

Modeling current and future distributions of key fodder grasses under climate change in Senegal using biomod2

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Abstract

Climate change and increasing human pressure are among the primary factors shaping the distribution of ecological niches for forage species in rangelands. This study investigates the impact of climate change on both current and future geographic distributions of *Zornia glochidiata* and *Andropogon pseudapricus* in Senegal, under two climate models (HadGEM3-GC31-LL and MIROC6) and two greenhouse gas emission scenarios (SSP245 and SSP585), with projections for 2070 and 2100. The analysis covers the entire Senegalese territory, with particular attention to rangelands and protected areas. Key environmental variables influencing the distribution of these two fodder species were identified, and future habitat changes were forecasted using climatic projections.

We employed six modeling techniques: artificial neural networks (ANN), generalized boosted models (GBM), generalized linear models (GLM), maximum entropy (MaxEnt), random forest (RF), and surface range envelope (SRE). Among the bioclimatic predictors, precipitation of the wettest quarter (Bio16), annual precipitation (Bio12), isothermality (Bio3), and elevation were the most influential. Random forest showed the highest predictive accuracy, with AUC values exceeding 0.95 for both species.

Currently, *Z. glochidiata* and *A. pseudapricus* occupy 54.4% and 36.17% of Senegal's surface area, respectively. However, all future scenarios forecast a substantial loss of suitable habitat for both species. These projected reductions underline their high vulnerability to changing climatic conditions. The results provide crucial insights for the conservation and management of forage resources in Sahelian ecosystems, supporting strategies for ecological resilience and socio-economic sustainability.

1. Introduction

In Sub-Saharan Africa, many farmers communities depend heavily on rangelands for their ecosystem services [1]. However, the sustainability and functioning of these ecosystems are increasingly threatened by climate change and human pressures [2]. Current projections indicate that greenhouse gas emissions could cause a rise in global average temperatures by 1.4 to 5.8°C during the 21st century [3, 4]. This temperature rise could have significant impacts on the key ecosystem's services of rangelands, particularly net primary productivity and biomass quality [5]. It is important to note that the effects of climate change on rangelands are being exacerbated by overgrazing and unsustainable land use practices [6].

Natural pastures are the main source of fodder for livestock, especially in the rainy season [7]. During the dry season, the availability of herbaceous fodder becomes scarce, pushing livestock to rely mainly on woody rangeland species [8]. These woody rangeland species are also the main sources of energy for most rural households [9]. Thus, grazing land and the harvesting of woody and non-woody forest products are the most significant sources of food and feed in pastoral and agro-pastoral ecosystems [10]. However, the continual expansion of farmlands has led to a reduction in natural grazing land, thereby decreasing pasture productivity [11]. These land use changes, together with recurrent climate variability and the spread of invasive species, have contributed to a significant decline in livestock

productivity [12]. This decline has, in turn, disrupted the socio-economic stability of local communities [12].

In Sahelian countries, ensuring regular supply of fodder for animals throughout the year is essential for achieving resilient livestock production [13]. Seasonal fodder availability remains a key constraint for livestock farmers in Sahelian region [14]. This challenge could be expected worsen due to increased livestock numbers, environmental and land use changes [7, 15]. Climate change is projected to have a negative effect on fodder supply chains, particularly in vulnerable regions where people's livelihoods are already limited [16, 10]

