Journal of Geoscience and Environment Protection, 2024, 12, 29-40
https://www.scirp.org/journal/gep
ISSN Online: 2327-4344
ISSN Print: 2327-4336

Influence of Climatic Changes and Anthropogenic Activities on the Distribution and Habitats of *Senegalia senegal* in Niger: A Forecast and Ecological Analysis

Abdoul Kader Soumaila Sina[1*], Idrissa Soumana[2], Amadou Garba[1], Ali Mahamane[1]

[1]Garba Mounkaila Laboratory, Department of Biology, Faculty of Science and Technology, Abdou Moumouni University of Niamey, Niamey, Niger
[2]National Institute of Agronomic Research of Niger (INRAN), Niamey, Niger
Email: *aksoumailasina@gmail.com

How to cite this paper: Sina, A. K. S., Soumana, I., Garba, A., & Mahamane, A. (2024). Influence of Climatic Changes and Anthropogenic Activities on the Distribution and Habitats of *Senegalia senegal* in Niger: A Forecast and Ecological Analysis. *Journal of Geoscience and Environment Protection, 12,* 29-40.
https://doi.org/10.4236/gep.2024.1211002

Received: September 21, 2024
Accepted: November 9, 2024
Published: November 12, 2024

Abstract

The primary objective of this study is to assess the impact of climate change on the current and future spatial distribution of areas suitable for the growth of *Senegalia senegal*, a forest species of significant agro-ecological and socio-economic importance. To achieve this objective, the MaxEnt (Maximum Entropy) model was utilized, incorporating species presence points alongside bioclimatic variables. To project future distributions, three climatic models-CCCMA, HadCM3, and CSIRO were employed under the A2 scenario to predict the species' distribution by the year 2050. Currently, habitats highly favorable for the conservation of the species are situated in the Sahelo-Sudanian and Sudanian zones, accounting for 6.81% of the national territory. All models forecast a substantial increase in habitats highly favorable for the future conservation of *S. senegal*, with a total expected growth of 448.9%. Conversely, moderately favorable and unfavorable habitats are predicted to decrease by 106.26% and 78.59%, respectively. These findings provide crucial data for the long-term conservation strategy of this species, which holds significant ecological and agronomic potential for the Sahelian region.

Keywords

Modeling, Maximum Entropy, Suitable Habitat, *Senegalia senegal* Distribution, Niger

1. Introduction

Rural populations maintain complex relationships with forest ecosystems through the exploitation of non-timber forest products (NTFPs), which play an essential role in contributing significantly to health care, energy, food, monetary income, and various other aspects of human well-being (Gbesso, Tente, Gouwakinnou, & Sinsin, 2013; Doyon & Roy-Malo, 2020). In this context, African species, particularly *Senegalia senegal*, hold an essential position in the rural development of arid zones, providing high-quality fodder for livestock and producing gums and tannins, which generate monetary income for local populations (Guinko, 1991; Benam, Ganota, & Froumsia, 2023).

Furthermore, these species play a key role in reforestation and land rehabilitation programs due to their resilience to water stress and ability to improve soil fertility (Klein, Roose, & Peltier, 2023; Ly, 2024). In Niger, agricultural land degradation has had a major impact on food security. Considering its multiple benefits, including carbon sequestration and combating the effects of climate change, *Senegalia senegal* is a promising species for reforestation and desertification control initiatives. The Kyoto Protocol's mechanisms have highlighted the carbon market's potential in fighting poverty and desertification through reforestation and agroforestry projects in dry regions (Tsegay, 2023).

However, this species faces extreme climatic events. Increasing variability in climate factors, such as precipitation and temperature, is likely to impact biodiversity and the geographical distribution of suitable species habitats (Traoré et al., 2004). Studies indicate that by 2085, 25% - 42% of plant species could be at risk of extinction due to the loss of 81% - 97% of suitable habitats (Ezéchiel, Joel, Abdon, & Roger, 2022). Other projections suggest a heightened extinction risk for 20% - 30% of plant and animal species if global warming exceeds 1.5˚C to 2.5˚C in Africa (Busby, Smith, White, & Strange, 2012).

Given such threats, the woody forage vegetation of natural rangelands is highly vulnerable, undergoing significant pressures (Zakari et al., 2017). Considering the socioeconomic and ecological value of *Senegalia senegal* in Sahelian regions, understanding the state of its habitats is crucial for sustainable resource management.

In an environmental scenario marked by climate change and rising anthropogenic pressures, maps depicting current and projected future distributions can elucidate spatial dynamics and endow us with significant insights for responsible and sustainable management of the species' populations in Niger. This study aims to evaluate the impact of climate change on the status of the natural populations of this species. The aim is to identify potential habitats favorable for the species' distribution and to model its current and future distribution.

