Modeling Earth Systems and Environment
https://doi.org/10.1007/s40808-022-01416-4

ORIGINAL ARTICLE

Habitat suitability modeling for the conservation and cultivation of the multipurpose fruit tree, *Balanites aegyptiaca* L., in the Republic of Chad, Sahel

A. A. Chérif[1,2] · A. I. Sodé[3] · J. S. H. Houndonougbo[2,3] · R. Idohou[3,4] · A. B. Fandohan[5] · R. Glèlè Kakaï[3] · A. E. Assogbadjo[2,3]

Received: 3 October 2021 / Accepted: 28 March 2022

Abstract

Balanites aegyptiaca, a key agroforestry species, is being overexploited in the Sahel due to increasing market demand for its derived products. The present study aims to model the potential current distribution of *B. aegyptiaca* and to assess the potential impact of the future climate (at 2055 and 2085 time horizons) on the species distribution in Chad to identify suitable areas for its further domestication. The principle of maximum entropy (MaxEnt) was used. Species occurrence data combined with bioclimatic data from the AFRICLIM database resulted in ten reduced general circulation models (GCMs) using five regional climate models (RCMs) under the RCP8.5 scenario. The results showed that the rainiest month (BIO13) and the number of dry months (dm) contributed the most to the models' prediction. GCM and RCM models predicted a slight decrease (22.8%) by 2055 and a significant increase (92%) by 2085 in the extent of suitable areas for *B. aegyptiaca* cultivation. Thereafter, a slight decrease (27.8%) by 2055 and a relatively large extension (56.40%) by 2085 in the extent of suitable areas for its conservation through protected areas were noted. Our findings revealed the conversion of parts of unsuitable areas for the species cultivation and conservation into very suitable areas by 2085. This suggests that further domestication of *B. aegyptiaca* will be possible over a large part of Chad (46%) in the context of changing climates. These findings should support policy-makers in making reliable decisions toward sustainable management of desert date in the Sahel.

Keywords *Balanites aegyptiaca* · Maxent · Climate change · Suitable habitats · Sustainable conservation · Sahel

Introduction

In sub-Saharan Africa, natural ecosystems have been threatened over recent decades by population growth, the increase in livestock and climate change (Bouko et al. 2016). Thus, climate change is identified as disrupting the local biodiversity and protected areas, which are undergoing variations in the species distribution, decrease in population size and even local extinctions (Hallegatte 2016; Bush et al. 2020). The increase in temperature and the irregularity of precipitation could lead to significant variations in species diversity and ecosystems functioning (Belle et al. 2016; IPCC 2018).

Indeed, a study on modeling the distribution of 5197 plant species based on the Hadley Center's climate projection predicted a reduction in the size of their most probable climatic ranges for more than 80% of the plant species in Africa and their migration to higher altitudes (IPCC 2013, 2018). Moreover, Boko (2007) estimated that approximately 42% of the species could be threatened with local extirpation

✉ J. S. H. Houndonougbo
julianohoundonougbo@gmail.com

1 Faculté Des Sciences Agronomiques, Université de Sarh, BP 105, Sarh, Tchad

2 Laboratoire d'Ecologie Appliquée, Faculté Des Sciences Agronomiques, Université d'Abomey-Calavi, 01 BP 526, Cotonou, République du Bénin

3 Laboratoire de Biomathématiques et d'Estimations Forestières (LABEF), Faculté Des Sciences Agronomiques, Université d'Abomey-Calavi, 04 BP 1525, Cotonou, République du Bénin

4 Ecole de Gestion et de Production Végétale Et Semencière (EGPVS), Université Nationale d'Agriculture, BP 43, Kétou, République du Bénin

5 Ecole de Foresterie Tropicale, Université Nationale d'Agriculture, BP: 43, Kétou, République du Bénin

Published online: 31 May 2022

due to the regression of the majority (i.e., 81–97%) of their suitable habitats by the 2085 time horizon in Africa. These trends suggest that the climate change could have an irreversible impact on the tropical biodiversity and in turn on its geographic distribution in Africa and especially in Chad.

Balanites aegyptiaca L. or desert date is a multipurpose tree species with high socioeconomic potential in both the semi-arid and arid regions of tropical Africa, the Middle East, and India (Chothani and Vaghasiya 2011; Elfeel and Warrag 2011; Okia et al. 2011). The species is used for both human (Elfeel 2010; Obidah et al. 2009) and animal food (Lohlum et al. 2012; Kaboré-Zoungrana et al. 2008), in pharmacopeia (Khatoon et al. 2013), in medicine (Dubey et al. 2011; Koko et al. 2017), in cosmetics (Sharma et al. 2019) and as biofuel (Kabo et al. 2020; Novidzro et al. 2019). However, *B. aegyptiaca* is now threatened through its natural habitats due to increasing anthropogenic pressures and potential impacts of climate change (Arbonnier 2009; Idrissa et al. 2018). Therefore, in the absence of an effective conservation measure under the current conditions (i.e., rise in temperature and decrease in precipitation), the remaining populations of *B. aegyptiaca* are expected to decline rapidly over the coming decades (Boulanodji 2014; Ngaryam 2016).

In Chad, despite the recognized importance of the species, studies were carried out only on ethnobotanical knowledge of *B. aegyptiaca* (Hounsou-Dindin et al. 2022; Abdoulaye et al. 2017; Creac'h 1940) and the biochemical aspects of its seeds (Makalao et al. 2015). Meanwhile, little is documented about the distributional ecology of the species along the climatic gradient throughout its native range countrywide. Moreover, no studies have already documented the potential impacts of climate change on the spatial distribution of *B. aegyptiaca* across its native habitats in Chad. Therefore, such studies become timely in a perspective to identify the suitable habitats for the sustainable management of *B. aegyptiaca* in the Sahel under changing climates.

As previously demonstrated by several scholars (Assogba et al. 2022; Guisan et al. 2013, 2017), it is crucial to clearly determine both the current and future potential distribution areas of target species in addition to identifying the factors shaping their geographic distribution. Thus, the species distribution modeling (SDM) based on the principle of maximum entropy "MaxEnt", and known as a key predictive tool, is critically used to forecast the dynamics of species' geographic range in the context of global change (Padalia et al. 2014; IPCC 2018). Hence, using such a modeling approach could give insights into guiding the detection of the suitable habitats for the cultivation and conservation of *B. aegyptiaca* under the future climates (Phillips et al. 2006; Warren and Seifert 2011).

The overall objective of this study is to provide decision-makers with useful tools that allow quick detection of suitable habitats for the cultivation and sustainable conservation of *B. aegyptiaca* in Chad. Specifically, the study is structured into the following research questions: Does the change climate observed in Chad influence the potential distributions of suitable areas for the cultivation and conservation of *B. aegyptiaca*? What are the potential impacts of climate change on the extent of these areas and their geographical distribution in terms of climate projections by 2055 and 2085 time horizons in Chad? How effective is the current protected area network in conserving *B. aegyptiaca* populations in Chad?

Materials and methods

Study area and model species

Study area

This study was conducted in the 23 provinces of the Republic of Chad, a country located in the heart of Africa between 8° and 23° north latitude and between 14° and 24° east longitude (Frenken 2005). The country covers an area of 1,284,000 km^2 and is largely covered by mountain ranges and vast sedimentary plains. The climate of the Republic of Chad is of the tropical unimodal type. The country is divided into six climatic zones, including (i) the Sahelian zone (250 and 500 mm/year and 18–43° C), which is the area of shrub savannas and steppes; (ii) the Sahel–Sudanian zone (400 and 600 mm/year and 15–40 °C) constituted of shrub and thorny steppes; (iii) the Sudanian zone (700–1000 mm/year and 15–34 °C) constituted of tree-lined savannahs; (iv) the Saharan zone (0–200 mm/year and 10–50 °C) characterized by meadows and oases; (v) the Sahara–Sahelian zone (200–400 mm/year 20–45 °C) constituted of the area of mainly thorny shrub steppes; and (vi) the Guinean zone (900–1200 mm/year 15–32 °C) characterized by the wooded savannah and clear forest (Frenken 2005).