Predicting the geographic distribution of fodder species is crucial for promoting rangeland species conservation [17]. Identifying suitable and unsuitable habitats for fodder species is also essential to prevent biodiversity loss and support climate change adaptation strategies in rangeland areas [18]. Species Distribution Models (SDMs) are widely used to estimate potential species ranges and to the effects of climate change on various plant species groups [19, 9]. As noted by Coulibaly et al. (2023) [9] anticipating shifts in plant distribution due to climate change is essential for effectively guiding sustainable management policies and thus maintaining ecosystem services. SDMs also allow for the projection of shifts in suitable habitats over time and help identify species that may persist or disappear under changing environmental conditions [20]. Forage species with high pastoral value play an important role in animal nutrition and ecological balance [21]. Among the key forage species in the Ferlo rangelands of northern Senegal are *Andropogon pseudapricus* and *Zornia glochidiata*, both of which are widely consumed by livestock [22]. Given their importance, further research is needed to assess the potential impacts of climate change on their geographic distribution and habitat suitability to support their conservation. In West Africa, climate change and human pressure have been shown to negatively affect species diversity and dynamics [23, 24]. SDMs have also been successfully used to identify suitable habitats for the conservation of multipurpose species such as *Vitellaria paradoxa* CF Gaertn. [25], *Garcinia kola* [17], *Cordyla pinnata* (A.Rich.) Milne-Redh. [26] and *Parkia biglobosa* (Jacq.) R.Br. ex G.Don [27]. Despite these growing publications on Senegal rangelands, there is a lack of SDMs applications targeting herbaceous fodder species with high pastoral value. This gap limits the ability to design effective conservation and management strategies for these important resources. Through this study, we aim to bridge this knowledge gap by modeling the geographic distribution of two herbaceous fodder species with high pastoral value in West Africa: *Andropogon pseudapricus* Stapf (a grass) and *Zornia glochidiata* Rchb. Ex DC. (a legume), both prominent in the Ferlo rangelands.

The aims of this study were to assess the geographic distribution of *Andropogon pseudapricus* and *Zornia glochidiata* in response to current and future climatic conditions. Specially, the research addresses the following questions: (i) which bioclimatic variables control the geographic distribution of each species? (ii) what is the current spatial extent of suitable habitats for the conservation of these species? (iii) how are the suitable habitats of *Andropogon pseudapricus* and *Zornia glochidiata* expected to change over time? (iv) and which factors affect the variations in species distribution models?

2. Methodology

2.1. Study areas

The current research study focused on the protected area, the rangelands, fallow lands and farmlands in the Senegal. Senegal is located in West Africa, between latitudes 12°20' -16°20' N and longitudes 11°20' -17°30' W (Fig. 1) [16]. The country has a unimodal rainfall pattern characterized by a short rainy season from June to September and a long dry season from October to May [22]. It is divided into three main climatic zones: Sahelian, North Sudanian, and South Sudanian [26]. In the Sahelian region, annual precipitation varies between 100 and 500 mm, while mean annual temperatures range from 23.3°C to 29.6°C [28]. In Senegal, the Wolof represent the largest ethnic group, followed by the Fulani [29]. Other ethnic groups are beginning to take their place in the composition of this population [30].

2.2. Study species

Andropogon pseudapricus is a tufted annual or perennial grass, with ascending, branched stems that can reach up to 150 cm in height [31]. The plant provides good fodder when young and is grazed even when in flower [32]. This specie is also appreciated as hay during the dry season by the herding communities in Senegal. *A. pseudapricus* is an important component of savannah vegetation in areas with an average annual rainfall of 500 to 700 mm [31]. It grows on shallow, sandy or gravelly lateritic soils [32].

Zornia glochidiata is a leguminous herb from the Fabaceae family, widely distributed throughout the Sahelian zone of West Africa [33]. It is recognized as an important forage species in the region [34]. It is an annual herb, with erect stems and grows up to 45 cm tall [35]. Its leaves are compound and broad leaves, typically bifoliate [34]. The stipules are lanceolate in shape and can reach up to 15 mm in length [36]. It is common in sandy areas with a mean annual rainfall of 300 to 600 mm or more during the rainy season and a dry season for up to 8 months [35].

2.3. Data collection

2.3.1. Species occurrence data

Presence data of the two species were recorded using a Global Positioning System (GPS) during fieldwork conducted throughout the distribution range of both species in Senegal (Fig. 2). The field data were supplemented by additional records gathered from the Global Biodiversity Information Facility website (GBIF, www.gbif.org/). To improve relevance and accuracy of the data, GBIF records were filtered to include only occurrences from 1990 to 2025, excluding older records of individuals that may not reflect. A total dataset of 2327 occurrence records were obtained for *Z. glochidiata*, of which 1523 records (65.45%) were collected from field surveys and 804 records (34.55%) from the GBIF database. Similarly, a total dataset of 1306 occurrence records were obtained for *A. pseudapricus*, of which 930 records (71.25%) were collected from field surveys and 376 records (28.75%) from the GBIF database. Following rigorous data quality control procedures, duplicate records were removed using the function 'spatially rarefy occurrence data' in SDMtoolbox [19]. To reduce sampling bias, spatial thinning was

performed using the ENMTools package in R [37]. Duplicate records within the same 1km² grid cell were removed to avoid over-representation [38, 39].

