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Habitat modelling of *Xylopia aethiopica* (Dunal) A. Rich. of the Guineo-Congolese region in Benin, West Africa

Essè Florentin DISSOU[1*], Hermeline Eliante Romualde Gbedande DOSSA[2], Soufiyanou KARIMOU[3], Agossou Brice Hugues TENTE[1] et Essin Florent DISSOU[4]

[1] University of Abomey-Calavi (UAC), Department of Geography and Land Planning, Laboratory of Biogeography and Environmental Expertise (LaBEE), BP 698 Abomey-Calavi, République du Bénin
[2] University of Abomey-Calavi (Benin), Faculty of Agricultural Sciences, Laboratory of Forest Sciences, BP 1493 Abomey-Calavi, Benin
[3] University of Abomey-Calavi (UAC), Department of Geography and Land Planning, Laboratory of Cartography, Remote Sensing and GIS (LaCarto), 10 BP 1082 Cotonou-Houéyiho, Benin
[4] University of Abomey-Calavi, Polytechnic School of Abomey-Calavi, Research Laboratory of Applied Biology (LARBA), 01 P.O. Box 2009 Cotonou, Benin

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* Correspondance, courriel : *defloty21@gmail.com*

Abstract

This study analyses current and future areas favourable to the conservation of *Xylopia aethiopica* in the Guineo-Congolese region of Benin, taking climate change into account up to 2055. The study used a total of 1201 *Xylopia aethiopica* occurrence points combined with current and future climate variables of the study area. The Maximum Entropy (MaxEnt), Random Forest (RF), Boosted Regression Trees (BRT), Generalized Additive Model (GAM) and Generalized Linear Model (GLM) algorithms were used, based on the RCP 4.5 and RCP 8.5 scenarios up to 2055. The AUC, TSS, correlation and deviance tests have shown the performance and the strong predictive capacity of the models. The environmental variables that contributed the most to the models were soil and In_Wat. Current climatic conditions indicate that 93.85% of the Guineo-Congolese region of Benin is less favourable for the conservation of *Xylopia aethiopica*. Forecasts for 2055 (RCP 4.5 and RCP 8.5) indicate that climatic conditions will contribute to an increase of moderately favourable and highly favourable habitats of *Xylopia aethiopica*, to the disadvantage of less favourable habitats, which will decline in the Guineo-Congolese region of Benin. The results obtained from this study show that consideration of the phytogeographical districts of the Guineo-Congolese region of Benin is crucial in policies for the protection and conservation of *Xylopia aethiopica* in Benin.

Keywords : *MaxEnt, modelling, ecological niche, climate change.*

Résumé

Modélisation de l'habitat de *Xylopia aethiopica* (Dunal) A. Rich. dans la région Guineo-Congolaise au Bénin, Afrique de l'Ouest

La présente étude porte sur l'analyse de la qualité des territoires favorables à la conservation actuelle et future de *Xylopia aethiopica* dans la région Guinéo-Congolaise du Bénin, en relation avec les changements climatiques, à l'horizon 2055. Un total de 1201 points d'occurrences de *Xylopia aethiopica* ont été utilisées en combinaison avec les variables climatiques actuelles et futures de la zone d'étude. Les algorithmes Maximum Entropy (MaxEnt), Random Forest (RF), Boosted Regression Trees (BRT), Generalized Additive Model (GAM) et Generalized Linear Model (GLM) ont été utilisés en tenant compte des scénarios RCP 4.5 et RCP 8.5 à l'horizon 2055. Les tests AUC, TSS, de corrélation et de déviance ont révélé la performance et la forte capacité prédictive des modèles. Les variables environnementales qui ont le plus contribué aux modèles sont respectivement le sol (soil) et le cours d'eau (In_Wat). Les conditions climatiques actuelles consacrent 93,85 % de la région Guinéo-Congolaise du Bénin moins favorable à la conservation de *Xylopia aethiopica*. Les projections à l'horizon 2055 (RCP 4.5 et RCP 8.5) indiquent que les conditions climatiques contribueront à augmenter les habitats moyennement favorables et très favorables de *Xylopia aethiopica* au détriment des habitats peu favorables qui connaîtront une régression dans la région Guinéo-Congolaise du Bénin. Les résultats de la présente étude impliquent que la considération des districts phytogéographiques de la région Guinéo-Congolaise du Bénin est capital dans les politiques de protection et de conservation de *Xylopia aethiopica* au Bénin.