Model species

The desert date or Egypt myrobolan (*Balanites aegyptiaca*) is a very thorny tree, of up to 8 m tall belonging to the Zygophyllaceae family. The species is widespread in both the Sahelian steppes and Sudano-Sahelian savannas of Africa, and found on different soil types (Chothani and Vaghasiya 2011; Gardette and Baba 2013). The species is valued for its fruits, flowers, wood, leaves, roots, bark, and seeds (Fig. 1) owing to its traditional uses (i.e., in food, medicinal, cultural and magico-religious practices) (Creac'h 1940; Abdoulaye et al. 2017). For example, its fruits are very appreciated among rural communities owing to the rich potential of its seeds in oil which is not only used for human consumption, but also in pharmacopeia in Uganda (Okia

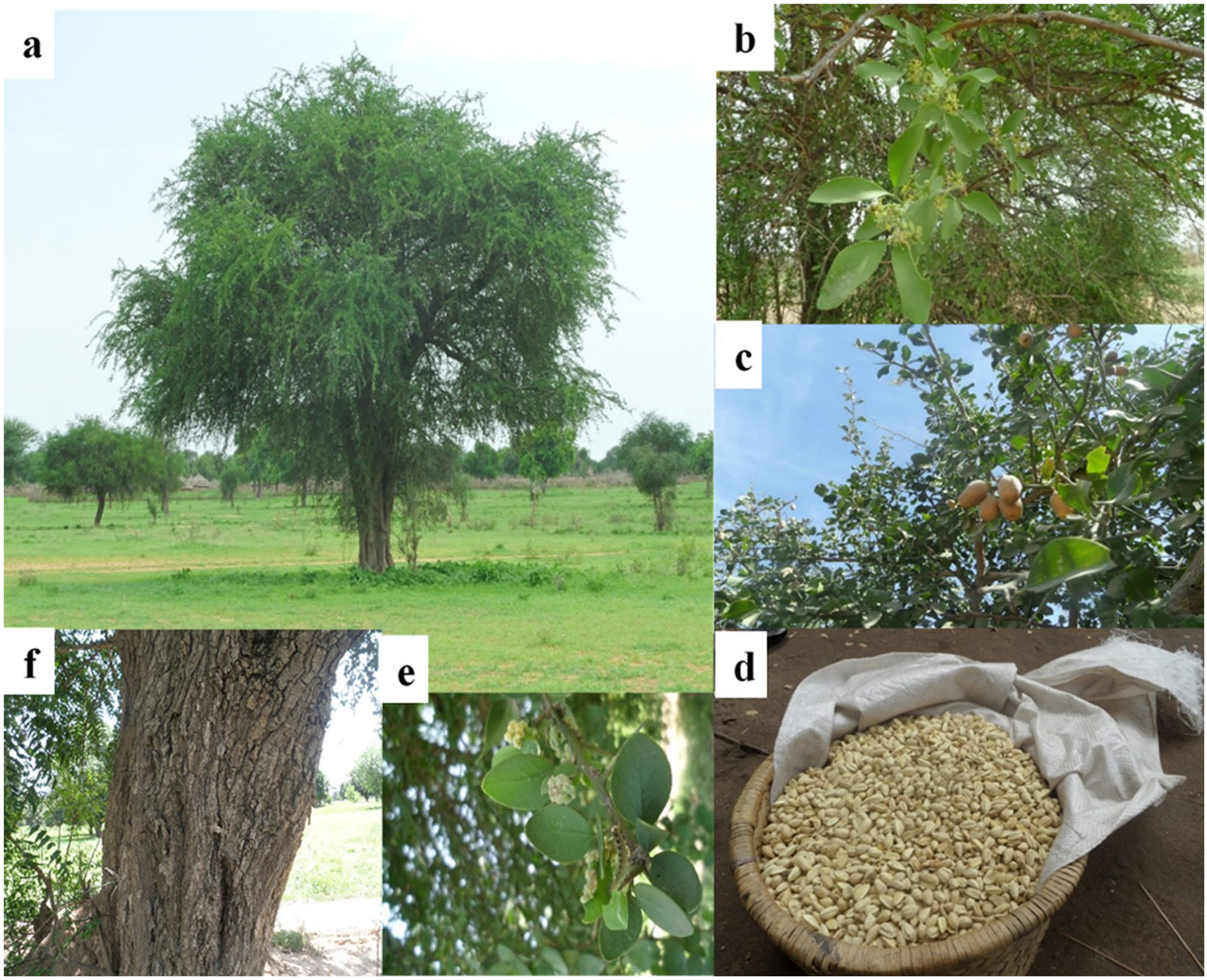

Fig. 1 Organs of *Balanites aegyptiaca* (**a**: tree in a fallow; **b**: flowers and leaves; **c**: fruits; **d**: kernels; **e**: leaves, inflorescences and thorns; **f**: bark)

et al. 2013), Senegal (Tayeau et al. 1955), and Sudan (Elfeel 2010). Besides, *B. aegyptiaca* is used in the pharmaceutical industry (Montasser et al. 2017) and as a biofuel (Novidzro et al. 2019).

Data collection

Occurrence records (longitude and latitude) of *B. aegyptiaca* were collected through fieldwork in all vegetation types harboring the species (protected areas, agroforestry parks, and natural formations). Additional data were obtained from online resources (Global Biodiversity Information Facility; www.gbif.org), to cover as much as possible the distribution range of the species. Data collected before 1950 were discarded. Indeed, a total of 438 occurrences (128 from fieldwork and 310 from GBIF) were collected and finally 265 (124 from field and 141 from GBIF) were kept for the modeling (Fig. 2), after eliminating exact-duplicated records using Environmental Niche Modeling Tools (Warren et al. 2010). The environmental data were compiled from climate variables extracted from the AFRICLIM 3.0 database (Platts et al. 2015) for the present and future conditions with a spatial resolution of 2.5 min. Soil layers were obtained from the FAO Harmonized Global Soil Database (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012). The current data was constituted of 21 bioclimatic variables derived from interpolation from meteorological stations of mean temperature and monthly maximum and minimum precipitation for the period 1970–2000. We projected the distribution of *B. aegyptiaca* through 2055 and 2085 under the most pessimistic RCP 8.5 scenario. Since Africlim ensemble models (https://www.york.ac.uk/environment/research/kite/resources/) provide the high-resolution ensemble climate projections for Africa, we used the version 3.0 of this database, spanning ten general