2.3.2. Environmental data

In this study environmental variables included bioclimatic, elevation and human footprint index data. A total of 19 bioclimatic variables covering current (1970–2000) and future (2070 and 2100) climate conditions, along with elevation data, were downloaded from WorldClim website (<https://www.worldclim.org/>; accessed on January 09, 2025) [40]. In addition, the human footprint index was downloaded from Wildlife Conservation Society (<https://wcshumanfootprint.org/data-access>). Thus, elevation and human footprint index data were resampled to match the resolution of the bioclimatic variables, which is 30 arc seconds (approx. 1 km²) [41]. To predict the future distribution of species, two Shared Socioeconomic Pathways (SSPs) scenarios from the updated CMIP6 were selected for analysis, the SSP 245(moderate) and SSP 585 (strong) for two periods 2070 and 2100. These scenarios were chosen because they represent more pessimistic and more optimistic greenhouse gas emission scenarios respectively [42]. Climate projection were based on two global climate models (GCMs): HadGEM3-GC31-LL and MIROC6, widely used in CMIP6 experiments [43]. In addition, it should be noted that these two climate models are widely used in the prediction of ecological niches in West Africa [44, 9, 11, 45].

2.3.3. Variable selection for fodder species modeling

To select relevant environmental predictors for ecological niche modeling, we conducted a variance inflation factors (VIF) analysis on 19 initial bioclimatic variables and the Human Footprint Index to assess multicollinearity [46]. We progressively eliminated variables with a Pearson correlation coefficient equal or higher to |0.7| ($r \geq |0.7|$) [25]. Then, 6 least correlated environmental variables for *Andropogon pseudapricus* and 7 variables for *Zornia glochidiata* and elevation were identified to run the model. Finally, a Jackknife test was conducted to identify the variables with the greatest contribution to the model [47].

2.3.4. Evaluation of model and potential distribution of forage species

The prediction of current and future suitable areas for forage species was carried out using R 4.3.2 software based on 6 machine learning algorithms via Biomod2 [48]. Biomod2 function was used to randomly generate pseudo-absence points with the same number as the recorded species occurrence data [48, 47]. Then, six algorithms best suited to species prediction were applied: artificial neural networks (ANN), generalized boosted models (GBM), generalized linear models (GLM), random forest (RF), surface range envelope (SRE) and maximum entropy (MaxEnt) [49, 47, 11]. These algorithms combine species occurrence data with current bioclimatic variables to generate a map of potential species distribution in the study area and future habitat suitability based on climate projections [9]. For each species, we used 25% of species occurrence records for model testing and 75% for model calibration [51]. The predictive capacity of the model was evaluated according to four measures, including the Area Under the Curve (AUC) which is threshold-independent, the threshold-dependent True

Skill Statistic (TSS), the Correlation Statistic (COR) and the KAPPA [52]. An AUC value equal to 0.5 indicates poor model performance, and when its value is close to 1 ($AUC > 0.75$) it indicates a very good performance of the model [53]. The TSS value ranges from -1 to $+1$, and is calculated using the following formula [54]:

$$TSS = \frac{ad - bc}{(a + c)(b + d)} = Sensitivity + Specificity - 1$$

1

Suitable habitat distributions for fodder species, both current and projected under future climate scenarios, were mapped based on logistic occurrence probabilities (p). Three suitable areas classes were considered: Low suitability ($p \leq 0.4$), medium suitability ($0.4 < p \leq 0.6$) and high suitability ($p > 0.6$) [55]. Moreover, the centroid shift of both species from the present to future SSP scenarios, across both time frames, were performed using R (version 4.3.2), primarily with the packages *sf*, *ggplot2*, *ggspatial*, and *patchwork* [73]. Maps of the species suitable areas were finally produced using ArcMap 10.8 for current and future climatic conditions under the two scenarios at the two horizons.