Mots-clés : *MaxEnt, modélisation, niche écologique, changement climatique.*

1. Introduction

Throughout Africa, forest products other than timber, industrial wood and their by-products, known as Non-Timber Forest Products (NTFPs), have played an important role in the survival of both rural and urban populations for centuries [1]. NTFPs (medicinal plants, food plants, art objects, utensils) provide people with income and are also key subsistence products [2]. Benin has a rich flora of 2,807 plant species, with an estimated forest cover of 4,561,000 ha in 2010 [3]. Some of these plants are used in traditional medicine, while others are used for food [4, 5]. Among these species is *Xylopia aetiopica* (Dunal) A. Rich., the Ethiopian or Guinean pepper tree, a non-hardy species belonging to the Annonaceae family, known in Africa for the Non-Timber Forest Products (NTFPs) it provides to local inhabitants [6]. Regarding uses, the fruits of the plant are the most solicited [7]. They are used to treat a range of local diseases [8], including malaria, diabetes, diarrhoea and animal diseases. Furthermore, their antimicrobial, anti-inflammatory and analgesic effects have been demonstrated [9 - 11]. Other scientific studies have also highlighted the ethnobotanical [12], socio-economic [7], nutritional [13] and biochemical potential of the species' essential oils [14]. *X. aethiopica* is a forest tree found in various types of habitats, such as primary forests, secondary forests, high-altitude forests, flooded forests, and low-mountain forests up to an altitude of 1,600 m. The species tolerates slightly salty soils, allowing it to blend with coastal plant communities. It can also tolerate mean annual temperatures between 20 and 31°C, and requires annual rainfall more than 500 mm [15]. In the Guineo-Congolese region of Benin, individuals of *X. aethiopica* have an aggregated distribution [16]. In addition, its habitat takes the form of crumbled and discontinuous forests, which are remnants of the later dry period of the late Holocene (4,000 to 3,000 years BP), during which the semi-evergreen forest was restricted to a few suitable areas [17]. Thus, despite the key role played by the species in African societies, its aggregated distribution, linked to the fragmentation of its habitat and the effects of climate change, could have a lasting impact on its spatial distribution. Furthermore, like other woody and non-woody forest products that are under threat from a whole range of factors, including deforestation, climate change, over-use, agriculture, demographic pressure, breeding, vegetation fires, *X. aethiopica* is one of the most vulnerable woody species listed on the International Union for Conservation of Nature (IUCN) Red List for Benin, in the medicinal plant category [18]. However, the trend can still be reversed by contributing to the sustainable management of the species through the study of the spatiotemporal evolution of its habitat. In this context, habitat modelling is a powerful predictive tool [19] because it enables us to address the major issues of understanding, describing and predicting the potential distribution of endangered species, which often have a limited number of observed occurrences [20]. The purpose of this article is to assess the effects of climate and environmental parameter change on the habitat of *X. aethiopica* in the Guineo-Congolese area of Benin up to 2055.

2. Material and methods

2-1. Study area

Surveys were carried out in the phytogeographic districts (Coastal, Pobe, Oueme Valley and Plateau) of the Guineo-Congolese region of Benin (6°25'-7°30'N and 1°-3°40'E). The vegetation in this area has different appearances. The rainfall pattern is bimodal with four seasons: two rainy seasons and two dry seasons, alternating throughout the year. In the south-west, rainfall is relatively lower (900 mm at Grand-Popo) than in the east (1300 mm at Pobe). The temperature ranges from 25°C to 29°C in the study area. The relative humidity ranges from 97 % to 69 %, and the Mangenot humidity index from 3.9 in Aplahoue to 5.8 in Porto-Novo [21].