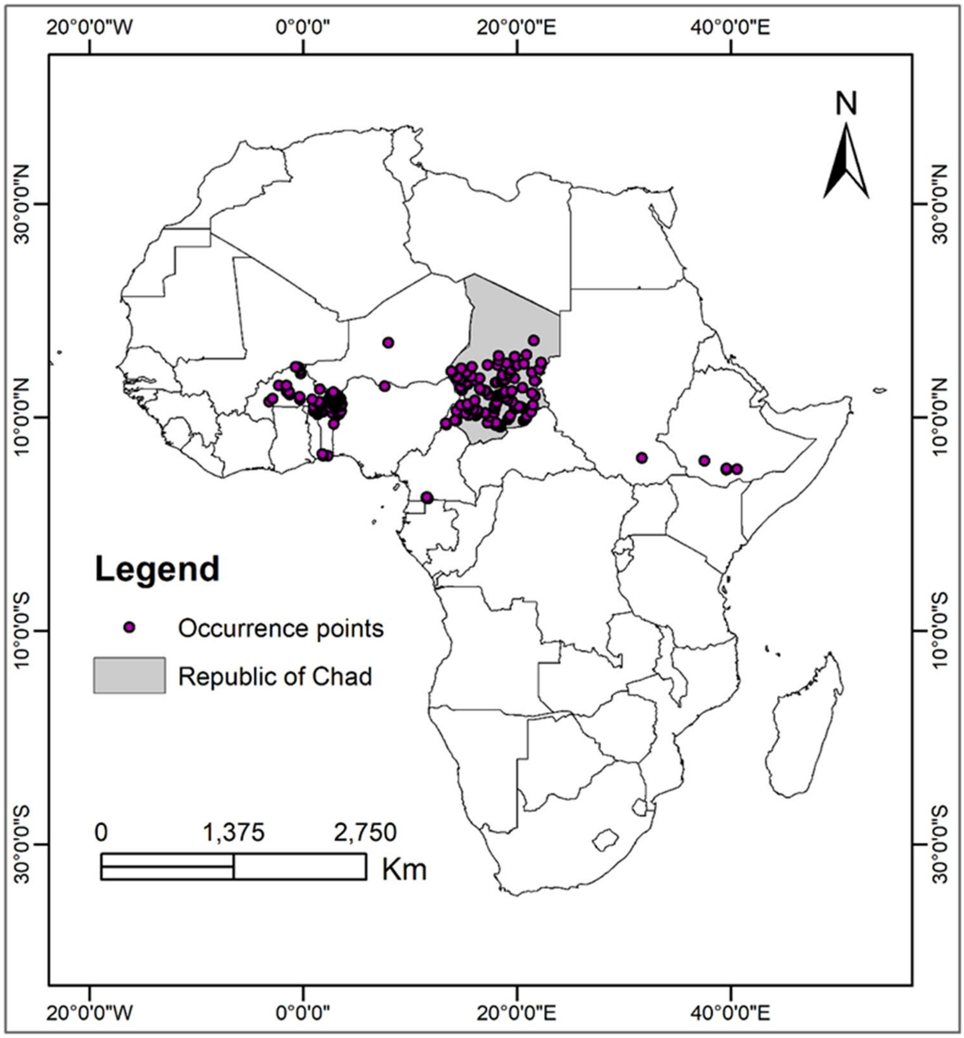

Fig. 2 Location of the occurrence records of the desert date used for modeling

circulation models (GCM: CCCma-CanESM2, MPI-M-MPI-ESM-LR, CNRM-CERFACS-CNRM-CM5, ICHEC-EC-EARTH, NOAA-GFDL-GFDL-ESM2M, CSIRO-QCCCE-CSIRO-Mk3-6–0, IPSL- IPSL-CM5A-MR, MIROC-MIROC5, MOHC-HadGEM2-ES, NCC-NorESM1-M). They were reduced using five regional climate models (RCM: CCCma-CanRCM4_r2, CLMcom-CCLM4-8-17_v1 (4 GCMs), DMI-HIRHAM5_v2, KNMI-RACMO22T_v1 (2 GCMs), SMHI-RCA4_v1 (10 GCMs) and four contemporary baselines under the most pessimistic RCP8.5 scenario (Platts et al. 2015). As previously described by Platts et al. (2015), these models are suitable for the best ecological applications in Africa.

Modeling techniques

Maxent version 3.4.1 (Phillips et al. 2017) was used to develop the species distribution models for *B. aegyptiaca*. In fact, Maxent is one of the most powerful techniques that uses presence-only data to estimate the probability of a species occurrence in a given location by relating the presence data to the corresponding environmental layers (Phillips et al. 2006). It helps to create a global map of potential habitats for a species and a global map of the future distribution of suitable habitats. A recent development using the software has shown that the same estimates of the effects of environmental variables can be obtained with maximum likelihood model from an inhomogeneous Poisson process (Fithian and Hastie 2013), which provides an estimate of the relative abundances of species. This relative abundance can then be converted to the probability of presence using "cloglog" (Phillips et al. 2017):

$$\text{Probability of presence} = 1 - \exp(-\exp(H)p_{\lambda}(z)),$$

where $H = -E_{\lambda}[\ln(p_{\lambda})]$ is the entropy of the relative distribution probability which derives from the intensity function at each point as follows (Fithian and Hastie 2013):

$$p_\lambda(z) = \lambda(z) / \int_D \lambda(z) dz,$$

$\lambda(z) = \exp(\alpha + \beta' \mathbf{x}(z))$ is the intensity function at each point z.

Model calibration and validation

Climatic variables used for training the models were selected using the ENMtools program (Warren et al. 2010) and based on Pearson correlation coefficients (ρ) generated by this tool. Thus, the least correlated variables ($|\rho| < 0.80$) were afterward selected (Elith et al. 2010). A jackknife test was further performed on the selected variables to determine which ones contributed the most to the models. Furthermore, a fivefold cross-validation method was implemented by dividing the occurrence data into five parts among which four parts were used for training the model and the other part was used as a test sample. The default "cloglog" format was maintained for the model's outputs. We created a bias file for selecting background points using a buffer distance of 100 km around occurrence records with SDMtoolbox (Brown 2014) in ArcMap version 10.1. Models' performance was evaluated using the area under the curve (AUC) and true skill statistic (TSS). According to Swets (1988), AUC gives the probability that the predictive power of a model is better than a random prediction (AUC = 0.5). Thus, a model with an AUC value close to 1 (AUC ≥ 0.75) is considered to have a good fit. In addition, the TSS metric measures the model's ability to detect true presences (sensitivity) and real absences (specificity) that is defined as the sensitivity plus specificity—1 (Allouche et al. 2006). In general, a TSS > 0.5 indicates a good predictive power of the models.

Mapping and spatial analysis

Modeling outputs were imported into ArcMap version 10.1 to map both the current and future geographic distributions of suitable habitats for *B. aegyptiaca* according to each of the projection horizon, using the probabilities of species' occurrence varying between 0 and 1. The habitat suitability maps were converted into binary maps by using the "10 percentile training presence cloglog" as threshold (Liu et al. 2005). For a probability value lower than this threshold, the habitat was considered unsuitable for the species, while for a probability value above this threshold the habitat was said to be suitable (Liu et al. 2005). Habitat proportions under present-day and future conditions were estimated to assess unsuitable and suitable areas for the species according to different projection horizons considered. To assess the present-day and future effectiveness of Chad's protected area network in conserving *B. aegyptiaca*, a gap analysis of suitable habitats for the species in protected areas was performed by overlaying each map from the modeling with the map of the protected area network in Chad.

Results

Correlation analysis and the jackknife test identified six less correlated variables ($|\rho| < 0.80$) as contributing the most to the models. Overall, soil layers (80.6%), the rainfall wettest month (Bio13) (7%) and the number of dry months (dm) (5.4%) were the main environmental variables contributing to the distribution of *B. aegyptiaca* in Chad (Table 1, Fig. 3).

The mean value of TSS is 0.74 with a standard deviation of 0.07, while the AUC value is 0.758 with a standard deviation of 0.007. These metric values demonstrate the very good performance of the models in predicting the suitable areas for the cultivation and conservation of *B. aegyptiaca*. The *cloglog* probability threshold used to define the habitat suitability levels was 0.331.