3. Results

3.1. Key environmental variables influencing the species distribution

The main bioclimatic variables influencing the potential distribution of the two fodder species in Senegal are shown in (Table 1). The main variables influencing *Z. glochidiata* were elevation (21%), min temperature of coldest month (15.6%), isothermality (13.5%), precipitation of coldest quarter (12.6%) and precipitation of wettest month (10.6%). Bio 16 (precipitation of wettest quarter) is the least influential bioclimatic variable for *Z. glochidiata*.

The bioclimatic variables significantly affecting the *A. pseudapricus* species were Bio16 (precipitation of wettest quarter) with a contribution of 34.8%, Bio12 (annual precipitation) with a contribution of 26.6%. Bio17 (precipitation of driest quarter) is the least influential variable, with a contribution of 5.3%.

Although climatic variables were predominant, the internal Jackknife test revealed that human footprint index variables also play a significant role, albeit to a lesser extent. Specifically, human footprint index contributed 18.3% to the potential distribution of *Z. glochidiata* and 8.5% for *A. pseudapricus*. These results highlight the complex interaction between climatic and human factors in determining the habitat suitability for the two fodder species.

Table 1
Variables contribution used in modelling of the two fodder species.

Species	Code	Variables name	Contribution (%)
<i>Zornia glochidiata</i>	Bio3	Isothermality (BIO2/BIO7) (×100)	13.5
	Bio6	Min temperature of coldest month	15.6
	Bio13	Precipitation of wettest month	10.6
	Bio16	Precipitation of wettest quarter	8.4
	Bio19	Precipitation of coldest quarter	12.6
	Elev	Elevation	21
	HFP	Human Footprint Index	18.3
<i>Andropogon pseudapricus</i>	Bio9	Mean temperature of driest quarter	12.7
	Bio12	Annual precipitation	26.6
	Bio16	Precipitation of wettest quarter	34.8
	Bio17	Precipitation of driest quarter	5.3
	Elev	Elevation	12.1
	HFP	Human Foot print Index	8.5

3.2. Model accuracy and performance

(Table 2) shows the performance of the six algorithms used to predict the distribution of the two fodder species based on various statistical metrics such as AUC, TSS, COR and KAPPA. All six algorithms demonstrated good predictive performance (AUC >0.8), except for the ANN, which had an AUC value of 0.75 for *Zornia glochidiata*. Indeed, *Zornia glochidiata* achieved an AUC of 0.96 and TSS 0.90 with RF, while *Andropogon pseudapricus* has an AUC of 0.98 and a TSS of 0.71 with the same algorithm (Table 2). ANN presented lower values than other algorithms, as seen in the case of *Z. glochidata* with an AUC of 0.75 and TSS of 0.63. For each species the performance of the models was also evaluated by the correlation statistic (COR) value and the KAPPA (Table 2).

Table 2
Performance of the six algorithms (RF, MaxEnt, GLM, GBM, SRE, ANN)

Species	Algorithm	AUC	COR	TSS	KAPPA
<i>Zornia glochidiata</i>	RF	0.98	0.95	0.91	0.89
	MaxEnt	0.95	0.87	0.86	0.84
	GLM	0.83	0.75	0.85	0.69
	GBM	0.91	0.71	0.68	0.67
	SRE	0.88	0.63	0.7	0.85
	ANN	0.75	0.67	0.63	0.78
<i>Andropogon pseudapricus</i>	RF	0.98	0.97	0.9	0.86
	MaxEnt	0.93	0.8	0.88	0.82
	GLM	0.89	0.71	0.82	0.66
	GBM	0.92	0.7	0.67	0.65
	SRE	0.8	0.72	0.61	0.7
	ANN	0.59	0.57	0.5	0.53

3.3. Current and future distribution of two fodder species

3.3.1. *Zornia glochidiata*

The current high suitable habitats for the species represent 22.9% (43,843.77 km²) of Senegal's total surface area (196,712 km²). Less suitable habitats cover 32.11% (63,161.36 km²), while 45.16% (88,834.02 km²) of the country's land area is unsuitable (Appendix A; Fig. 3). These habitats are mainly located in the Sudano-Sahelian zone and the Sudanian zones of the country (Fig. 4). Both climate models (HadGEM3-GC31-LL and MIROC6) predicted a significant overall decline in the species' range under the moderate (SSP 245) and high-emission (SSP 585) scenarios across all time horizons. Under the HadGEM3-GC31-LL model's moderate scenario (SSP245), habitat loss is projected to reach 48.99% (22,364.17 km²) by 2061–2080 and 47.96% (22,815.99 km²) by 2081–2100. In the worst-case scenario (SSP585) for the same model, projected losses range from 48.58% (22,543.28 km²) by 2061–2080 to 50.18% (21844.18 km²) by 2081–2100. The MIROC6 model under SSP585 also forecasted drastic changes in the species' spatial distribution, with only 9.65% and 8.9% of Senegal's area remaining suitable by 2070 and 2100, respectively.