2. Materials and Methods

The methodology for this study is underpinned by a detailed exploration of the study environment and a systematic approach to methodological choices.

2.1. Distribution of the Species

This study was performed nationwide, specifically targeting gum-producing sites distributed across the eight regions of the country. To ensure comprehensive coverage, individuals from the natural populations of the species were included (Figure 1). The *Senegalia senegal* gum sites are primarily found in the Sahelian and Sahelo-Sudanian zones, where average annual precipitation ranges from 300 to 400 mm and 400 to 600 mm, respectively. These sites are located on degraded lands, including bare plateaus or crusted barren soils unsuitable for agriculture, with clay or sandy-clay soils. Vegetation and fauna are nearly non-existent in these ecosystems.

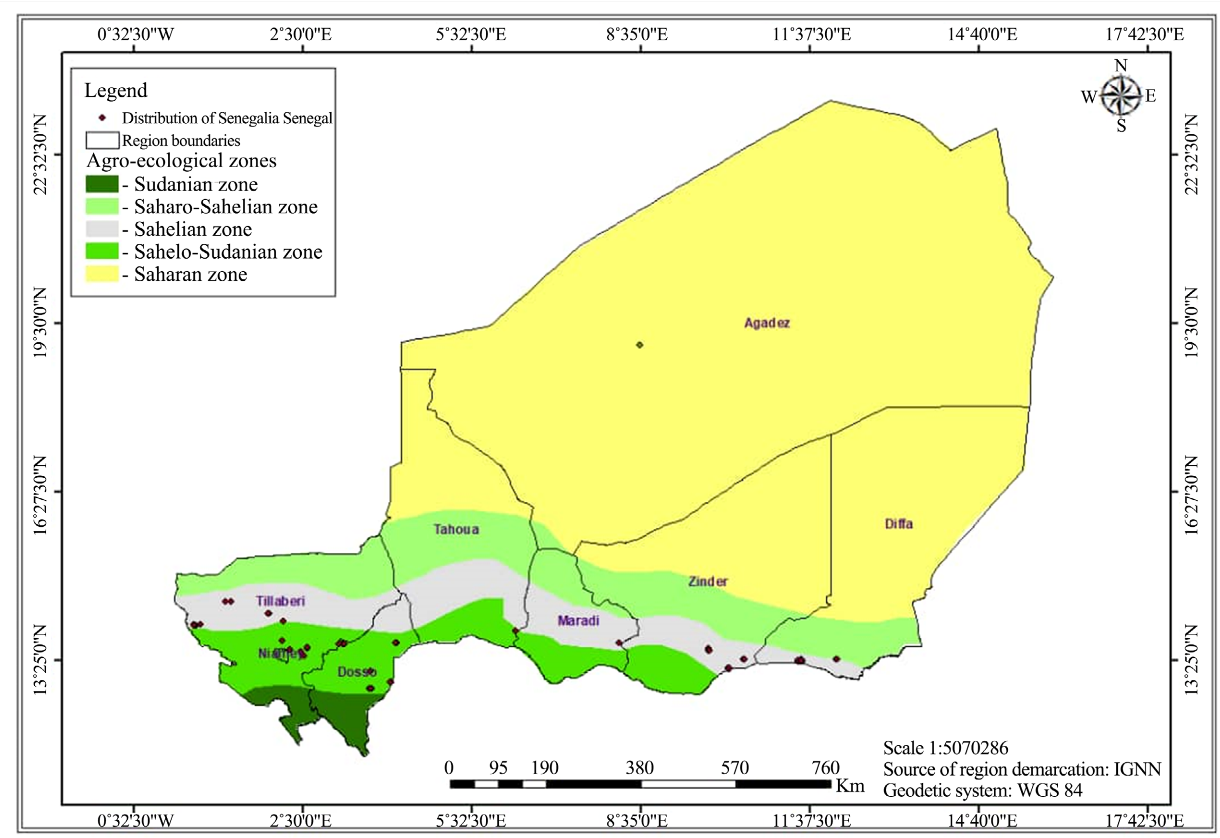


Figure 1. Map of gum sites in Niger.

2.2. *Senegalia senegal* Occurrence Data

Senegalia senegal occurrence data include the geographic coordinates of the presence points of the gum tree sites and individuals of the species' natural stands, obtained from GPS (Global Positioning System) surveys as well as downloads from the GBIF (Global Biodiversity Information Facility, https://www.gbif.org) website. In total, 361 presence points were collected to constitute the species database. The GBIF website is an online platform dedicated to the biodiversity information system.