This figure shows on the y-axis the environmental variables that contributed to the model calibration. The band in front of each variable indicates the model's performance (training gain) when the variable is used alone for model training (blue) or omitted from model (green). The red band shows the training gain of the model with all variables.

Modeling outputs showed that approximately 24% of the Chad territory (Table 2 and Fig. 4A) is currently suitable to host populations of *B. aegyptiaca*. These habitats were located in almost all provinces of Chad, apart from the Guinean and Saharan zones. The probability of the species' occurrence is extremely high in the central part of the country, in the semi-arid, Sahelo-Sudanian and Sahelian zones, more precisely in the provinces of Hadjer-Lamis, Chari-Baguirmi, Guera and Batha, as well as in the southern and south-eastern part of Chad in the sub-humid Sudanian zone in the provinces of Salamat and Moyen Chari. On the other hand, unsuitable areas for the species distribution were located in the arid and Guinean zones (Fig. 4A).

The GCM and RCM models under the RCP 8.5 scenario following the two time horizons (2055 and 2085) showed

Table 1 Environmental variables and their contribution to the model

Variable code	Variable meaning	Contribution (%)
Soil	Soil	80.6
bio13	Rainfall wettest month	7.0
Dm	Number of dry months	5.4
bio14	Rainfall driest month	5.4
bio4	Temperature seasonality	1.0
Pet	Potential evapotranspiration	0.7

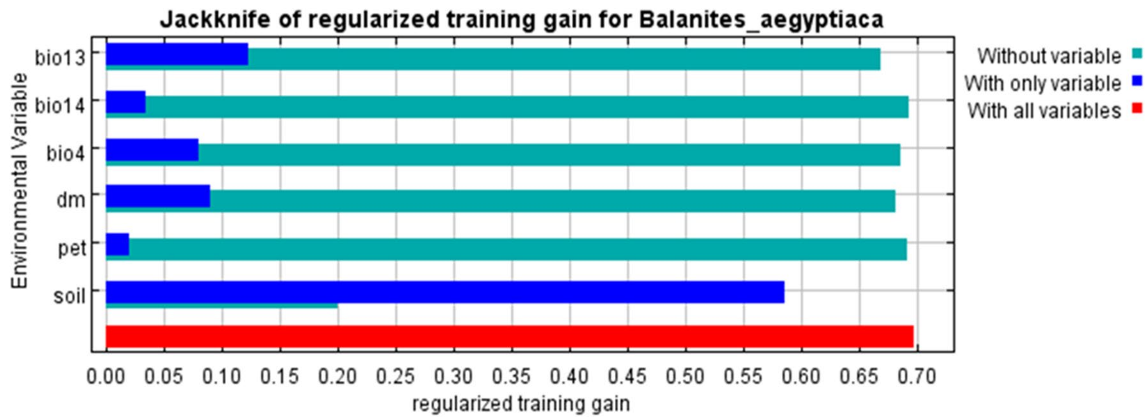

Fig. 3 The jackknife test for evaluating the relative importance of environmental variables for *B. aegyptiaca* in Chad

Table 2 Dynamics of the suitable areas for the cultivation of *B. aegyptiaca* in Chad

Models	High		Low		Total (km^2)
	Area (km^2)	Trend (%)	Trend (%)	Area (km^2)	
Present	309,315.763		101,4646.989		132,3962.752
RCP 8.5 (2055)	238,784.794	− 22.802	108,5177.958	+6.951	132,3962.752
RCP 8.5 (2085)	593,506.483	+91.877	73,0456.269	− 28.009	132,3962.752

The sign (–) indicates a loss in suitable habitat and the sign (+) indicates a gain

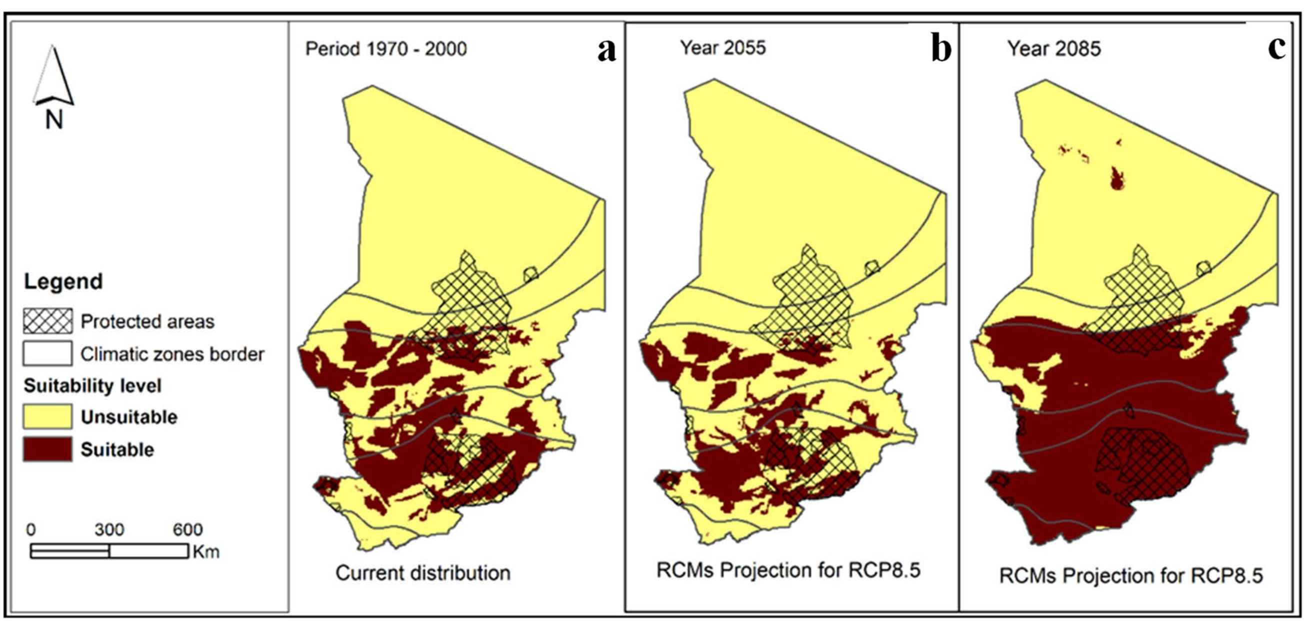

Fig. 4 Current projection (**A**) and future (**B**, **C**) of the distribution areas of *B. aegyptiaca* according to the RCP 8.5 scenario in Chad

significant changes in the present-day and future distribution of *B. aegyptiaca*. Indeed, by the 2055 time horizon, the Ensemble RCMs model projects a decrease of 22.8% of the areas currently a suitable habitat for the species (Table 2 and Fig. 4B), and therefore only 18% of the Chad territory will remain suitable by 2055. This scenario also predicts an increase of about 7% in unsuitable habitats in 2055. This could be due to the conversion of some currently suitable habitats into unsuitable habitats. On the other hand, according to the projections of the same scenario by 2085, the model predicts 46% of Chad territory to be suitable for the cultivation of the *B. aegyptiaca*, i.e., an increase of 92% in the currently suitable habitats (Table 2 and Fig. 4C). This increase results in the conversion of 28% of the currently unsuitable habitats into suitable habitats. Models therefore project a loss and gain in habitat suitability for the cultivation of *B. aegyptiaca* by 2055 and 2085, respectively.

