats to *T. scleroxylon* such as overexploitation, erratic seed production [5,14,16], and reduced seed viability over long storage periods [15], no empirical study has investigated the potential effect of environmental variables on its spatial distribution. In addition, the species had earlier been evaluated by the International Union for Conservation of Nature as least concern (LC), and reports have also noted that the exploitation of the wood is severe and unsustainable, both for local use and the international timber trade [7,17].

In the last century, significant changes in spatial and temporal environmental patterns have resulted from global climate change, and these changes determine the viability and conservation of species [18]. Consequently, there has been a strong interest in the understanding of species distribution, habitat suitability, and ecology for improved environmental management across the world climates and terrestrial ecosystems [19]. With the application of modern statistical tools and geographic information systems (GIS), species distribution models (SDMs) have in recent times been a useful approach in improving such understanding of species distribution and predicting climatically

suitable habitats across landscape [20–25]. Outcomes of such prediction are usually predictive maps that hypothesize habitat suitability and provide information on resource conservation strategies. SDM analyses utilize the combine application of bioclimatic (e.g., temperature, rainfall, precipitation, etc) and non-bioclimatic (elevation, land surface, geology, soil properties) and this concept are becoming increasingly important at smaller scales. Methods for SDM vary in terms of assumptions, data requirements and usability [26–28]. Maximum Entropy (MaxEnt) models have been used for SDM of different plant species to predict population trends, suitable areas for endangered/economic species, investigate relationships between climatic factors and specific species, and make priority assessments for conservation over time [25,29–32]. Also, the model uses presence data only, produces reliable results for small sample size, and have been used in studies [23,33].

Given the paucity of up-to-date ecological information on the focal species therefore, the present study determined the current distribution pattern, analysed the effects of environmental factors on the distribution of *T. scleroxylon* and further predicted the suitable habitats or hotspot regions under future climatic scenarios in the years 2050 and 2070 for effective conservation of the species in Nigeria. We hypothesized that the occurrence and abundance of *T. scleroxylon* is largely determined by bioclimatic variables rather than topography. We anticipate that findings from this study will contribute to the understanding of the distribution pattern of this under-studied and over-exploited tree species, in the face of complex climatic and environmental conditions, as well as suggest possible steps for its conservation and sustainable management throughout distribution areas.

2. Material and methods

2.1. Study area

The present study focused on the distribution of *T. scleroxylon* in Nigeria, a sub-Saharan African country with a total area of 923,770 km² (<https://www.worlddata.info/africa/nigeria/index.php>). Typically, the climate differs across the three different regions of the country: while Southern Nigeria is classified equatorial, the Central region is tropical, and the Northern is arid. Nigeria has two distinct seasons (wet and dry), annual rainfall ranging from 3800 mm at the coast to <650 mm in the extreme northeast [34], and relatively high temperatures throughout the year, which vary from 18 to 35 °C in the north and 23 to 31 °C in the south. The country's vegetation is characterised by forest and savannah ecosystems [35]. People living suburbs or rural areas often rely on the collection of forest products that provide food, medicines, fuel wood and construction material, to sustain their livelihoods. This high demand has increased the pressure on forests resources, which resulted into forest degradation and exposed some species to high risk of conservation priorities.

2.2. Occurrence data

We retrieved occurrence data of *T. scleroxylon* from specimens deposited at the Forest Herbarium Ibadan (FHI) and the University of Ibadan Herbarium (UIH) [36], as well as from the Global Biodiversity Information Facility [37]. In addition, we surveyed forests in Oyo, Ogun, Ekiti, and Osun states, being areas with large populations known from previous collections. We gathered a total of 366 occurrence records and these data were used to present the current distribution of *T. scleroxylon* in Nigeria (Supplementary - 1; Fig. 1) across vegetation zones following White's classification [38]. To avoid systematic and computational errors, the occurrence data were checked by removing duplicates using OpenRefine v.3. and R v.3.6.3. As a result, only 95 unique records were used for the analyses (Supplementary - 1) and the cleaned CSV file was used as the input file for QGIS v.2.18.3 and MaxEnt analyses.

2.3. Environmental variables

For this study, 19 bioclimatic variables (Supplementary - 2) were downloaded from the WorldClim database v.2.1 (www.worldclim.org). Digital Elevation Model (DEM) was retrieved from the Shuttle Radar Topography Mission (SRTM) database available on <https://earthexplorer.usgs.gov>, while we obtained the slope data using the Surface Analyst tool implemented in ArcGIS v.10.3.1 [39]. The bioclimatic variables (initially downloaded in GeoTIFF formats) were clipped to the study area and converted to ASCII format using QGIS v.2.18.3, before they were used to run the model in MaxEnt v.3.4.1 [33]. Following Fick & Hijmans [40], all downloaded variables had a 30 arc-second spatial resolution (1 km spatial resolution).

To model the potential effect of climate change on the future distribution of *T. scleroxylon* in Nigeria, we selected two global climate models: CNRM-CM5 and HadGEM2-ES and two greenhouse gas concentration (GHG) scenarios, otherwise known as Representative Concentration Pathways (RCP) for the time periods 2050 and 2070 at a spatial resolution of 30 arc-seconds. These were downloaded from <https://www.worldclim.org>. Four RCPs (RCP2.6, RCP4.5, RCP6, and RCP8.5) were adopted by the Intergovernmental Panel on Climate Change in 2014 [41], which supersedes the Special Report on Emissions Scenarios (SRES) projections of the year 2000 [42,43]. The RCPs are named after a possible range of Radiative Forcing values in the year 2100 relative to pre-industrial values (+ 2.6, + 4.5, + 6.0, and + 8.5 W/m²) [22,44]. They are preferred to SRES because they allow more flexibility and prescription of GHG concentration in climate models, thereby reducing computational costs in modelling physical processes [43]. Therefore, we selected RCP4.5 and RCP8.5 to project the future spatial distribution of

T. scleroxylon by the years 2050 and 2070. Under RCP4.5, the atmospheric CO₂ could reach ≤500 ppm, thereby causing projected surface temperatures to rise above industrial levels by at least 1.5 °C in West Africa. On the other hand, temperatures are estimated to rise by 2.8 °C and atmospheric CO₂ to be >550 ppm [45] under the extreme RCP 8.5 projection. It is also assumed that global GHG emissions might begin to decline by 2040 in line with RCP4.5 if the current concerted measures being taken globally are sustained [26,46].