2.3. Bioclimatic and Environmental Data

Current and future climate data for the *S. senegal* distribution area were downloaded from the WorldClim website (http://www.worldclim.org). These data include nineteen bioclimatic variables (Fandohan et al., 2013) (**Table 1**), collected at a resolution of 2.5 arc-minutes on the ground (Gbesso et al., 2013; Hijmans et al., 2006; Laouali, 2016). For future modeling, three of the most recommended models were used (Solomon, Manning, Marquis, & Qin, 2007): CCCMA (Canadian Centre for Climate Modelling and Analysis), HadCM3 (Hadley Centre for Climate Prediction and Research model version 3), and CSIRO (Commonwealth Scientific and Industrial Research Organisation). These models were applied taking into account the A2 emissions scenario, which is considered the most likely for Africa by 2050 (Williams, Jackson, & Kutzbach, 2007). This scenario describes a very heterogeneous world, with a fast-growing population but a low level of technology and development. The correlation coefficients determined between the 19 variables enabled the identification of highly correlated variables. Two variables are considered highly correlated if the Pearson correlation coefficient exceeds 0.7.

Table 1. Bioclimatic variables used to model the distribution of *S. senegal*.

Codes	Environmental variables
BIO 1	Average annual temperature
BIO 2	Average daily temperature variation [monthly average (max temperature-min temperature)]
BIO 3	Ratio of daily thermal amplitude to annual thermal amplitude
BIO 4	Temperature seasonality (standard deviation*100)
BIO 5	Maximum temperature of the hottest month
BIO 6	Maximum temperature of the coldest month
BIO 7	Annual temperature variation
BIO 8	Average temperature of the wettest quarter
BIO 9	Average temperature of the driest quarter
BIO 10	Average temperature of the warmest quarter
BIO 11	Average temperature of the coldest quarter
BIO 12	Annual precipitation
BIO 13	Precipitation in wettest month
BIO 14	Precipitation in the driest month
BIO 15	Seasonality of precipitation (coefficient of variation)
BIO 16	Precipitation in the wettest quarter
BIO 17	Precipitation in the driest quarter
BIO 18	Precipitation in the warmest quarter
BIO 19	Precipitation in the coldest quarter

Source: http://www.wordclim.org.

2.4. Data Processing and Analysis

What are the technical foundations for data processing and analysis? Although this question may seem complex at first, it will be effectively addressed through examining the concepts of validating the MaxEnt model, modeling the current and future distribution of *S. senegal*, as well as mapping its present and future habitats.

2.4.1. Modeling the Current and Future Distribution of *S. senegal*

To model the current and future distribution of *S. senegal*, the MaxEnt program was used (Phillips et al., 2006). It is one of the most appropriate modeling methods as it allows for the clear distinction between favorable and unfavorable habitats for a species from a bioclimatic perspective (Abdou et al., 2016; Gbesso et al., 2013; Moukrim et al., 2018). Its effectiveness is linked to the fact that it uses a statistical approach called maximum entropy to make predictions from incomplete data. MaxEnt estimates the spatial distribution of the species based on the maximum entropy of each environmental variable submitted (Phillips et al., 2006).

2.4.2. Validation of the MaxEnt Model

For the modeling of the distribution area, the bioclimatic variables were subjected to a correlation test to select those with weak correlations ($r < 0.85$), aiming to avoid bias in future predictions (Elith & Leathwick, 2009). Thus, five bioclimatic variables were retained due to their weak correlation (Laouali, 2016). A Jackknife test was performed on these variables to identify those contributing the most to the modeling (**Table 2**, infra). To evaluate the model, 25% of the species observation points were used to test the model, while 75% were used to calibrate it. The accuracy of the model was measured by the AUC (Area Under the Curve) statistic, in accordance with Phillips et al. (2006). A model is considered of good quality if the AUC value exceeds 0.90 (Swets, 1988). Cross-validation was repeated three times to improve model performance.

Table 2. Bioclimatic variables retained for current and future distribution.

Codes	Environmental variables
BIO 3	Ratio of daily thermal amplitude to annual thermal amplitude
BIO 9	Average temperature of the driest quarter
BIO 10	Average temperature of the warmest quarter
BIO 12	Annual precipitation
BIO 18	Precipitation in the warmest quarter

2.4.3. Mapping of Current and Future Habitats of *S. senegal*

As part of the mapping of the current and future distribution areas of *S. senegal* in Niger, the results obtained from MaxEnt modeling (raster image) were integrated into ArcGIS 10.1 software. This integration allowed us to classify habitats according to the logistic probabilities of occurrence: very favorable, moderately favorable, not very favorable, and not favorable. This tool was also used to assess the extent of each habitat type. Subsequently, the proportions of these areas in relation to the total surface area of Niger were determined and their trends were estimated.