3.3.2. *Andropogon pseudapricus*

The predicted high suitable areas for *A. pseudapricus* currently account for 20.14% (19,942.38 km²) of Senegal's total area (Appendix A, Fig. 5), while less suitable areas cover 36.03% (51,197.06 km²). About 43.83% (12,5578.23 km²) of the total area of Senegal is unsuitable for *A. pseudapricus* conservation under current climatic conditions. The species' habitat range highly and moderately suitable to the species were found in the northern part of the Sahelian zone of Senegal (Fig. 6). The total potential distribution area of *A. pseudapricus* was projected to decrease substantially over time under the two future emission scenarios. Specifically, the areas accounted for 88.11% and 88.37% of the total area of Senegal in the years 2061–2080 under moderate and strong scenarios, respectively with the HadGEM3-GC31-LL model. However, under SSP 585, the MIROC6 model predicts a crucial decrease of 5448.75 km² (89.36%) in 2061–2080, followed by a small decrease of 14.59% (43,729.66 km²) in 2081–2100 (Fig. 5). These trends highlight the species' vulnerability to future climate conditions.

3.3.3. Trajectory of the two species according to current and future climate conditions

Centroid shift analysis under future climate scenarios revealed contrasting patterns between the two species (Fig. 7). For *A. pseudapricus*, the centroid consistently moved northeastward across all scenarios, with a particularly pronounced shift under SSP585-2100, indicating a likely migration of suitable habitat toward higher latitudes and eastern regions. In contrast, *Z. glochidiata* exhibited a southwestward shift, especially under MIROC6 projections, suggesting a relocation of favorable conditions toward lower latitudes and western areas. These divergent directions of centroid movement highlight species-specific responses to climate change and underscore the need for tailored management strategies.

4. Discussion

4.1. Variable importance for the habitat suitability of the two fodder species in Senegal

Temperature and precipitation are the primary bioclimatic variables influencing plant growth and reproduction [12]. Based on the relative importance of the environmental predictors, the distribution of *Z. glochidiata* is primarily shaped by elevation, minimum temperature of the coldest month, isothermality, and precipitation during the coldest quarter. In contrast, *A. pseudapricus* is most affected by precipitation in the wettest quarter, total annual rainfall, and mean temperature of the driest quarter. Comparable patterns have been highlighted in earlier research conducted across West Africa [11, 18, 56], reinforcing the role of temperature and rainfall in determining the ecological niches of tropical species [58]. According to O'donnell and Ignizio [60], species can adapt to environments characterized by lower temperature variability, which enhances their persistence across different climatic zones. Comparable observations were made for *Afzelia africana* [19] and *Carapa procera* [61] in Burkina Faso, as well as for other multipurpose species in Benin [18]. The present findings are consistent with previous research on

the spatial distribution of fodder species in West Africa [73]. Numerous studies have emphasized that precipitation and temperature are the dominant climatic factors influencing the distribution patterns of woody vegetation throughout the region [61, 62, 63, 64].

In this study, human activities accounted for 18.3% and 8.5% of the factors influencing the distribution of *Z. glochidiata* and *A. pseudapricus*, respectively. These results indicate that anthropogenic pressures such as land-use change, infrastructure development, and population expansion negatively affect the growth, habitat suitability, and reproductive capacity of both species [12]. The growing intensity of human use of rangelands has been identified as a major driver of the widespread degradation of fodder vegetation in recent years [12].