Protected areas (PA) cover 169,911 km^2, i.e., 10.1% of national territory of the country. The current extent of protected areas suitable for the conservation of *B. aegyptiaca* is about 66,052 km^2 (38.87% of the extent of the national PA network of Chad; Table 3; Fig. 4A). Protected areas in the center and southeast of the country were projected to conserve the species better than those located in the northern region (arid zone). The suitable PA included Siniaka Minia and Barh Salamat wildlife reserves, the Aouk and Melfi hunting zones, and the Zakouma National Park.

Using the GCM and RCM models under the RCP 8.5 scenario, we then projected a decrease in 27.80% of the present-day suitable habitats for the conservation of *B. aegyptiaca* in 2055. In particular, this will result in an increase of 17.66% of unsuitable habitats for the species' conservation (Table 3, Fig. 4B). On the other hand, models project an increase of about 56.40% of the currently suitable habitats for the conservation of *B. aegyptiaca* within the PA network in Chad by 2085, and this extension results in the conversion of 35.86% of unsuitable habitats into suitable habitats (Table 3, Fig. 4C). In addition, the decrease in suitable habitats for the conservation of the species by 2055 will especially occur in the Ouadi Rimé–Ouadi Achim wildlife reserve in the northern part of Chad, in the Siniaka-Mina wildlife reserve in the center and in Zakouma National Park in the Sudan–Sahelian zone (Fig. 4B). Moreover, the significant extension of the currently suitable habitats for the conservation of *B. aegyptiaca* in the protected areas of Chad in 2085 will especially occur in the wildlife reserves of Aboutelfane, Siniaka-Minia, Binder-Léré, and in southern part of Ouadi Rimé–Ouadi Achim, and in the Zakouma, Manda and Sena Oura National Parks (Fig. 4C).

Discussion

Modeling and reliability of the model

Ecological niche modeling is used by scientists globally and regionally to predict and assess the impact of climate change on current and future species distributions (Beaumont et al. 2005; Van Zonneveld et al. 2009). This modeling approach, used to characterize suitable habitats for *B. aegyptiaca*, has been implemented by several scholars in targeting the geographic distribution of wild fruit tree species from West Africa (Assogba et al. 2022; Dimobe et al. 2020; Imorou 2020; Habou et al. 2021) and North Africa (Moukrim et al. 2018; Rifai et al. 2020).

Results showed that the mean AUC value was 0.75. This indicates the good quality of the models (GCM and RCM) in predicting the geographical distribution of suitable areas for cultivation and conservation of *B. aegyptiaca*. It also demonstrates the good quality of the models, often cited as a powerful predictive tool in mapping the current and future geographic distribution of a target species (Van Zonneveld et al. 2009; Nakao et al. 2011). Nevertheless, the Maxent approach has limitations such as population dynamics, demographic parameters, and difficulties in regulating ecological interactions (Elith et al. 2006; Schwartz 2012). It is therefore worth conducting further geographic distribution studies to determine the relative contribution of each of these parameters to the distribution ecology of the desert date in Africa. In addition, precipitation and temperature were the critical environmental factors underlying the local persistence of the species across its native habitats. These trends are consistent with previous studies that have already noted the adverse effects of both temperature increase and rainfall irregularity on the conservation of native fruit tree species in their natural habitats in the Sahel (Alhassane et al. 2013; Ly et al. 2013; Sarr et al. 2015). Furthermore, our results showed an expansion of suitable habitats for the species by 2085, suggesting that the possible cultivation areas of *B. aegyptiaca* will be increased due to climate changes in this time horizon. As a result, the map of the potential range of *B. aegyptiaca* (Fig. 4) could be used to provide decision makers and forest managers with a tool to set sustainable

Table 3 Dynamics of suitable areas for the conservation *B. aegyptiaca* in protected areas in Chad

Models	High		Low		Total (km^2)
	Area (km^2)	Trend (%)	Area (km^2)	Trend (%)	
Present	66,052.813		103,858.790		169,911.603
RCP 8.5 (2055)	47,709.594	– 27.771	122,202.010	+ 17,662	169,911.603
RCP 8.5 (2085)	103,299.021	56.389	66,612.582	– 35,862	169,911.603

The sign (–) indicates a loss in suitable habitat and the sign (+) indicates a gain conservation and management strategies for desert date in a context of global change.

Identification of suitable areas for the culture and conservation of *B. aegyptiaca*

The bioclimatic projections of the GCM and RCM models under the RCP 8.5 scenario for the cultivation of *B. aegyptiaca* are more expected in Chad up to the 2085 time horizon compared to 2055 (Table 2; Fig B-C). Besides, the observed differences in suitable areas for *B. aegyptiaca* countrywide support previous results showing the potential impact of climate change on the dynamics of the geographic range of multipurpose tree species (Wouyou et al. 2022; Assogba et al. 2022; Vale et al. 2014; Variawa 2017; Tshwene-Mauchaza and Aguirre-Gutiérrez 2019; Habou et al. 2021). Thus, the bioclimatic projections of the GCM and RCM models under the RCP 8.5 scenario seem to confirm the hypothesis that climate change could alter the range of species as suggested in previous studies (Gbètoho et al. 2017; Djotan et al. 2018b; Asseh et al. 2019).

The GCM and RCM models under the RCP 8.5 scenario predict a slight reduction in current suitable habitats for cultivation and production of *B. aegyptiaca* in favor of suitable habitats by 2055 in Chad. These results confirm those reported by Christensen et al. (2007) on climate change impacts, predicting an increase in temperature and a decrease in precipitation in the Sahel. Therefore, temperature and precipitation will be the climatic factors responsible for the reduction of cultivated areas and the decline in tree species' productivity in Africa, as some studies have pointed out (Alhassane et al. 2013; Ly et al. 2013; Sarr et al. 2015). The future state of the species by 2085 is generally not threatened by the effects of climate change. This could be explained by the adaptability of *B. aegyptiaca* to the potential impacts of climate change. In fact, *B. aegyptiaca* is a desert species with a root system up to 7 m in the soil and can live for 2 years without precipitation (Depierre and Gillet 1991; Bouguerra 1994), which would favor its adaptation to the potential impacts of future climates. The species could then be led to develop other adaptation strategies to climate change.

Moreover, to our knowledge, 38.9% of Chad's current protected area network is suitable for in situ conservation of *B. aegyptiaca*. This trend partly supports prior studies that have demonstrated the critical role of Protected areas (PA) in conserving biological diversity worldwide (Leriche et al. 2010). Overall, this study shows a decrease in suitable habitats in the current network of PA in Chad by 2055 and an expansion thereof by 2085. Such results will thus contribute to decision-making in setting the sound management strategies of desert date. However, in the PA network, *B. aegyptiaca* is not only exposed to the impacts of climate change, but also to vegetation clearing by elephants particularly in Zakouma National Park (Poilecot et al. 2007). Therefore, effective management actions are required for limiting increasing pressures on this overharvested fruit tree species. The suitable habitats for the species under future climatic conditions in the Sahara–Sahelian zone (Ouadi Rimé–Ouadi Achim wildlife reserve) would be along temporary rivers. Protected areas in the Sahelo-Sudanian and Sudanian zones will better ensure the conservation of *B. aegyptiaca* in Chad by 2085 with the expected changing climate. In addition, since some uncertainties remain in the projections of climate models, a genetic study in combination with these models seems to be necessary to select ecotypes suitable for drylands.