3. Results

The results of the research conducted will be analyzed by focusing on the following areas: the contribution of the variables, the validation of the model, and the current and future distribution of *S. senegal* habitats.

3.1. Contribution of Variables and Validation of the Model

Figure 2 below shows the AUC (Area Under the Curve) curve, with values of 0.909 and 0.878, respectively. These results indicate that the distribution model predicted by the MaxEnt algorithm is of excellent quality, with a margin of error of 0.5%.

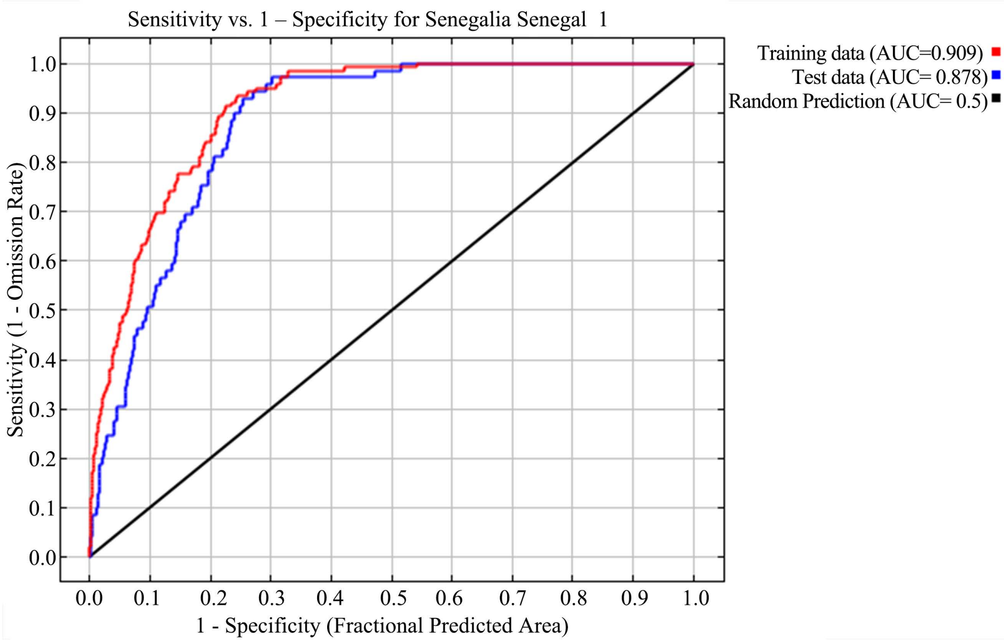


Figure 2. AUC value.

Figure 3 illustrates the Jackknife test, while Table 3 presents the contribution of the different variables to the model. From this analysis, BIO 12 (annual precipitation) emerges as the environmental predictor with the greatest gain, contributing 54.8%. When used alone in the model, this variable provides the most valuable information. It is followed by BIO3 (ratio of daily thermal amplitude to annual thermal amplitude) and BIO9 (mean temperature of the driest quarter), which contribute 31.2% and 5.7%, respectively.

Table 3. Contribution of variables to the model.

Codes	Bioclimatic variables	Contribution (%)
BIO 3	Ratio of daily thermal amplitude to annual thermal amplitude	31.2
BIO 9	Average temperature of the driest quarter	5
BIO 10	Average temperature of the warmest quarter	5.7
BIO 12	Annual precipitation	54.8
BIO 18	Precipitation in the warmest quarter	3.2