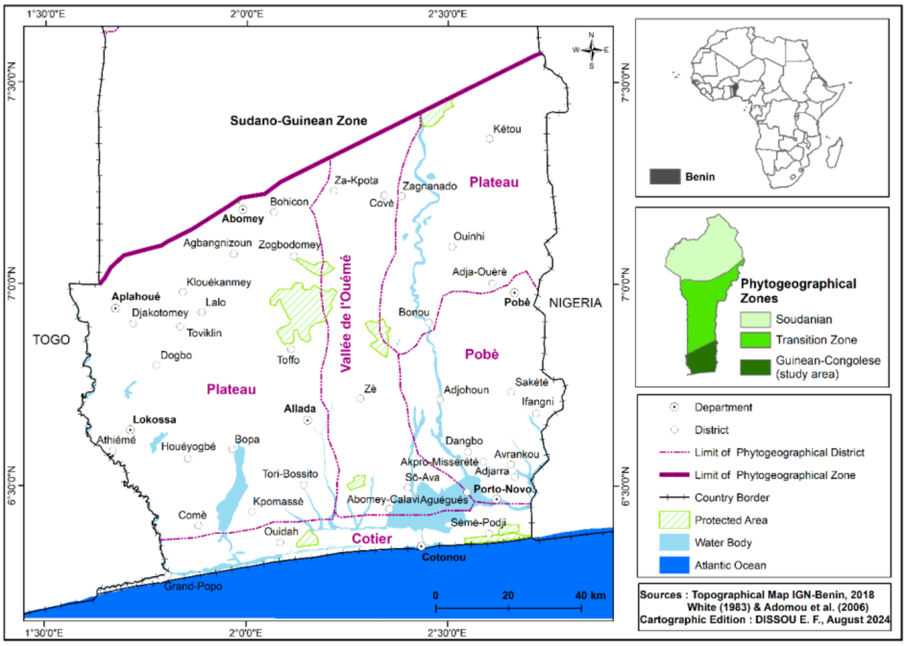

Figure 1 : *Localization of the Benin Guineo-Congolese region*

2-2. Algorithm of modeling

Five modeling algorithms implemented with Rstudio 4.4.4 were used to model the habitat of *X. aethiopica* in the Guineo-Congolese region of Benin. It includes the Maximum Entropy or MaxEnt, the Random Forests (RF) and the Boost Regression Trees (BRT), the Generalized Additive Model (GAM) and the Generalized Linear Model (GLM). The package's "sdm" function was used to build models of the *X. aethiopica* distribution using different modeling methods. The use of the cross-validation (cv) argument resulted in replication of the models. This means the data was divided into several parts, and the model was trained several times on different sub-parts of the data to assess model performance. In addition, 70 % of the occurrence data was used to run the model, while the remaining 30 % was used to evaluate the performance of the model after training. This process (cross-validation) was performed ten times to increase the strength and accuracy of the results.

2-3. Input Data

Two data types were used to model the habitats of *X. aethiopica*. It includes species occurrence data and environmental data (bioclimatic or not).

2-4. Occurrence Data

The occurrence data come from two sources. Firstly, they were collected in the field using GPS through direct observations of *X. aethiopica*. Afterward, they have been downloaded from the Global Biodiversity Information Facility (GBIF) platform on May 27, 2025, from the link https://doi.org/10.15468/dl.6xvhaj. A total of 1,201 points of occurrence were collected, comprising 1,008 points collected in the field and 193 points from the GBIF website. The data banks were then merged and cleaned using Excel 2016. The cleanup consisted of removing duplicates, missing values and columns other than species, longitude and latitude. Then, saved in .csv format, the three-column file containing *X. aethiopica* occurrences was exported to R-4.4.4 software for further cleaning before being converted into a spatial object for more appropriate uses. ***Figure 2*** shows the spatialization of the occurrence data used.

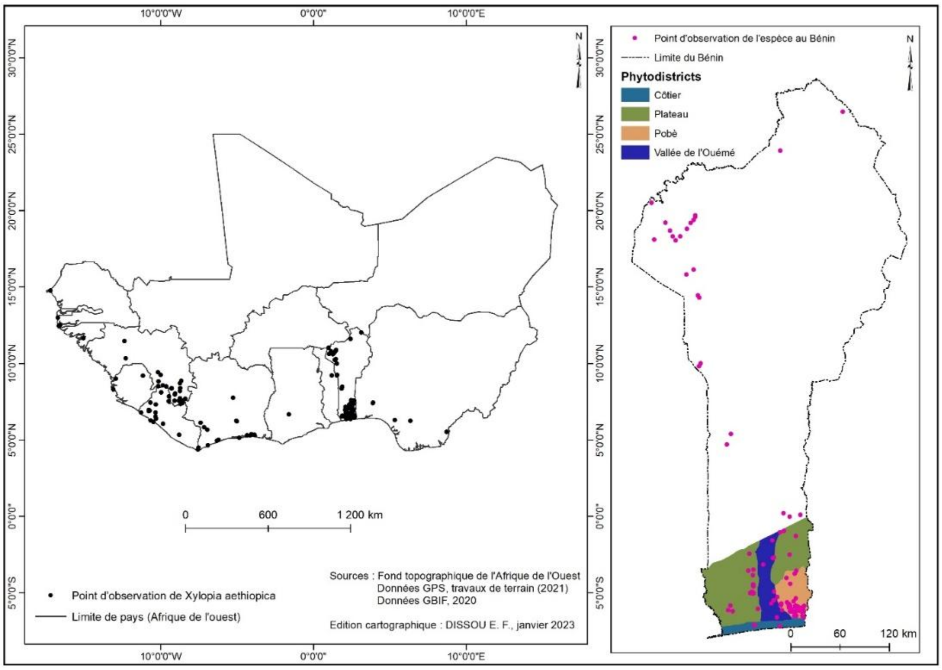

Figure 2 : *Spatialization of occurrence data used*

2-5. Environmental variables

The environmental variables were downloaded from the Africlim website [33], because the species is endemic to Africa and the study focuses on part of Benin, an African country. Africlim enables a much more accurate task to be performed, as its data is better suited to the African context and reflects it more closely [22]. Twenty-one (21) bioclimatic variables were downloaded from the Africlim website ***(Table 1)***.