2.4. Species distribution modelling

Prior to the modelling analyses, we determined the most reliable bioclimatic variables by conducting a multicollinearity test for the 19 bioclimatic variables [47], using the ENMTTools package implemented in R studio v. 4.1.2. To establish a more reliable model for the analysis, we included elevation and slope data and retained only one variable from each set of highly correlated bioclimatic variables based on a correlation coefficient ≥ 0.8 [48]; and this yielded a total of 8 environmental variables (Supplementary - 2,3). Response curves for each predictor variable, which are reflected through the jackknife were also generated using MaxEnt [22,49]. In the present study, we analysed MaxEnt model performance according to the omission/commission rate, a threshold-dependent binomial test based on omissions and predicted area [50]. Occurrence data were partitioned into training (75%) and test (25%). We developed the model applying a regularization of 10,000 background points, default prevalence of 0.7, regularization multiplier of 0.5, and employed a 10-fold cross-validation for testing the model performance. We replicated the model 10 times and averaged the results. Graphs were plotted using the library “ggplot2” implemented in R [51]. To further evaluate the conservation status of *T. scleroxylon*, we downloaded land use and land cover map of West Africa [52], and overlaid our distribution data on the map to identify non-protected areas and to evaluate the extent of the distribution of the focal species across different ecosystems.

2.5. Model simulation and evaluation

Previous studies suggested that MaxEnt is prone to overfitting or poorly performing models using its default settings [53,54]. To overcome this shortcoming, we tested a range of values for the regularization multipliers (RM; increments of 0.5) and six feature class combinations (FC; L, LQ, H, LQH, LQHP, LQHPT; where L = linear, Q = quadratic, H = hinge, P = product and T = threshold) using the ENMeval package in R [55].

We used corrected Akaike information criterion (AICc) and delta. AICc model selections to distinguish among the models, and selected the FC and RM combinations with the least value. The AIC was used to estimate prediction error, and quality of statistical models for any given dataset [56]. It is considered the first model selection criterion that should be used in any modelling practice. AIC value is calculated for every candidate model and the “best” model is the candidate model with the smallest AIC [57,58]. However, in lieu of AIC, the *second-order Akaike information criterion* (AICc) is used for a small sample size, see the mathematical expression below;

$$AIC = -2\log \hat{L}(\hat{\theta}) + 2k \quad (1)$$

$$AICc = -2\log \hat{L}(\hat{\theta}) + 2k + (2k + 1)/(n - k - 1) \quad (2)$$

where $\hat{\theta}$ = the set of model parameters

$L(\hat{\theta})$ = the likelihood of the candidate model given the data when evaluated at the maximum likelihood estimate of $\hat{\theta}$

k = the number of estimated parameters in the candidate model

n = number of observations

Similar to previous studies, the model was also evaluated using the receiver operating characteristics (ROC) curve generated from the

Table 1
Selected environmental variables retained for the species distribution modelling with MaxEnt.

Variable type	Code	Variable
Topographic	Elev	Elevation
	Slope	Slope
Bioclimatic	Bio7	Temperature annual range (bio5 - bio6)
	Bio8	Mean temperature of wettest quarter
	Bio9	Mean temperature of driest quarter
	Bio13	Precipitation of wettest month
	Bio14	Precipitation of driest month
	Bio18	Precipitation of warmest quarter

MaxEnt model [23,61]. The area under curve (AUC) is useful for characterizing distribution models; hence, we took this value into account while running the model. The AUC value evaluation followed Araujo et al. [59]: 0.50–0.60 (failed/unreliable model) and 0.90–1.00 (excellent/reliable model). To further validate the reliability of the model, we calculated the sensitivity of occurrence points using the approach described by Anderson et al. [60]. Also, we considered the ability of the model to predict true presence (sensitivity) and true absence (specificity) using true skill statistics (TSS) [61,62]. Models with TSS value ≤ 0 are indicative of random predictions, while those with values close to 1 ($TSS > 0.5$) are regarded as good models with good predictive power [61,63]. We employed the Spatial Analyst Tools implemented in ArcGIS v.10.3 [39] to categorize the habitat suitability into five classes according to Ma & Sun [29] — highly unsuitable habitat (0–0.2),

unsuitable habitat (0.2–0.4), low suitable habitat (0.4–0.6), moderately suitable habitat (0.6–0.8), and indicated highly suitable habitat (0.8–1.0).