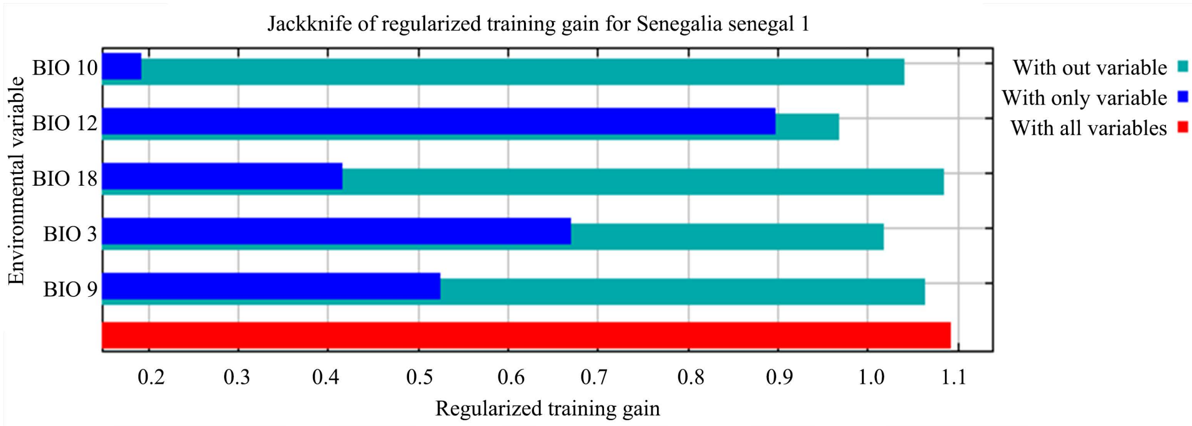
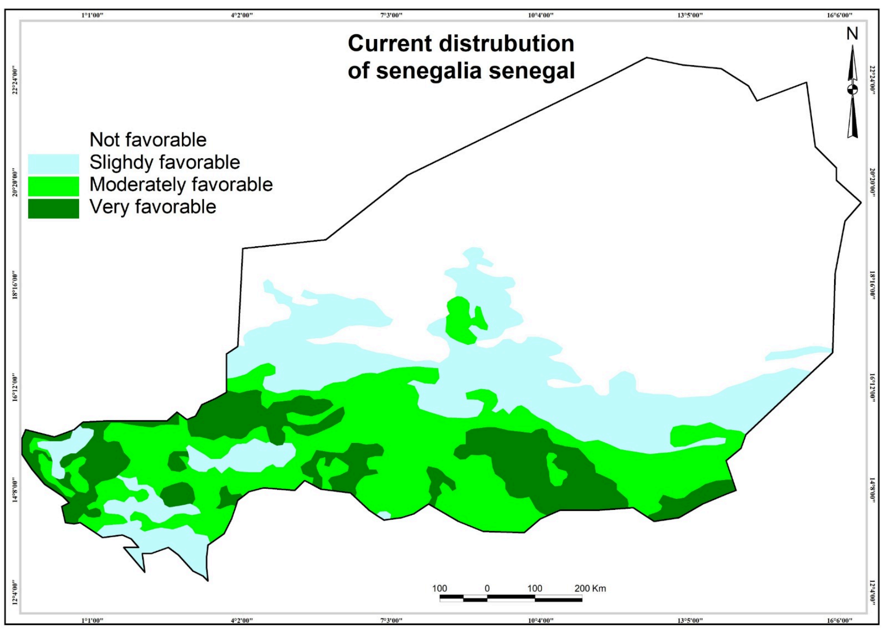


Figure 3. Jackknife test.

3.2. Current and Future Habitat Distribution of *S. senegal*

The modeling results reveal that the habitats currently highly favorable for the conservation of *S. senegal* are located in the Sahelo-Sudanian and Sudanian zones, covering an area of 86,259.80 km^2, or 6.81% of the entire territory of Niger. Moderately favorable and unfavorable habitats represent 18.83% and 18.19% of the territory, respectively. The rest of the territory, or 56.17%, is occupied by unfavorable habitats.

Regarding future projections to 2050, all models predict an increase in the area of highly suitable habitats for *S. senegal*. According to the CCMA, CSIRO, and HadCM3 models, these highly suitable habitats are projected to increase by 35.41%, 163.84%, and 249.65%, respectively. In contrast, for moderately suitable and unsuitable habitats, a slight decrease is projected by 2050 (**Figure 4**). Overall, their areas are projected to decrease by 106.26% and 78.59%, respectively (**Table 4**).