Our findings demonstrate the key role of protected areas for in situ conservation of indigenous fruit tree species as suggested by Djotan et al. (2018a) for *Garcinia kola* H., Fandohan et al. (2013) for *Tamarindus indica* L., and Gouwakinnou (2011) for *Sclerocarya birrea* (A Rich.) Hochst in sub-Saharan Africa. The findings are also in line with the results of Mansourian et al. (2009) who examined the role played by the protected areas in the adaptation strategies using examples from the work of the World Wildlife Fund (WWF). Depending on the projection horizon of the GCM and RCM models used in this study, the Sahel zone would be more or less humid in the future (Meehl et al. 2007).

However, we should not overlook some limitations related to our modeling approaches, namely the plasticity of physiological limits, difficulties in accounting for ecological interactions, species dispersal ability, and adaptive responses of dispersal agents (Fandohan et al. 2013; Wisz et al. 2013). Indeed, a number of studies revealed the importance of ecological interactions, dispersal constraints, and demographic parameters in shaping species distributions and their assemblages, even on a global scale (Engler and Guisan 2009; Brotons et al. 2012; Zurell 2017). Furthermore, land use dynamics and its evolutionary trend (lakes, agglomerations, Sahara and croplands) were not taken into account in the models. Despite their limitations, these models provide very important bioclimatic information for making appropriate decision regarding the identification of new potentially suitable areas for the cultivation (Cuni-Sanchez et al. 2010) or conservation of a particular species (Schwartz 2012). Nonetheless, in our study, we found that despite the expected rise in temperature over the millennium for the region we considered (Boko 2007), the range of the species will expand by 2085.

Conclusion

Climate change poses a serious threat to native agroforestry species in Africa. This study made it possible to make predictions about the current and future suitable habitats for the cultivation and conservation of *B. aegyptiaca*. The use of the

Maxent algorithm with the GCM and RCM models under the RCP8.5 scenario with two horizons (2055 and 2085) demonstrated its performance in predicting the ecological niches of desert date. The results of the bioclimatic projections showed us that most environmental conditions in Chad will remain suitable for the cultivation and conservation of *B. aegyptiaca* until 2085, despite the effects of climate change. This study also highlighted the key role that protected areas play in conserving *B. aegyptiaca* under the expected impacts of climate change countrywide. Therefore, considering these findings should guide the elaboration of conservation actions and sustainable management strategies to be implemented by policy makers and conservationists in a perspective of domestication of this overexploited fruit tree species in Chad.

Acknowledgements The authors express their gratitude to all data providers. Idohou R. acknowledges the support from the Rufford Grant (Grant Number 31042-D) which enabled collaboration on the current project.

Authors' contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Chérif AA, Sodé AI, Houndonougbo JSH and Fandohan AB. The first draft of the manuscript was written by Chérif AA and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding This study was partly supported by the Faculty of Agronomic Sciences of the University of Sarh (Chad).

Availability of data and material The datasets generated during and/or analyzed during the present study are available from the authors upon request.

Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

Code availability 'Not applicable' for that section.

Additional declarations Not applicable.

Ethics approval The authors confirm that this work has neither been published in a journal nor under consideration by another journal. All authors attest that they have read the manuscript, approve the validity and legitimacy of the data and its interpretation, and thereafter agree to its submission to Modeling Earth Systems and Environment for possible consideration.

Consent to participate Not applicable.

Consent for publication Not applicable.

References

Abdoulaye B, Bechir AB, Mapongmetsem PM (2017) Utilités socioéconomiques et culturelles du *Balanites aegyptiaca* (L.) Del. (Famille Zygophyllaceae) chez les populations locales de la Région du Ouaddaï au Tchad. J Appl Biosci 111:10854–10866. https://doi.org/10.4314/jab.v111i1.2

Alhassane A, Salack S, Ly M et al (2013) Évolution des risques agroclimatiques associés aux tendances récentes du régime pluviométrique en Afrique de l'Ouest soudano-sahélienne. Science Et Changements Planétaires/ Sécheresse 24:282–293. https://doi.org/10.1684/sec.2013.0400

Allouche O, Tsoar A, Kadmon R (2006) Assessing the accuracy of species distribution models: prevalence, kappa and the true skill statistic (TSS). J Appl Ecol 43:1223–1232. https://doi.org/10.1111/j.1365-2664.2006.012014.x

Arbonnier M (2009) Arbres, arbustes et lianes des zones sèches d'Afrique de l'Ouest. Editions Quae

Asseh EE, Ake-Assi E, Koffi KJ (2019) Diversité biologique et influence des changements climatiques sur la distribution géographique de quelques espèces d'Acanthaceae en Côte d'Ivoire. Int J Biol Chem Sci 13:676–692. https://doi.org/10.4314/ijbcs.v13i2.9

Assogba D, Idohou R, Chirwa P, Assogbadjo AE (2022) On opportunities and challenges to conserve the African baobab under present and future climates in Benin (West Africa). J Arid Environ 198:104692. https://doi.org/10.1016/j.jaridenv.2021.104692

Beaumont LJ, Hughes L, Poulsen M (2005) Predicting species distributions: use of climatic parameters in BIOCLIM and its impact on predictions of species' current and future distributions. Ecol Model 186:251–270. https://doi.org/10.1016/j.ecolmodel.2005.01.030

Belle EMS, Burgess ND, Misrachi M, et al. (2016) Impacts du changement climatique sur la biodiversité et les aires protégées en Afrique de l'Ouest, Résumé des résultats du projet PARCC, Aires protégées résilientes au changement climatique en Afrique de l'Ouest. UNEP-WCMC, Cambridge, UK

Boko M (2007) Climate change: Impacts, vulnerabilities, and adaptation in developing countries. Climate Change 2007: Impacts, Adaptation and Vulnerability The Working Group II Contribution to the IPCC Fourth Assessment Report 433–467

Bouguerra A (1994) Le balanites, l'arbre intelligent du Sahel, Courrier International, 1994/09/22. accès en ligne 6/06/2020

Bouko BS, Dossou PJ, Amadou B, Sinsin B (2016) Exploitation des ressour ces biologiques et dynamique de la foret classee de la Mekrou au Bénin. Eur Sci J. https://doi.org/10.19044/esj.2016.v12n36p228

Boulanodji E (2014) Analyse et compréhension des liens existant entre le changement climatique, les aires protégées et les communautés au Tchad. La Tribune 30

Brotons L, Cáceres MD, Fall A, Fortin M-J (2012) Modeling bird species distribution change in fire prone Mediterranean landscapes: incorporating species dispersal and landscape dynamics. Ecography 35:458–467. https://doi.org/10.1111/j.1600-0587.2011.06878.x

Brown JL (2014) SDM toolbox: a python-based GIS toolkit for landscape genetic, biogeographic and species distribution model analyses. Methods Ecol Evol 5:694–700. https://doi.org/10.1111/2041-210X.12200

Bush ER, Whytock RC, Bourgeois S et al (2020) Long-term collapse in fruit availability threatens Central African forest megafauna. Science 370:1219–1222. https://doi.org/10.1126/science.abc7791

Chothani DL, Vaghasiya HU (2011) A review on *Balanites aegyptiaca* Del (desert date): phytochemical constituents, traditional uses, and pharmacological activity. Pharmacogn Rev 5:55. https://doi.org/10.4103/0973-7847.79100

Christensen JH, Hewitson B, Busuioc A, et al. (2007) Regional climate projections. In: Climate Change, 2007: The Physical Science Basis. Contribution of Working group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, University Press, Cambridge, Chapter 11. pp 847–940