3. Results

3.1. Habitat richness, model performance and evaluation

Cumulative distribution of the occurrence showed that *T. scleroxylon* is currently restricted to forest regions in southern Nigeria, especially in south-western areas (e.g., Ogun, Ondo, Osun and Oyo states; Fig. 1). The correlation analysis of the 19 bioclimatic variables (Supplementary - 3) yielded six least correlated variables as a significant predictor of the distribution of *T. scleroxylon* (Table 1). The model evaluation analyses all supported the reliability and good-fit of the algorithm for the prediction of the distribution pattern of *T. scleroxylon* in Nigeria (Supplementary - 4A); at $FC = L$ and $RM = 0.5$, the values of $AICc$ (2361.18) and $\Delta AICc$ (0.0) were at their lowest and hence provided the best combinations for the model, which also yielded high AUC values (AUC and ROC values > 0.9). On the overall, the variables that influenced the distribution of *T. scleroxylon* are evident through the higher regularized training gains and training AUC (Supplementary - 5A). While the individual contributions as generated by MaxEnt is provided in Supplementary - 5B. Further evaluations showed that the model performance was excellent. Average TSS value was well above 0.6, sensitivity, specificity, and overall accuracy were also very high (Supplementary - 5C). The jackknife test of variable importance showed that among the 8

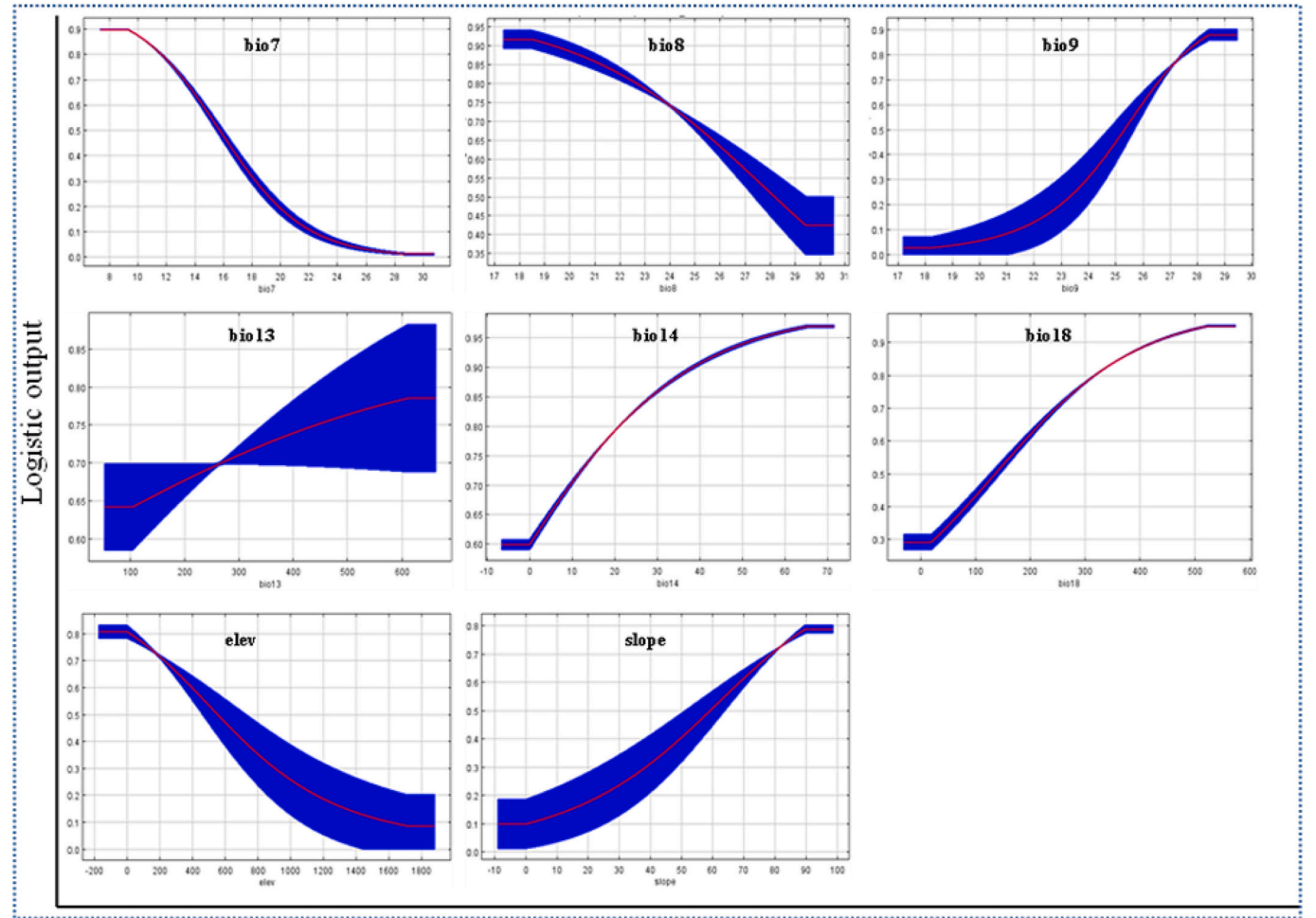


Fig. 2. Response curve of the environmental variables in the distribution of *T. scleroxylon* in Nigeria. Bio9, Bio13, Bio14 and Bio18 show similar curves while Bio 3 and Bio 8 were in opposite direction.