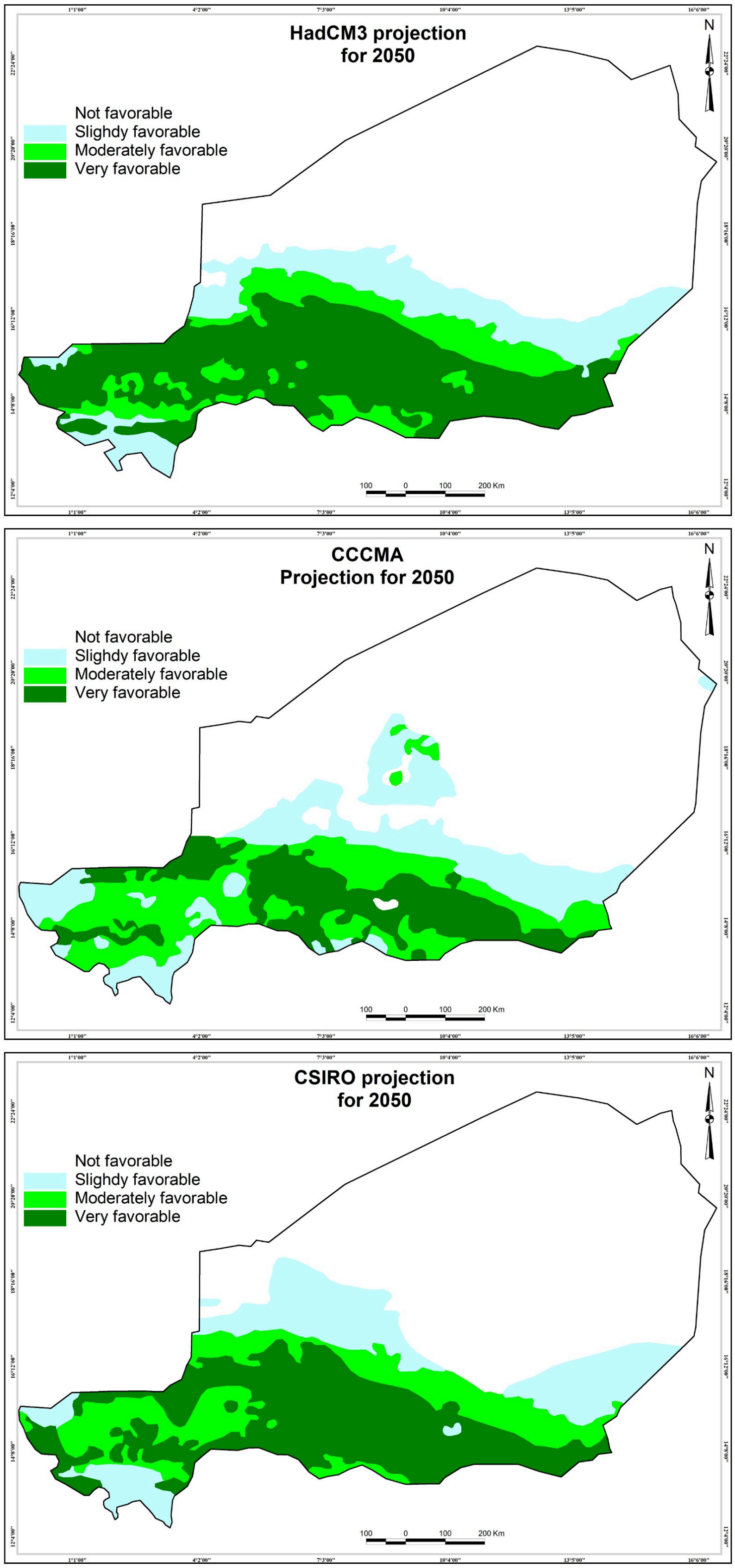


Figure 4. Spatialization of habitats favorable to the conservation of *S. senegal* in Niger.

Table 4. Variation in the areas of habitats favorable to the conservation of *S. senegal*.

Scenarios	Habitats					
	Very favorable		Moderately favorable		Unfavorable	
	Areas (km^2)	Tendency (%)	Areas (km^2)	Tendency (%)	Areas (km^2)	Tendency (%)
Here	86259.79851	-	238,538.43	-	230513.99	-
CCCMA	116800.2649	+35.41	187,500.98	−21.40	184222.982	−20.08
CSIRO	227590.0454	+163.84	166 131.63	−30.35	168568.951	−26.87
HadCM3	301604.4565	+249.65	108,508.81	−54.51	157569.005	−31.64

4. Discussion

The current and future distribution of *Senegalia senegal* was modeled and mapped using bioclimatic variables. Among these, the BIO 12 variable (annual precipitation) plays the most significant role in predicting areas favorable to the conservation of the species in Niger, followed by the BIO3 variable (ratio of daily thermal amplitude to annual thermal amplitude). These results reveal that annual precipitation and temperatures significantly influence the distribution of the species, which aligns with the conclusions of Maydell (1983), stating that *Senegalia senegal* can tolerate annual precipitations of between 100 and 800 mm. Similarly, the work of Zerbo et al. (2011) underscores that temperature and precipitation are determining factors in its distribution.

The deployment of predictive niche models demonstrates their value in delineating, with high probability, areas where species are likely to persist, a crucial step in defining priority areas for reintroduction (Gouwakinnou, 2011).

In this study, all models project an increase in the area of highly favorable habitats for the future distribution of *S. senegal*, accompanied by a decrease in the areas of moderately and unfavorable habitats in Niger. These variations are consistent with studies by Fandohan et al. (2013), Gbesso et al. (2013), Pittock (2009), and Zakari et al. (2017), who used similar scenarios to predict the distribution of potential plant niches, related to the type of model and scenario used. However, Tosso (2013) obtained different results regarding the current distribution of *S. senegal* using MaxEnt and logistic models, reporting an absence of the species in the Guinean-Congolese and Guinean-Congolese-Sudanese transition phytogeographic territories in Benin (1950-2000).

The results of Tosso (2013) also show that *S. senegal* has a high probability of occurrence in dry tropical areas with non-desert vegetation formations, where only 5.15% of the projected distribution area constituted an area of absence and 68.21% represented highly favorable habitat.