Table 1 : *List of bioclimatic variables used*

N°	Bioclimatics variables	Short form
	Temperature	**tbio**
1	Mean annual temperature	bio1_wc30s
2	Diurnal average temperature	bio2_wc30s
3	Isothermality	bio3_wc30s
4	Temperature seasonality	bio4_wc30s
5	Maximum temperature of the warmest month	bio5_wc30s
6	Minimum temperature of the coolest month	bio6_wc30s
7	Annual temperature range	bio7_wc30s
8	Average temperature in the warmest quarter	bio10_wc30s
9	Average temperature in the coolest quarter	bio11_wc30s
10	Potential evapotranspiration	pet_wc30s
	Moisture	**mbio**
11	Average annual rainfall	bio12_wc30s
12	Rainfall in the wettest month	bio13_wc30s
13	Rainfall in the driest month	bio14_wc30s
14	Rainfall seasonality	bio15_wc30s
15	Rainfall in the wettest quarter	bio16_wc30s
16	Rainfall in the driest quarter	bio17_wc30s
17	Annual moisture index	mi_wc30s
18	Moisture index of the wettest quarter	mimq_wc30s
19	Dry quarter moisture index	miaq_wc30s
20	Number of dry months	dm_wc30s
21	Length of the longest dry season	llds_wc30s

Source : [22], *https://webfiles.york.ac.uk/KITE/AfriClim*

Besides bioclimatic variables, additional variables ***(Table 2)*** were added while considering the ecology and distribution range of *X. aethiopica* [23]. Indeed, according to [24], the distribution of a species is not exclusively governed by climatic environmental variables. Non-environmental climatic variables must also be considered where appropriate.

Table 2 : *List of additional variables used*

N°	Variables	Short form	Sources
22	LandCover	LandCov	FAO
23	GloSlopes	Slope	FAO
24	Soil	Soil	FAO
25	GloElev	Elv	FAO
26	Distance to OSM major road	maj-road	WorldPop
27	Distance to ESA-CCI-LC inland water	In_wat	WorldPop
28	Distance to OSM major waterways	wat_way	WorldPop
29	Africa Population 2020	Afri_pop20	WorldPop

Once the necessary environmental variables were set up, the remaining work was done with RStudio (R-4.4.4). The most used packages were raster, sdm, dismo, dplyr, tidyr, usdm, sp, sf and tidyverse. They have been used to develop raster and occurrence data to model the potential distribution of species. This includes pre-processing steps such as the checking and harmonization of Reference Coordinate Systems (RCS) and extents, as well as reducing the multicollinearity of variables.

2-6. Predictive Power of the Models

The predictive power of the models was determined by analyzing the values of the Area Under the Curve (AUC), True Skill Statistic (TSS), correlation and deviance tests. The AUC values indicate the discrimination capacity of each model, which takes values between 0 and 1 [25]. The AUC test is a benchmark commonly used in ecological niche modeling [25], to verify the accuracy of the model. In addition to the value, the next one, the better is the capacity of the prediction of the model. The closer the value is to 1, the better the model's predictive ability. According to [26], the AUC value is independent, meaning that it accurately measures the performance of ordinal score models. So, depending on the values obtained :

- 0.5-0.7: means poor discrimination
- 0.7-0.9: means reasonable discrimination
- 0.9-1.0: means very good discrimination

True Skill Statistic (TSS) refers to the model's ability to accurately detect true presence (sensitivity) and true absence (specificity) [27, 28]. Higher values indicate a better predictive ability of the model. A model with TSS ≤ 0 indicates random prediction, while a model with a TSS close to 1 (TSS $>$ 0.5) has a good predictive power [27]. Correlation measures the linear relationship between model predictions and real observations. Higher values indicate a better fit between model predictions and real observations. Finally, the deviance measures the adjustment of the model to the data. Lower values indicate a better model fit.