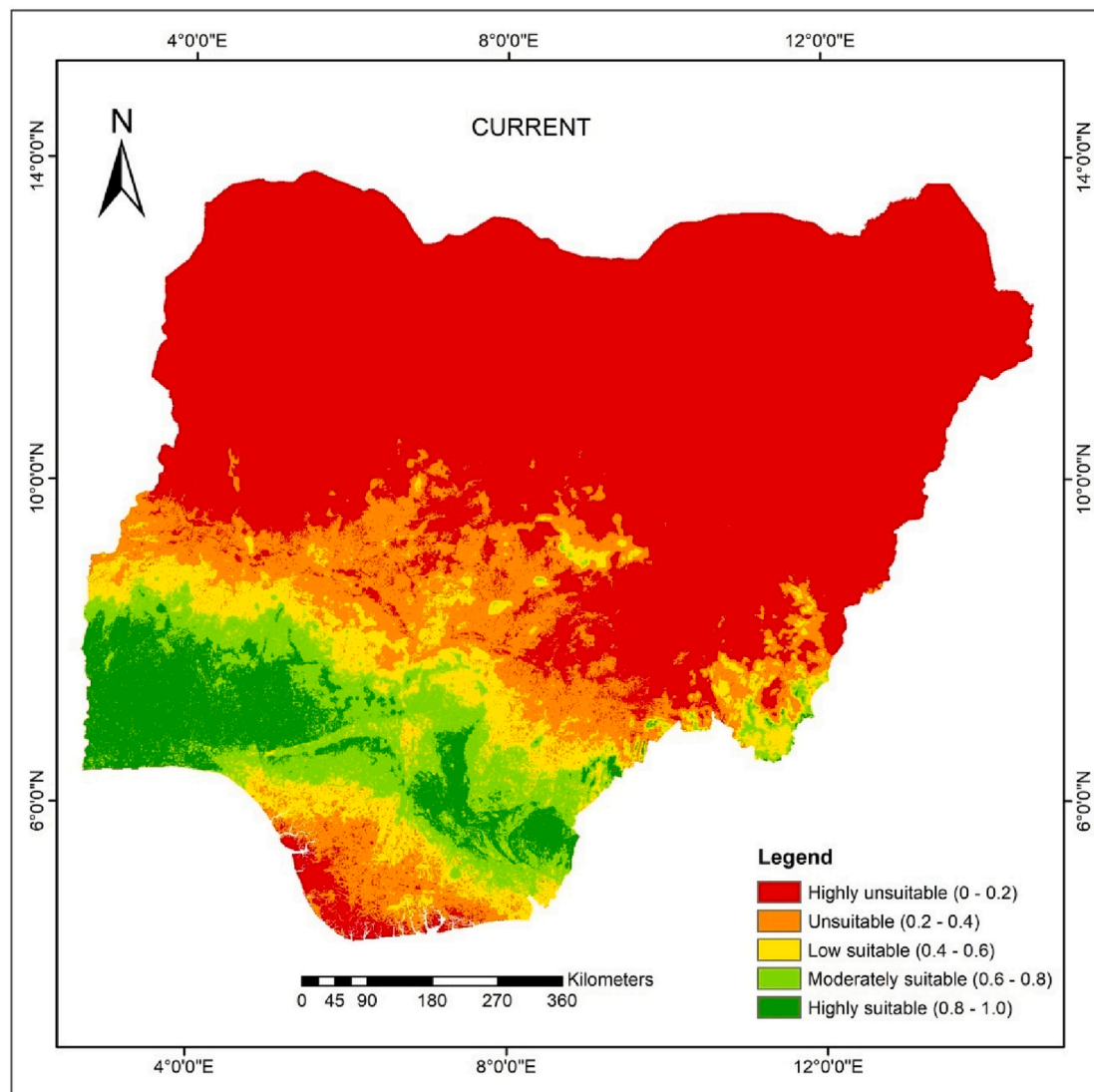


Fig. 3. Distribution of *T. scleroxylon* in Nigeria under current climatic conditions.

environmental variables used to establish the model, temperature annual range (Bio7) was the most influential on the habitat suitability for *T. scleroxylon*, contributing about 70% of the total variance.

3.2. Response of habitat suitability to environmental variable

Our prediction revealed that *T. scleroxylon* responded differently to the different environmental variables (Fig. 2). The response curves of the variables showed similar trend (i.e., suitable habitats increases with increasing variables) for the precipitation parameters (Bio 13, Bio14 and Bio18) and slope but inverse (i.e., suitable habitats decreases as the variables increases) for two temperature variables (Bio 7 and Bio 8), and elevation. In short, while the probability of occurrence decreased with an increase in temperature annual range (Bio7) and mean temperature of wettest quarter (Bio8), its increase was directly proportional to a gradual increase in mean temperature of driest quarter (Bio9).

Specifically, optimal temperatures for an ideal habitat were identified at 9 °C (Bio7), 18.5 °C (Bio8), and 28.5 °C (Bio9). For the precipitation variable, there was a slow increase in habitat suitability at Bio13 ≥ 100 mm; however, areas that receive precipitation between 100 and 600 mm during the wettest month, ca. 65 mm during the driest months, and up to 525 mm during the warmest quarter are identified as the most suitable for the occurrence of *T. scleroxylon*. Our prediction further

revealed that the most suitable habitat for the species are regions with low temperature, moderately high precipitation, elevation < 400 m at a slope of 90°, respectively (Fig. 2).

3.3. Habitat suitability and current distribution of *T. scleroxylon*

Habitat suitability prediction analysis for *T. scleroxylon* in Nigeria inferred in MaxEnt based on the selected environmental variables re-confirmed that the current suitable habitats are mostly located in the south-western region of Nigeria (e.g. Ogun, Ondo, Osun, and Oyo states), and extends to the south-eastern regions (e.g. Abia, Anambra and Imo states), and Cross-River in the south-south (Figs. 1 & 3). As evident, approximately 85% of the occurrence points occupied the region with the highest prediction; hence, the sensitivity of the model was very reliable. The model showed that *T. scleroxylon* would experience loss of suitable habitats as it extends towards northern Nigeria (e.g. Niger) because of lower precipitation. As estimated, only about 68,344 km² of the total land cover of Nigeria is currently highly suitable for the survival of *T. scleroxylon*; and this is mostly of the rainforest areas of the country (Table 2; Fig. 3).