Creac'h P, (1940) Le *Balanites ægyptiaca*. Ses multiples applications au Tchad. Journal D'agriculture Traditionnelle Et De Botanique Appliquée 20:578–593. https://doi.org/10.3406/jatba.1940.1576
Cuni-Sanchez A, Osborne PE, Haq N (2010) Identifying the global potential for baobab tree cultivation using ecological niche modelling. Agrofor Syst 80:191–201. https://doi.org/10.1007/s10457-010-9282-2
Depierre D, Gillet H (1991) L'arbre désertique source de vie. Bois & Forêts des Tropiques 227:43–50. https://doi.org/10.19182/bft1991.227.a19714
Dimobe K, Ouédraogo A, Ouédraogo K, et al. (2020) Climate change reduces the distribution area of the shea tree (*Vitellaria paradoxa* CF Gaertn.) in Burkina Faso. J Arid Environ 181:104237. https://doi.org/10.1016/j.jaridenv.2020.104237
Djotan AKG, Aoudji AKN, Codjia SAF et al (2018a) How far can climate changes help to conserve and restore *Garcinia kola* Heckel, an extinct species in the wild in Benin (West Africa). Int J Biodivers Conserv 10:203–213. https://doi.org/10.5897/IJBC2018.1180
Djotan AKG, Aoudji AKN, Tessi DRY et al (2018b) Vulnerability of *Khaya senegalensis* Desr & Juss to climate change and to the invasion of *Hypsipyla robusta* Moore in Benin (West Africa). Int J Biol Chem Sci 12:24–42. https://doi.org/10.4314/ijbcs.v12i1.3
Dubey PK, Yogi M, Bharadwaj A et al (2011) *Balanites aegyptiaca* (L.) Del., a semi-arid forest tree: a review. Acad J Plant Sci 4:12–18
Elfeel AA (2010) Variability in *Balanites aegyptiaca* var. *aegyptiaca* seed kernel oil, protein and minerals contents between and within locations. Agric Biol J N Am 1:170–174
Elfeel AA, Warrag EI (2011) Uses and conservation status of *Balanites aegyptiaca* (L.) Del. (Hegleig Tree) in Sudan: Local people perspective. Asian J Agric Sci 3:286–290
Elith J, Graham HC, Anderson PR et al (2006) Novel methods improve prediction of species' distributions from occurrence data. Ecography 29:129–151. https://doi.org/10.1111/j.2006.0906-7590.04596.x
Elith J, Kearney M, Phillips S (2010) The art of modelling range-shifting species. Methods Ecol Evol 1:330–342. https://doi.org/10.1111/j.2041-210X.2010.00036.x
Engler R, Guisan A (2009) MigClim: Predicting plant distribution and dispersal in a changing climate. Divers Distrib 15:590–601. https://doi.org/10.1111/j.1472-4642.2009.00566.x
Fandohan B, Gouwakinnou GN, Fonton NH et al. (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. BASE. https://popups.uliege.be/1780-4507/index.php?id=10186
FAO, IIASA, ISRIC, ISSCAS, JRC, 2012. Harmonized world soil database (version 1.2). Food and Agriculture Organization of the United Nations, International Institute for Applied Systems Analysis. ISRIC — World Soil Information, Institute of Soil Science — Chinese Academy of Sciences, Joint Research Centre of the European Commission, Laxenburg
Fithian W, Hastie T (2013) Finite-sample equivalence in statistical models for presence-only data. Ann Appl Stat 7:1917–1939. https://doi.org/10.1214/13-AOAS667
Frenken K (2005) Irrigation En Afrique En Chiffre Enquete Aquastat 2005. Food & Agriculture Organization. http://www.fao.org
Gardette J-L, Baba M (2013) FTIR and DSC studies of the thermal and photochemical stability of *Balanites aegyptiaca* oil (Toogga oil). Chem Phys Lipid 170:1–7. https://doi.org/10.1016/j.chemphyslip.2013.02.008
Gbètoho AJ, Aoudji AK, Roxburgh L, Ganglo JC (2017) Assessing the suitability of pioneer species for secondary forest restoration in Benin in the context of global climate change. Bois & Forêts des Tropiques 332:43–55. https://doi.org/10.19182/bft2017.332.a31332
Gouwakinnou NG (2011) Population Ecology, Uses and Conservation of *Sclerocarya birrea* (A. Rich) Hocchst. (Anacardiaceae) in Benin, West Africa. PhD Thesis, Ph. D. Thesis, University of Abomey-Calavi, Abomey-Calavi, 176
Guisan A, Tingley R, Baumgartner JB et al (2013) Predicting species distributions for conservation decisions. Ecol Lett 16:1424–1435. https://doi.org/10.1111/ele.12189
Guisan A, Thuiller W, Zimmermann NE (2017) Habitat suitability and distribution models: with applications in R. Cambridge University Press
Habou KMA, Abdou L, Rabiou H, Mahamane A (2021) Impact des changements climatiques sur la dynamique de l'habitat potentiel de *Balanites aegyptiaca* (L.) Del. au Niger. Revue Marocaine des Sciences Agronomiques et Vétérinaires 9:
Hallegatte S (2016) Shock waves: managing the impacts of climate change on poverty. World Bank Publications
Hounsou-Dindin G, Idohou R, Akakpo AD, Adome N, Adomou AC, Assogbadjo AE, Glèlè Kakaï R (2022) Assessment of wild oil plants diversity and prioritization for valorization in Benin (West Africa): a multivariate approach. Trees Forest People. https://doi.org/10.1016/j.tfp.2022.100210
Idrissa B, Soumana I, Issiaka Y et al (2018) Trend and Structure of Populations of *Balanites aegyptiaca* in Parkland Agroforests in Western Niger. Annu Res Rev Biol. https://doi.org/10.9734/ARRB/2018/38650
Imorou IT (2020) Spatial distribution and ecological niche modelling of *Triplochiton scleroxylon* K. Schum., in the Guineo-Congolese region of Benin (West Africa). Int J Biol Chem Sci 14:32–44. https://doi.org/10.4314/ijbcs.v14i1.4
IPCC (2013) Climate change : the scientific elements. Contribution of Working Group I to the 5th IPCC assessment report. Cambridge University Press, Cambridge
IPCC (2018) Global Warming of 1.5 C. An IPCC Special Report on the impacts of global warming of 1.5 C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Cambridge, UK, Cambridge University Press, 562 p. https://www.ipcc.ch/site/assets/uploads/sites/2/2018/07/SR15_SPM_High_Res.pdf
Kabo KS, Ali T, Ogbesejana AB (2020) Extraction and physico-chemical parameter analysis of desert date (*Balanites aegyptiaca*) oil from Dutsin-Ma. Fudma J Sci 4:409–413
Kaboré-Zoungrana C, Diarra B, Adandedjan C, Savadogo S (2008) Valeur nutritive de *Balanites aegyptiaca* pour l'alimentation des ruminants. Livest Res Rural Dev 20:2008
Khatoon R, Jahan N, Ahmad S, Shahzad A (2013) Antifungal activity of aerial parts as well as in vitro raised calli of the medicinal plant, *Balanites aegyptiaca* Del. Afr J Plant Sci 7:476–481. https://doi.org/10.7324/JAPS.2014.40121
Koko SE, Talib MA, Elfatih F et al (2017) Antioxidant activity and phytochemical screening of *Balanites aegyptiaca* fruits. World J Pharm Med Res 3:47–50
Leriche A, Saatkamp A, Beaume S, Guende G (2010) Distribution et écologie de la Garidelle fausse nigelle. Courrier scientifique du Parc naturel régional du Luberon et de la Réserve de biosphère Luberon-Lure, 60–73
Liu C, Berry PM, Dawson TP, Pearson RG (2005) Selecting thresholds of occurrence in the prediction of species distributions. Ecography 28:385–393. https://doi.org/10.1111/j.0906-7590.2005.03957.x
Lohlum SA, Forcados EG, Agida OG et al (2012) Enhancing the chemical composition of *Balanites aegyptiaca* seeds through ethanol extraction for use as a protein source in feed formulation. Sustain Agric Res 1:251. https://doi.org/10.5539/sar.v1n2p251
Ly M, Traore SB, Alhassane A, Sarr B (2013) Evolution of some observed climate extremes in the West African Sahel. Weather