3. Results

3-1. Predictive power of models

The statistical results obtained from the predictive models of suitable habitats for the current and future occurrence of *X. aethiopica* in the Guineo-Congolese region of Benin are provided in ***Table 3***.

Table 3 : *Predictive power of algorithms for modeling X. aethiopica habitats*

Method	AUC (Standard deviation)	TSS (Standard deviation)	COR (Standard deviation)	Deviance (Standard deviation)
Maxent	0.85±0.005	0.57±0.012	0.45±0.009	0.88±0.015
BRT	0.83±0.007	0.57±0.014	0.53±0.011	0.6±0.013
RF	0.88±0.004	0.64±0.010	0.65±0.008	0.46±0.012
GLM	0.74±0.009	0.29±0.018	0.43±0.010	0.67±0.020
GAM	0.85±0.006	0.56±0.013	0.6±0.012	0.58±0.014

An analysis of ***Table 3*** leads to the following conclusions :

- The RF model revealed the highest AUC value (0.88), suggesting that it had a better capacity for discrimination than the other models.
- The RF model has the highest TSS value (0.64), indicating that it had the best performance in predicting classes.
- The RF Model recorded the highest correlation (0.65), indicating that it provides the best fit between predictions and observations.
- The RF Model recorded the lowest deviance (0.46), suggesting a better adjustment of the model to observed data.

3-2. Contribution of variables

The multi-colinearity test was used to select six (06) of the twenty-nine (29) initial variables. The selected variables are soil (soil), watercourses (ln_wat), average temperature of warmest quarter (bio10_wc30s), number of driest months (dm_wc30s), main access roads (maj_road) and slope (slope). ***Figure 3*** illustrates the importance of the variables' contribution to the model.

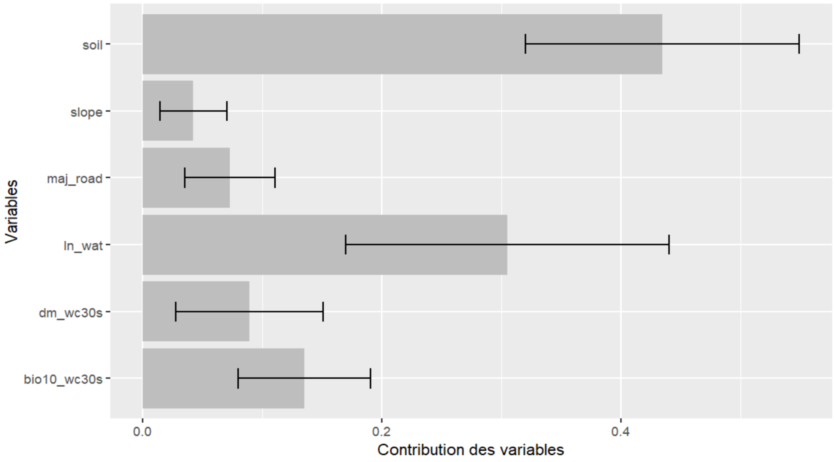

Figure 3 : *Contribution of the variables used in the model*

Figure 3 shows that soil (soil) was the most important variable in predicting the habitats of *X. aethiopica*. It is followed by watercourses (ln_wat). Each of the other variables had less weight in the prediction of the model. In order of importance, these are average temperature of warmest quarter (bio10_wc30s), number of driest months (dm_wc30s), main access roads (maj_road), and slope (slope).

3-3. Importance of variables and their application to the conservation of *X. aethiopica* habitats

UAC and correlation tests were performed to find out how much each variable matters in the prediction process. ***Figure 4*** shows the weight of the variables based on AUC and the correlation test values.

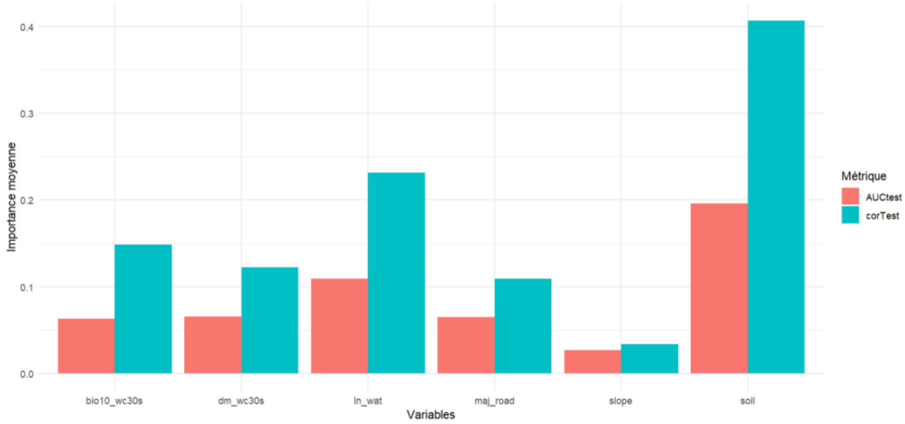

Figure 4 : *Importance of variables based on AUC and correlation test values*

Figure 4 shows that, the most important variables for the conservation of the species are: i) soil, ii) water, iii) average temperature of the warmest quarter, iv) number of driest months, v) main access routes and vi) slope. Importance values have been analyzed in ***Table 4***.