Table 2
Habitat suitability for *T. scleroxylon* under current and future climatic models.

Model	Scenario	Year	Total land area	Highly unsuitable		Unsuitable		Low suitable		Moderately suitable		Highly suitable	
				Area (km ²)	Proportion (%)	Area (km ²)	Proportion (%)	Area (km ²)	Proportion (%)	Area (km ²)	Proportion (%)	Area (km ²)	Proportion (%)
CNRM-CM5	RCP 4.5	2050	909,499.3	567,189	62.4	130,376	14.3	71,118	7.8	72,473	8.0	68,344	7.5
		2070	909,499.3	702,547	77.2	76,470	8.4	48,878	5.4	47,062	5.2	34,542	3.8
CNRM-CM5	RCP 8.5	2050	909,499.3	676,433	74.4	82,797	9.1	57,505	6.3	58,675	6.5	34,090	3.7
		2070	909,499.3	684,181	75.2	85,682	9.4	48,593	5.3	53,780	5.9	37,264	4.1
HadGEM2-ES	RCP 4.5	2050	909,499.3	672,154	73.9	76,747	8.4	66,438	7.3	51,107	5.6	43,053	4.7
		2070	909,499.3	710,029	78.1	71,017	7.8	51,483	5.7	45,973	5.1	30,997	3.4
HadGEM2-ES	RCP 8.5	2050	909,499.3	668,327	73.5	85,117	9.4	60,555	6.7	53,880	5.9	41,620	4.6
		2070	909,499.3	679,982	74.8	85,797	9.4	48,056	5.3	54,550	6.0	41,115	4.5
		2070	909,499.3	691,737	76.1	82,273	9.0	50,848	5.6	51,902	5.7	32,740	3.6

3.4. Predicted future spatial distribution of *T. scleroxylon*

The future habitat suitability for *T. scleroxylon* in 2050 and 2070 under RCP4.5 and RCP8.5 are shown in Table 2 and Figs. 4–5. The extent of suitable habitat for the species decreased under both scenarios for 2050 and 2070. Similar to the current suitable areas, we observed that the future habitat of *T. scleroxylon* would remain within the forest zones of southern Nigeria, under the two scenarios (RCP4.5, Fig. 4 and RCP8.5, Fig. 5) using CNRM-CMS and HadGEM2-ES but with slight difference. Comparatively, loss of suitable habitat as predicted by the GCMs and RCPs reflects the potential effect of climate change on the distribution of “obeche” in the absence of conservation strategies even in the suitable areas. However, both models revealed that climate change would cause the loss of highly suitable habitats for *T. scleroxylon* from current day to the future (see Table 2): RCP4.5–2050 (CNRM-CMS = 34,542 km² and HadGEM2-ES = 30,997 km²) and 2070 (CNRM-CMS = 34,090 km² and HadGEM2-ES = 41,620 km²); RCP8.5–2050 (CNRM-CMS = 37,264 km² and HadGEM2-ES = 41,115 km²) and 2070 (CNRM-CMS = 43,053 km² and HadGEM2-ES = 32,740 km²). This further suggests that the future distribution of *T. scleroxylon* in Nigeria will reduce with an increase in temperature. *T. scleroxylon* predominantly occurs in southern Nigeria, which also falls within the transitional equatorial climate region of West Africa. Much of this area has been greatly degraded through several human anthropogenic activities; with only some patches of pure forest remaining (Fig. 6).

4. Discussion

The distribution of African species and its connection with climate change, using the methods of Species Distribution Modelling (SDM) is becoming topical among ecologists [21,26,63,64]. This method, however, has not only been widely utilized in understanding the potential effect of climate change on natural distribution of species, but also in the prediction of species richness and biological invasion [65,66]. In ecological restoration, it has been useful in the selection of species [67], and to target areas where endangered species are likely to occur [68]. In the present study, we employed SDM to investigate the challenges posed by climate change on the current and future distribution of “Obeche” in Nigeria; and the results provided additional evidence in support of previously reported climate-driven diversity loss.

Findings from this study agree with the currently known distribution range of the focal species in Nigeria as reported in previous studies [5,12], and further revealed that precipitation and temperature are significantly important factors for the existence of species in humid areas, as earlier highlighted by Purseglove [69] and Idohou et al. [70]. Studies have shown that *T. scleroxylon* occurs in tropical rainforests with moderate rainfall and high humidity whereas absent in areas with exceptionally high rainfall and where the dry season is longer than three months [5,9,11,]. Our study thus suggests that *T. scleroxylon* may not be a drought tolerant species as reflected by its distribution pattern. Although, its current distribution in Nigeria is predominantly within the low temperate regions, the model projected that its future distribution even in these areas will be affected by the rise in temperature brought about by climate change and habitat destruction. Following the results therefore, areas identified as suitable habitats for the growth of *T. scleroxylon* in Nigeria lies between latitude 5°45′ – 8°30′N and longitude 2°45′ – 10°30′E, which currently occupies ca 23.3% of the total land cover but could reduce to only 14.1% by the year 2050 under HadGEM2-ES. While the model predicted some gains under certain RCPs and GCMs, overall findings rather support the hypothesis that climate change could affect the distribution pattern of this species over time.