Clim Extremes 1:19–25. https://doi.org/10.1016/j.wace.2013.07.005
Makalao MM, Savadogo A, Zongo C, Traore AS (2015) Composition nutritionnelle de 10 fruits sauvages consommés dans trois départements du Tchad. Int J Biol Chem Sci 9:2385–2400. https://doi.org/10.4314/ijbcs.v9i5.11
Mansourian S, Belokurov A, Stephenson PJ (2009) Rôle des aires protégées forestières dans l'adaptation aux changements climatiques. Unasylva 60:231–232
Meehl GA, Stocker TF, Collins WD et al (2007) Global climate projections. Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press
Montasser AO, Saleh H, Ahmed-Farid OA et al (2017) Protective effects of *Balanites aegyptiaca* extract, Melatonin and Ursodeoxycholic acid against hepatotoxicity induced by Methotrexate in male rats. Asian Pac J Trop Med 10:557–565. https://doi.org/10.1016/j.apjtm.2017.06.003
Moukrim S, Lahssini S, Alaoui HM et al (2018) Modélisation de la distribution spatiale des espèces endémiques pour leur conservation : cas de l'*Argania spinosa* (L.) Skeels. Revue d'Ecologie, Terre et Vie 73:153–166. HAL Id : hal-03532905, version 1
Nakao K, Matsui T, Horikawa M et al (2011) Assessing the impact of land use and climate change on the evergreen broad-leaved species of *Quercus acuta* in Japan. Plant Ecol 212:229–243. https://doi.org/10.1007/811258-010-9817-7
Ngaryam B (2016) La problématique de gestion durable de la biodiversité au Tchad: impacts des aires protégées sur les zones périphériques-cas des parcs nationaux de Manda et Sena Oura. PhD Thesis, Paris 8
Novidzro KM, Fagla BA, Houndji BS, et al. (2019) *Balanites aegyptiaca* Fruits' Valorization by Liquid Biofuels Production. Am J Chem Eng 7:102–112. https://doi.org/10.11648/j.ajche.20190704.11
Obidah W, Nadro MS, Tiyafo GO, Wurochekke AU (2009) Toxicity of crude *Balanites aegyptiaca* seed oil in rats. J Am Sci 5:13–16
Okia CA, Agea JG, Kimondo JM et al (2011) Use and Management of *Balanites aegyptiaca* in Drylands of Uganda. Res J Biol Sci 6:15–24. https://doi.org/10.3923/rjbsci.2011.15.24
Okia CA, Kwetegyeka J, Okiror P et al (2013) Physico-chemical characteristics and fatty acid profile of desert date kernel oil in Uganda. Afr Crop Sci J 21:723–734
Padalia H, Srivastava V, Kushwaha SPS (2014) Modeling potential invasion range of alien invasive species, *Hyptis suaveolens* (L.) Poit. in India: Comparison of MaxEnt and GARP. Ecol Inf 22:36–43. https://doi.org/10.1016/j.ecoinf.2014.04.002
Phillips SJ, Anderson RP, Schapire RE (2006) Maximum entropy modeling of species geographic distributions. Ecol Model 190:231–259. https://doi.org/10.1016/j.ecolmodel.2005.03.026
Phillips SJ, Anderson RP, Dudík M et al (2017) Opening the black box: An open-source release of Maxent. Ecography 40:887–893. https://doi.org/10.1111/ecog.03049
Platts PJ, Omeny PA, Marchant R (2015) AFRICLIM: high-resolution climate projections for ecological applications in Africa. Afr J Ecol 53:103–108. https://doi.org/10.1111/aje.12180
Poilecot P, Boulanodji É, Taloua N et al. (2007) Parc national de Zakouma: des éléphants et des arbres. Bois & Forêts des Tropiques 291:13–24. https://doi.org/10.19182/bft2007.291.a20353
Rifai N, Moukrim S, Khattabi A, et al (2020) Prédiction de l'aire potentielle de répartition du genévrier thurifère (*Juniperus thurifera*) au Maroc. Revue Marocaine des Sciences Agronomiques et Vétérinaires 8:
Sarr B, Atta S, Ly M, Salack S (2015) Adapting to climate variability and change in smallholder farming communities: A case study from Burkina Faso, Chad and Niger. J Agric Extension Rural Dev 7:16–27. 5897/JAERD14.0595
Schwartz MW (2012) Using niche models with climate projections to inform conservation management decisions. Biol Cons 155:149–156. https://doi.org/10.1016/j.biocon.2012.06.011
Sharma P, Saini MK, Prasad J, Gour VS (2019) Evaluation of robustness of the biosurfactant derived from *Balanites aegyptiaca* (L.) Del. J Surfactants Deterg 22:403–408. https://doi.org/10.1002/jsde.12249
Swets JA (1988) Measuring the accuracy of diagnostic systems. Science 240:1285–1293. https://doi.org/10.1126/science.3287615
Tayeau F, Faure F, Séchet-Sirat J (1955) Étude sur le Soumpe (*Balanites aegyptiaca*). Valeur alimentaire de ses protéines. Journal D'agriculture Traditionnelle Et De Botanique Appliquée 2:40–49
Tshwene-Mauchaza B, Aguirre-Gutiérrez J (2019) Climatic drivers of plant species distributions across spatial grains in Southern Africa tropical forests. Front for Glob Chang. https://doi.org/10.3389/ffgc.2019.00069
Vale CG, Tarroso P, Brito JC (2014) Predicting species distribution at range margins: testing the effects of study area extent, resolution and threshold selection in the Sahara-Sahel transition zone. Divers Distrib 20:20–33. https://doi.org/10.1111/ddi.12115
Van Zonneveld M, Koskela J, Vinceti B, Jarvis A (2009) Impact of climate change on the distribution of tropical pines in Southeast Asia. Unasylva 60:24–28
Variawa T (2017) Modeling the environmental niche of a South African fynbos endemic tree aloe, kumara plicatilis, and predicting impacts of climate change on the species' distribution. PhD Thesis
Warren DL, Seifert SN (2011) Ecological niche modeling in Maxent: the importance of model complexity and the performance of model selection criteria. Ecol Appl 21:335–342. https://doi.org/10.1890/10-1171.1
Warren DL, Glor RE, Turelli M (2010) ENMTools: a toolbox for comparative studies of environmental niche models. Ecography 33:607–611. https://doi.org/10.1111/j.1600-0587.2009.06142
Wisz MS, Pottier J, Kissling WD et al (2013) The role of biotic interactions in shaping distributions and realised assemblages of species: implications for species distribution modelling. Biol Rev 88:15–30. https://doi.org/10.1111/j.1469-185X.2012.00235.x
Wouyou HG, Lokonon BE, Idohou R, Zossou-Akete AG, Assogbadjo AE, Glèlè Kakaï, R (2022). Predicting the potential impacts of climate change on the endangered *Caesalpinia bonduc* (L.) Roxb in Benin (West Africa). Heliyon, e09022
Zurell D (2017) Integrating demography, dispersal and interspecific interactions into bird distribution models. J Avian Biol 48:1505–1516. https://doi.org/10.1111/jav.01225