Table 4 : *Significance of variable importance values*

N°	Importance	Variables	CORtest	AUCtest	Interprétation
1	High importance	Soil	0.407044	0.196216	The soil variable appeared to be of crucial importance for *X. aethiopica*. This indicated that the quality or type of soil is a key factor in the species' conservation. It is therefore essential to preserve or improve soil conditions to support the species' population.
		In_wat	0.231354	0.109180	The variable In_wat refers to the availability of water. Its importance showed that the presence of water is also vital for conservation in its habitat.
2	Moderate importance	Bio10_wc30s	0.148228	0.062852	The moderate importance of the thermic variables bio10_wc30s (average temperature of the warmest quarter) and dm_wc30s (number of driest months) also influence the conservation of *X. aethiopica*, but to a lesser extent than the variables soil and In_wat.
		Dm_wc30s	0.122404	0.065588	
3	Low importance	Maj_road	0.109086	0.064620	The maj_road (main access roads) and slope variables were less important. This suggests that they may have a lesser or indirect impact on the conservation of the species. For example, the presence of a dense road network or steep slopes may be insignificant.
		Slope	0.033348	0.026780	

Table 4 analysis has led to the following conclusions :

- Habitat management: By focusing on the most important variables (such as soil and water), we can prioritize specific actions for conservation. For example, we can work to improve soil quality or manage water resources to support the species.
- Monitoring and assessment: Soil and water variables can be used to assess habitat changes and their influence on the species.
- Conservation planning : These factors can be introduced into management plans to create more targeted and successful strategies to preserve *X. aethiopica*.

3-4. Current and future distribution areas in the Guineo-Congolese region of Benin

The area of current and future distribution of *X. aethiopica* is analyzed from information in ***Table 5*** and ***Figures 5*** and ***6***. The results clearly show that under current conditions ***(Figure 5)***, habitats that are less favorable for the conservation of *X. aethiopica* are the most widespread (12,163,395 km^2, or 93.85 %). From a morpho-pedological point of view, the least favorable habitats are located on the plateau of southern Benin, on either side of the Lama Depression. More specifically, these habitat types are found in the southwest part of the Coastal and Plateau Phytodistricts, from north to northeast part of Plateau Phytodistrict, from center to northern part of the Oueme Valley phytodistrict, in the northeastern part of the Pobe Phytodistrict with an intrusion in the south of the Coastal Phytodistrict. However, the distribution of the moderately favourable habitats is oriented north-west – south-east, intercepting on either side the less favourable habitats of the plateau and Oueme Valley Phytodistricts. Very favourable habitats are dominant in the centre and east of the Coastal Phytodistrict and in the southern part of the Phytodistrict of Pobe. In addition, they have also been found in discontinuous (fragmented) form in the Plateau (south-east; north-west), Oueme Valley (south-east) and Pobe (north-west) Phytodistricts.

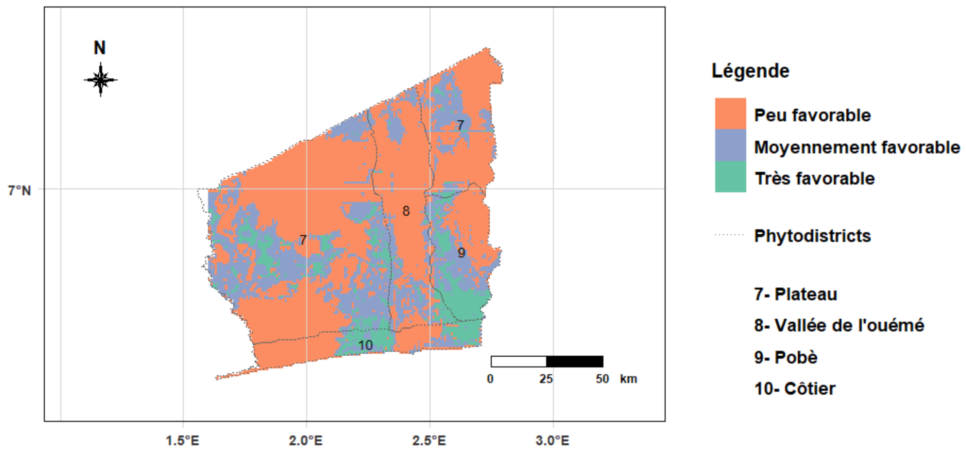

Figure 5 : *Spatialization of current habitats of X. aethiopica in the Guineo-Congolese region*