With the disappearance of habitat cover resulting from over-exploitation of forest resources along the coast; it appears that the distribution of *T. scleroxylon* has dramatically reduced even within its natural ecosystem. Herbarium collections and personal observations during fieldwork showed that the species is found in small forest

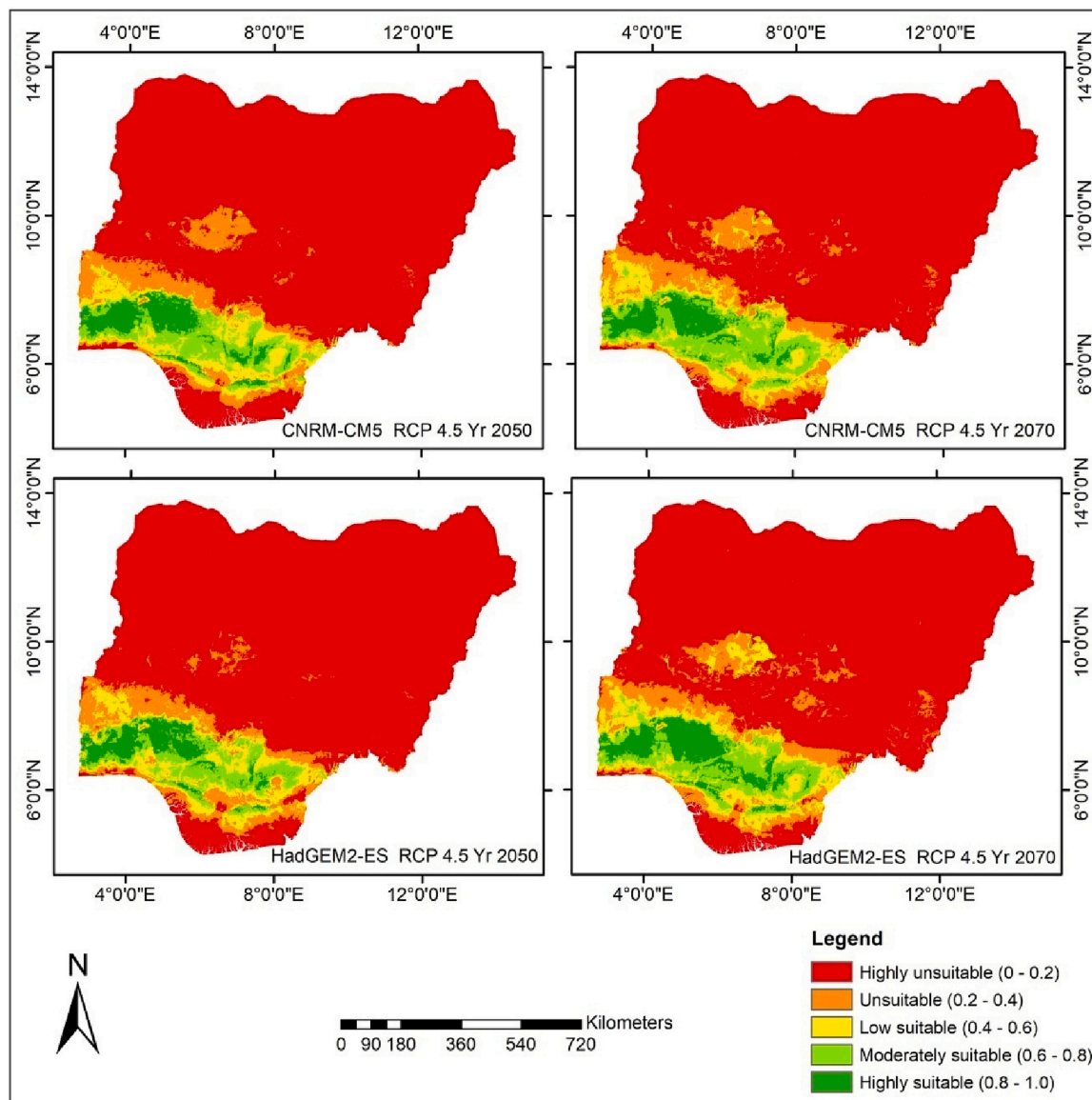


Fig. 4. Future distribution models for *T. scleroxylon* in Nigeria under RCP4.5. A–B are predicted maps for CNRM-CM5 for the years 2050 and 2070. C–D are predicted maps for HadGEM2-ES for same years respectively.

fragments along the coast and with several other species under acute threats. Additionally, the most suitable habitats for the growth of *T. scleroxylon* require an elevation below 400 m. This is congruent with previous reports on its distribution in its natural habitat. For instance, Hall & Bada [10] revealed that the highest concentration of the tree is associated with elevations below 500 m, mean annual rainfall from 1100 to 1800 mm, a seasonal and two-peaked rainfall distribution, average temperatures 20–35 °C and well-drained ferruginous soils.

The Global Climate Models (GCMs) applied in this study showed similar trends for the habitat suitability for *T. scleroxylon* in Nigeria under two RCPs and two time periods. While the species maintained its distribution range under current climatic conditions, it demonstrated some habitat reduction under future projections. Thomas et al. [71] had noted that many species could be threatened by human-induced climate change resulting from incessant habitat degradation and over-exploitation of plant genetic resources. This was evident in our study, as the model predicted significant loss in the habitat suitability for *T. scleroxylon* in Nigeria (e.g. Ogun) from the current day to 2050, and a further decline from 2050 to 2070, since it is unable to adapt – neither genetically nor by phenotypic plasticity [72]. We identified that the

percentage climatically suitable habitat would decrease with time — 2050 (3.0–4.7%) and 2070 (2.8–3.9%), and consequently an increase in highly unsuitable habitats for *T. scleroxylon* in Nigeria. As forest degradation shifts towards the eastern part of Nigeria, and extends further north, the spatial distribution of *T. scleroxylon* in the southwestern zone may not exhibit an intense change as much as it would in the east. By implication, this result provides evidence for the need to establish management practices in the former and suggests the imminent need for the conservation of the remaining forested areas in the latter.