For future projections, the Tosso (2013) logistic model indicates a loss of more than 45% of suitable habitats by 2060, while the MaxEnt model envisages a reduction of only 1.2%. According to IUCN criterion A3, the MaxEnt model does not predict that *S. senegal* will be classified as a species threatened by climate change, unlike the logistic model which considers it vulnerable. Accordingly, climate change can affect the distribution of *Senegalia senegal*; however, measures must be taken to ensure its sustainable exploitation.

5. Conclusion

The results of this study demonstrate that modeling remains a valuable tool in ecology to predict ecological niches for both plant and animal species. Faced with the threats of environmental changes on species, this tool allows anticipation of variations in distribution areas and can offer avenues for their sustainable conservation. The development of the current and future map of *S. senegal* can provide decision-makers and land managers with a decisive tool, promoting reasoned and sustainable management of the species. Thus, areas identified as highly favorable but currently unoccupied could be considered for the development and domestication of the species. In habitats where conditions are moderately favorable or unfavorable, measures must be taken to ensure the sustainable exploitation of the species. The present study addresses the effect of climate change on the distribution of *Senegalia senegal* in an area where anthropogenic pressure is high due to the significant population increase in the region. The combined effect of human activities and climate change on the distribution of the species still needs to be assessed.

Acknowledgements

We extend our sincere gratitude to all the staff of the Garba Mounkaila Laboratory at Abdou Moumouni University, whose efforts enabled us to process and analyze the data we collected and downloaded from the Internet. We also warmly thank the residents of Lido (Commune of Guéchémé) for their hospitality during our stay. Our heartfelt thanks go as well to all the members of the management committees of the *Senegalia senegal* plantations (Biocarb Initiative) in Niger.

Conflicts of Interest

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

References

Abdou, L., Morou, B., Abasse, T., & Mahamane, A. (2016). Analysis of the Structure and Diversity of *Prosopis africana* (G. et Perr.) Taub. Tree Stands in the Southeastern Niger. *Journal of Plant Studies, 5,* 58-67. https://doi.org/10.5539/jps.v5n1p58

Benam, C., Ganota, B., & Froumsia, M. (2023). Diversité et effets d'exploitation des produits forestiers non-ligneux d'origine animale dans la réserve forestière de Dodjé, au sud-ouest du Tchad. *Revue Ivoirienne des Sciences et Technologie, 42,* 142-189.

Busby, J. W., Smith, T. G., White, K. L., & Strange, S. M. (2012). Locating Climate Insecurity: Where Are the Most Vulnerable Places in Africa? In J. Scheffran, et al. (Eds.), *Climate Change, Human Security and Violent Conflict: Challenges for Societal Stability* (pp. 463-511). Springer. https://doi.org/10.1007/978-3-642-28626-1_23

Doyon, S., & Roy-Malo, O. (2020). Produits forestiers non ligneux, cueilleurs paysans et fermiers-forestiers: Cueillir et habiter la région autrement. In *D'espoir et d'environnement? Nouvelles ruralités et mise en valeur de la nature au Bas-Saint-Laurent* (pp. 89-128).

Presses de l'Université Laval. https://doi.org/10.2307/j.ctv1h0p0k1.8

Elith, J., & Leathwick, J. R. (2009). Species Distribution Models: Ecological Explanation and Prediction across Space and Time. *Annual Review of Ecology, Evolution, and Systematics, 40,* 677-697. https://doi.org/10.1146/annurev.ecolsys.110308.120159

Ezéchiel, K., Joel, T. K., Abdon, A., & Roger, D. D. (2022). Accessibility and Effects of Binder Types on the Physical and Energetic Properties of Ecological Coal. *Heliyon, 8,* e11410. https://doi.org/10.1016/j.heliyon.2022.e11410

Fandohan, B., Gouwakinnou, G. N., Fonton, N. H., Sinsin, B., & Liu, J. (2013). Impact des changements climatiques sur la répartition géographique des aires favorables à la culture et à la conservation des fruitiers sous-utilisés: Cas du tamarinier au Bénin. *Biotechnology, Agronomy, Society and Environment, 17,* 450-462. https://web.archive.org/web/20180428050432id_/http://www.pressesagro.be/base/index.php/base/article/viewFile/665/652

Gbesso, F., Tente, B., Gouwakinnou, G., & Sinsin, B. (2013). Influence des changements climatiques sur la distribution géographique de *Chrysophyllum albidum* G. Don (Sapotaceae) au Benin. *International Journal of Biological and Chemical Sciences, 7,* 2007-2018. https://doi.org/10.4314/ijbcs.v7i5.18

Gouwakinnou, N. (2011). *Population Ecology, Uses and Conservation of Sclerocarya birrea (A. Rich) Hocchst. (Anacardiaceae) in Benin, West Africa* (p. 176). Ph.D. Thesis, University of Abomey-Calavi.