Regarding the future, the results showed an 83.16 % reduction in the area of less favourable habitats of *X. aethiopica* ***(Figure 6a)*** under the RCP 4.5 scenario (mitigation of greenhouse gas emissions), and an 84.93 % reduction ***(Figure 6b)*** under the RCP 8.5 scenario (increase in greenhouse gas emissions). The areas affected by the regression of less favourable habitats include all the Phytodistricts of the Guineo-Congolese region, with some exceptions: the south-western part of Coastal Phytodistrict, the central-northern and eastern parts of plateau Phytodistrict and a gap in the north-eastern part of Pobe Phytodistrict. The surface area loss of less favourable habitats has benefited both moderately favourable habitats and, to a large extent, highly favourable habitats (Figure 6). The area of highly favourable habitats will change at an average rate of 4597.62 % under both scenarios. These changes can be seen in all districts of the Guineo-Congolese region of Benin ***(Table 5 ; Figure 6)***.

Table 5 : *Current and future areas of distribution of X. aethiopica in the Guineo-Congolese region*

X. aethiopica	**Very favourable habitat**		**Moderately favourable habitat**		**Low favourable Habitat**	
	Surface (Km²)	Proportion (%)	Surface (Km²)	Proportion (%)	Surface (Km²)	Proportion (%)
Present	119,276	-	677,26	-	12163,40	-
RCP 4.5	5705,76	4684,08	5206,42	668,75	2047,75	-83,16
RCP 8.5	5499,53	4511,16	5626,92	730,84	1833,47	-84,93

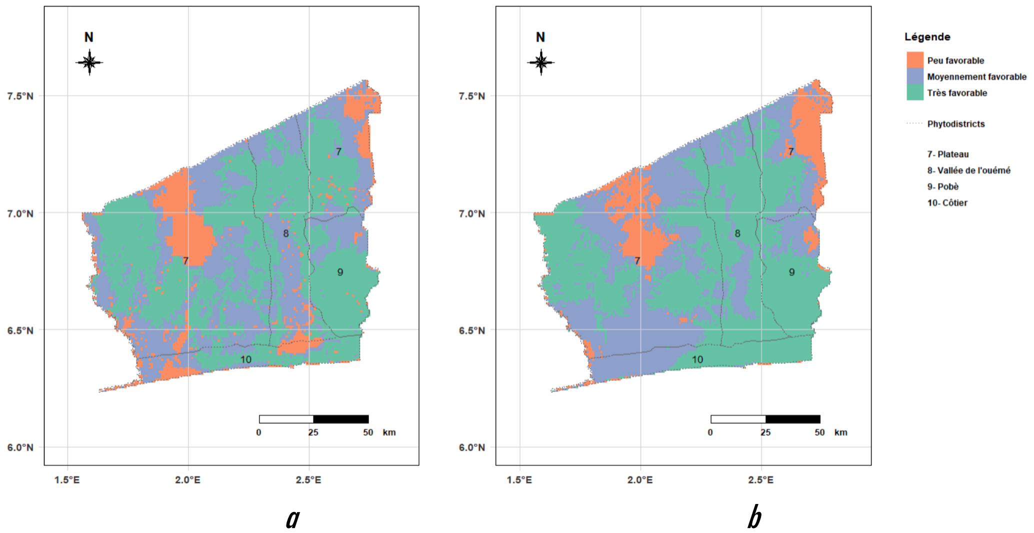

Figure 6 : *Spatialization of X. aethipica habitats in the Guineo-Congolese region*