Species conservation status can be assessed by synthesizing information for each of its known populations, particularly concerning changes in historical range and vulnerability status within its characteristic habitat [22]. Tappan et al. [52] earlier hinted that of the entire rainforest vegetation of Nigeria, about 47,896 km² have been degraded, while only 20,756 km² remains as forest. In the present study, the current distribution of *T. scleroxylon* occurs predominantly in the degraded area as evident in the map provided. In addition, the over-exploitation of this species was evident during the ground check and field observations, as the timbers produced from this species were found in the milling

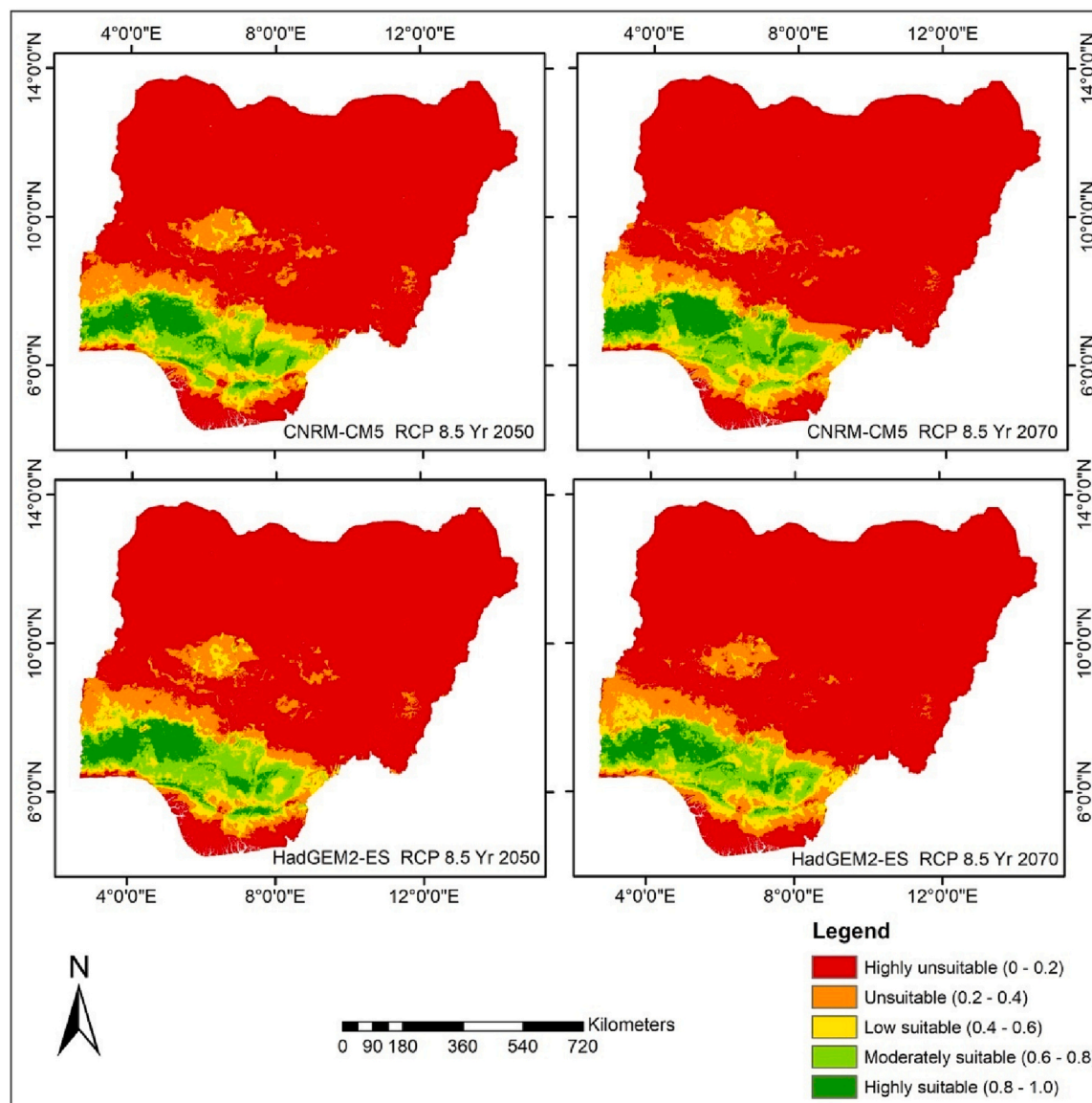


Fig. 5. Future distribution models for *T. scleroxylon* in Nigeria under RCP8.5. A–B are predicted maps for CNRM-CM5 for the years 2050 and 2070. C–D are predicted maps for HadGEM2-ES for same years respectively.

factories in some areas. The absence of juveniles of the species is reflective of the difficulties in the natural regeneration rate, and as such, leading to its consistent population decline within the local habitats. However, it is worthy to note that SDM has been criticized because it ignores the impact of other factors such as biotic interactions, species dispersal, topography, microclimate, and soil on the distribution of species [73,74]. Conversely, Elith et al. [75] noted that studies using presence-only data are satisfactorily accurate in planning conservation, while Midgley et al. [76] had earlier suggested that the combined effects of future land transformations and climatic changes will increase unsuitable habitats in floristic regions even beyond what is estimated.

Previous studies revealed that climatic patterns establish the broad limits of the distribution of plant taxa at regional to global level [77,78]. In this study, we have clearly identified the transitional equatorial (tropical rainforest) climatic zone as the most suitable region for *T. scleroxylon*, even though much of this area has been lost to human activities. Given the present state of Nigerian forests, the threat of climatically determined environmental changes will be multifaceted if the remaining natural habitats of this species continue to face human-induced anthropogenic forest activities, including exploitation.