Guinko, S. (1991). Rôle des Acacias dans le développement rural au Burkina Faso et au Niger, Afrique de l'Ouest. *Etudes Flore et Végétation du Burkina Faso, 3,* 3-16. https://horizon.documentation.ird.fr/exl-doc/pleins_textes/pleins_textes_6/colloques2/010012402.pdf

Hijmans, R. J., Cameron, S. E., Parra, J. L., Jones, P., & Jarvis, A. (2006). The WorldClim Interpolated Global Terrestrial Climate Surfaces. Version 1.3.

Klein, H. D., Roose, E., & Peltier, R. (2023). *Quelques plantes utiles pour maîtriser l'érosion et restaurer la fertilité des sols tropicaux.*

Laouali, A. (2016). *Importance ethnobotanique, dynamique des peuplements et écologie de Prosopis africana (G. et Perr.) Taub. au Niger.* Thèse Présentée pour obtenir le grade de Docteur de l'Université Dan Dicko.

Ly, F. (2024). *Amélioration des plantations d'espèces forestières en zone sylvopastorale du Sénégal par l'utilisation de gel hydro-rétenteur.*

Maydell, H. V. (1983). *Arbres et arbustes du Sahel: Leurs caractéristiques et leurs utilisations.* Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ)/GmbH.

Moukrim, S., Lahssini, S., Mharzi Alaoui, H., Rifai, N., Arahou, M., & Rhazi, L. (2018). Modélisation de la distribution spatiale des espèces endémiques pour leur conservation: Cas de *l'Argania spinosa* (L.) Skeels. *Revue d'Écologie (La Terre et La Vie), 73,* 153-166. https://doi.org/10.3406/revec.2018.1923

Phillips, S. J., Anderson, R. P., & Schapire, R. E. (2006). Maximum Entropy Modeling of Species Geographic Distributions. *Ecological Modelling, 190,* 231-259. https://doi.org/10.1016/j.ecolmodel.2005.03.026

Pittock, B. (2009). *Climate Change: The Science, Impacts and Solutions* (2nd ed.). CSIRO.

Solomon, S., Manning, M., Marquis, M., & Qin, D. (2007). *Climate Change 2007—The Physical Science Basis: Working Group I Contribution to the Fourth Assessment Report of the IPCC* (Vol. 4). Cambridge University Press.

Swets, J. A. (1988). Measuring the Accuracy of Diagnostic Systems. *Science, 240,* 1285-1293. https://doi.org/10.1126/science.3287615

Tosso, D.-N. F. (2013). *Modélisation de la distribution de six espèces d'arbres Multi-Usages en Afrique et évaluation de l'effet des changements climatiques*. Université de Liège.

Traoré B., Letreuch-Belarouci N., Sahki-Boutamine R., & Gaouar A. (2004). Caractérisation dendrométrique et étude des possibilités d'amélioration des performances germinatives de *Balanites aegyptiaca* (L.) Del. dans la région de Tamanrasset (Ahaggar, Algérie). *Sécheresse, 15*, 137-146.

Tsegay, B. (2023). *Green Economy for Climate Change Mitigation and Poverty Reduction in Sub-Saharan Africa: A Critical Analysis of Carbon Finance in Ethiopia*. Doctoral Dissertation, SOAS University of London.

Williams, J. W., Jackson, S. T., & Kutzbach, J. E. (2007). Projected Distribution of Novel and Disappearing Climates by 2100 AD. *Proceedings of the National Academy of Sciences of the United States of America, 104*, 5738-5742. https://doi.org/10.1073/pnas.0606292104

Zakari, S., Arouna, O., Toko, I. I., Yabi, I., & Tente, B. A. H. (2017). Impact des changements climatiques sur la distribution de deux espèces ligneuses fourragères (*Khaya senegalensis* et *Afzelia africana*) dans le bassin versant de la Sota, Bénin. *Afrique Science, 13,* 1-14. https://www.researchgate.net/publication/320229552_Impact_des_changements_climatiques_sur_la_distribution_de_deux_especes_ligneuses_fourrageres_Khaya_senegalensis_et_Afzelia_africana_dans_le_bassin_versant_de_la_Sota_Benin

Zerbo, P., Millogo Rasolodimby, J., Nacoulma Ouedraogo, O., & Van Damme, P. (2011). Plantes médicinales et pratiques médicales au Burkina Faso: Cas des *Sanan*. *Bois & Forets des Tropiques, 307,* 41-53. https://doi.org/10.19182/bft2011.307.a20481