4. Discussion

4-1. Contribution of environmental variables to the prediction model

Five prediction algorithms were used in this study (MaxEnt, BRT, RF, GLM and GAM). These algorithms have been used either individually or in combination in a number of scientific publications aimed at mapping the current and future distribution of plant species [29, 30] or animal species [31] or to assess the capacity of ecosystems to conserve threatened or endangered species [32, 33]. The study used data on current *X. aethiopica* occurrence and several bioclimatic and environmental variables to predict the future distribution of the species in the Guineo-Congolese region of Benin. First of all, the results of the study showed that the high value of the AUC test for each of the models demonstrated that they were significantly efficient and predictive [34]. However, the RF model was the best performing, with the highest AUC and TSS values (0.88 and 0.64). However, this result does not mean that the RF model is the best of all the models used in modelling. Indeed, in a study carried out on *Anogeissus leiocarpa* (DC.) Guill & Perr, in Benin, Maxent and BRT were the most predictive [30]. In addition, [35] classified Maxent, BRT, and RF as the most effective algorithms for predicting *Chrysophyllum albidum* G. Don on the African continent. A total of six (06) variables were used to establish the multi-colinearity test. These were soil, water courses (In_wat), average temperature of the warmest quarter (bio10_wc30s), number of driest months (dm_wc30s), main access roads (maj_road) and slope. However, it was respectively the variables soil and watercourse (In_wat) that contributed the most to the prediction of the species' habitats. The strong contribution of these two variables is linked to the species' ecological preference for wet or swampy environments [36]. Indeed, there is no doubt that the physico-chemical properties of the soil can help to better forecast the distribution area of a species in the current climate [36]. However, the suitability of *X. aethiopica* for a wide range of soil types and its domestication by human beings for its great ethnobotanical and economic usefulness could, over time, make the demographic variable an important determinant of its distribution in the Guineo-Congolese region of Benin, as it is the case for *Caesalpinia bonduc* [37]. Furthermore, according to [38], plants can easily be affected by a lack or excess of humidity. It therefore becomes obvious to justify the contribution of the average temperature of the warmest quarter (bio10_wc30s), and the number of driest months (dm_wc30s) in predicting the species' future habitats. In fact, *X. aethiopica*, like the species characteristic of the Guineo-Congolese region, is sensitive to dry and wet periods in the area [15].

4-2. Current and Future Habitats of *X. aethipioca* in the Guineo-Congolese region of Benin

The current and future distribution areas of *X. aethiopica* in the phytogeographical districts of the Guineo-Congolese region of Benin were analyzed in consideration of the Intergovernmental Panel on Climate Change (IPCC) Radiative concentration pathways (RCP), which are greenhouse gas emission scenarios and references on the evolution of radiative forcing for the period 2006-2300 [39]. This study was based on two of the four scenarios defined by the Intergovernmental Panel on Climate Change (IPCC) community of scientists [40], to predict the future distribution of the species by 2055. These are RCP 4.5 and RCP 8.5, widely used as a reference in predicting the future habitats of species in the intertropical world and in Benin. The results revealed a predominance (in the present time) of habitats that are not very favourable for the conservation of *X. aethiopica* in the Guineo-Congolese region in Benin (93.85 % of areas). However, in the future, the RCP 4.5 and RCP 8.5 scenarios predict a contrary trend in favour of moderately favourable and highly favourable habitats across all phytogeographical districts in the study area. These results are like those of [37] on *C. bonduc* in southern Benin and [29] on *Triplochiton scleroxylon* K. Schum., in the Guineo-Congolese region of Benin. Overall, it is significant to note that, currently, highly favourable habitats are mainly found in the centre and extreme east part of the Coastal Phytodistrict, in the south part of the Pobe Phytodistrict and in the south-eastern part of the Oueme Valley Phytodistrict. However, in the future, these habitats will expand significantly in all the Phytodistrict of the study area, including the major cities. In fact, demographic growth is not the only factor determining the conservation of species, as highlighted by [51], because when a species becomes rare, the most effective way to preserve it is through protection in agroforestry systems and household gardens. The two scenarios used in the present study (RCP 4.5 and RCP 8.5) have jointly projected a strong expansion in the areas of very favorable and moderately favorable habitats at the expense of less favorable habitats. Thus, it is important to note that the hypothesis that climate change affects the modification of species distribution is confirmed for *X. aethiopica* in the Guineo-Congolese region of Benin.

5. Conclusion

Based on the results of this study, it can be concluded that the variability of certain climatic and environmental parameters has an influence on the distribution of the current and future habitat of *X. aethiopica* in the Guineo-Congolese region of Benin. Overall, current and future climatic conditions in the study area are favourable for forestry and conservation of *X. aethiopica* in southern Benin. The RCP 4.5 and RCP 8.5 scenarios were found to be optimistic and predicted a reduction in the area of less favourable habitats to the benefit of moderately favourable and highly favourable habitats by 2055. Consequently, although climate change is likely to improve the distribution of *X. aethiopica* in the Guineo-Congolese region of Benin, this region and its phytodistricts constitute the ideal biotopes for the conservation of *X. aethiopica* in Benin.

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