Considering its potential for the production of moderate quality paper, the present study suggests a negligible loss in the abundance of *T. scleroxylon* in south-western Nigeria in the near future, if efforts are put in place to sustain the current habitats. While we recognize the shortcomings of SDM, it serves as a useful starting point for mapping the potential range of any species even under climate change situations, as illustrated in this study.

5. Conclusion

The present study has identified the environmental predictors for the future distribution of *T. scleroxylon* in Nigeria using the MaxEnt model. Our study revealed a latitudinal distribution pattern for *T. scleroxylon* linked with rainfall and temperature. It showed that species distribution is chiefly governed by alterations in climatic variables such as temperature and precipitation. Based on the model, the future distribution of *T. scleroxylon* would witness a gradual change from its current pattern; it would be confined to southern Nigeria but be more abundant in the west. Specifically, the model showed that much of *T. scleroxylon* is distributed in the degraded forests, and future projections suggest

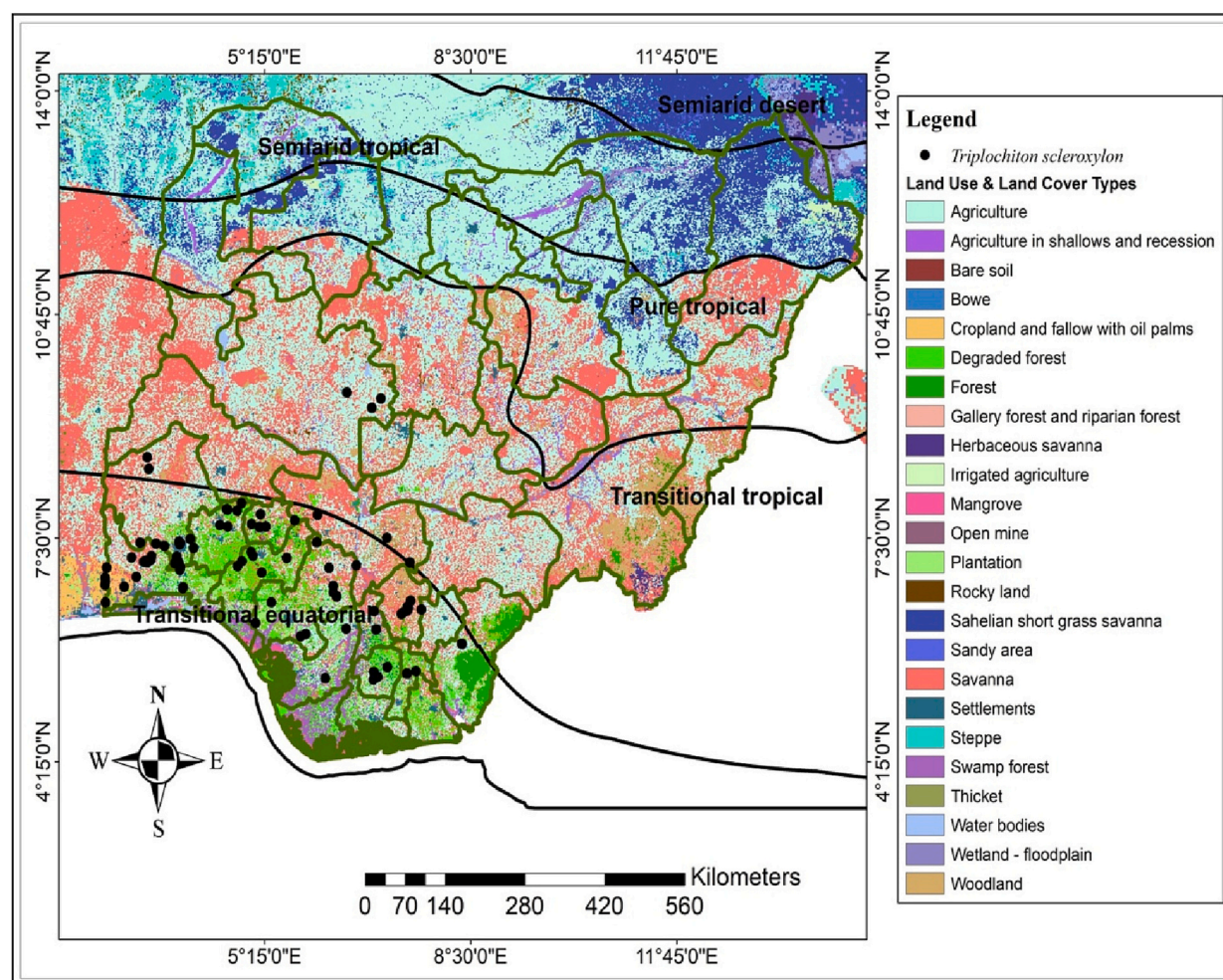


Fig. 6. Species conservation map. An overlay of *T. scleroxylon* distribution data on Land use map, showing current population spread predominantly in degraded forest areas of Southern Nigeria.

further loss as habitat degradation extends towards south-eastern Nigeria, and further precipitation decline in the north. The current study provides insight into the population dynamics of *T. scleroxylon*, the need to mitigate overexploitation and develop a solid framework for the conservation of the species for posterity.

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Consent for publication

The authors give consent for the publication of the article.

Authors contributions

ECC and OOO conceived the idea; ECC and DMC retrieved data from herbaria; BBT, KAB, SBA and AS participated in data cleaning and field assessment; ECC performed the analyses; ECC, OOO, DMC and AEA wrote the manuscript. All authors revised the manuscript and supported the submission.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

the work reported in this paper.

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Appendix A. Supplementary data

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