4.2. Model performance

The present study employed the Biomod2 package to model both current and projected suitable habitats for the two fodder species, using six algorithms: ANN, GBM, GLM, MaxEnt, RF, and SRE. Among these approaches, the Random Forest (RF) algorithm consistently produced the most reliable predictions for both species, as reflected by its superior AUC and TSS scores. This finding aligns with earlier works by Huang et al. [48]; Coulibaly et al. [9], and Sambou et al. [26], which also identified RF as the most effective method for species distribution modeling. Similarly, recent studies by Dogbo et al. [18] and Gbadamassi et al. [57] reported that Random Forest was the most robust algorithm for predicting the spatial distribution of twelve multipurpose species in Benin and *Prosopis africana* in Togo. However, the integration of multiple algorithms in species distribution modeling remains a topic of scientific debate [18]. Araújo and New (2007) [66], emphasized that combining different modeling techniques can improve predictive robustness and minimize algorithm specific bias. Several studies have further demonstrated that ensemble models, which aggregate multiple algorithms, generally outperform single-model approaches in predicting species distributions and evaluating the potential effects of climate change [67].

4.3. Current distribution of the two species

The predicted current suitable habitats for *Z. glochidiata* in Senegal cover more than half of the national territory (54.84%), whereas those of *A. pseudapricus* occupy approximately 36.17% of the country's surface area. These favorable habitats extend mainly across the Sudanian and Sudano-Sahelian ecological zones. This pattern aligns with the known distribution range of *Z. glochidiata* in West Africa [34]. In contrast, model projections for *A. pseudapricus* indicate a broader presence throughout Senegal, with a stronger concentration in the northern Sahelian region. Furthermore, the species appears to be absent from certain protected areas as well as from some unprotected rangelands.

These results indicate that protected areas do not always provide effective conservation sites for species such as *A. pseudapricus*. Some regions currently classified as unsuitable may become more favorable for the species in the future, potentially offering better conservation opportunities than areas already considered suitable. Additionally, the extent of suitable habitat for *Z. glochidiata* identified in this study exceeds that reported for other socio-economically important plant species in West Africa. For

example, Balima et al. [19] estimated that approximately 25.54% of Burkina Faso's territory is suitable for *Afzelia africana* conservation, while only about 2.37% of Mali's territory was deemed highly suitable for *Bombax costatum* Pellegr. & Vuill. [9]. The substantial areas identified as unsuitable for *Z. glochidiata* and *A. pseudapricus* highlight the urgent need to prioritize their conservation in Senegal.

4.4. Future distribution of the two species

Climate projections for 2070 suggest that *A. pseudapricus* and *Z. glochidiata* are likely to lose between 53.24% and 89.36% of their highly suitable habitats under the SSP2-4.5 and SSP5-8.5 scenarios, respectively. These results are consistent with observed distribution patterns for *Bombax costatum* Pellegr. & Vuill. in Mali, reported by Coulibaly et al. [9], and for *Combretum glutinosum* Perr. ex-DC. in Burkina Faso, documented by Dembélé et al. [45]. Compared to other multipurpose species in West Africa, the projected future ranges for these two fodder species are relatively extensive. For instance, Djibo Moussa et al. [65] estimated that 37.89% of Niger's territory could be suitable for *Balanites senegalensis* conservation, while approximately 32.91% and 26.44% of the territories of Senegal and Benin were identified as suitable for the conservation of *Cordyla pinnata* [11] and *Parkia biglobosa* (Jacq.) R.Br. ex G. Don [18], respectively.

Our results indicate that suitable habitats for both *Z. glochidiata* and *A. pseudapricus* are projected to contract primarily within the Sudano-Sahelian region of West Africa. This pattern is consistent with previous studies predicting future range reductions for *Pterocarpus erinaceus* [68] and *Adansonia digitata* under changing climatic conditions in the region [9]. The observed decline can be attributed to rising temperatures, reduced precipitation, and the increasing frequency of extreme climatic events, all of which compromise the ecological viability of these species in areas that were previously suitable. These findings also align with climate models forecasting a general decrease in rainfall across West Africa [69]. By 2100, *Z. glochidiata* is expected to lose approximately 69.25% (19,419.32 km²) of its less suitable habitats, while *A. pseudapricus* is projected to lose about 56.81% under the MIROC6 / SSP2-4.5 scenario. This difference may reflect the higher anthropogenic pressures on *Z. glochidiata*, as well as species-specific ecological and environmental sensitivities. This decline may be further exacerbated by the expansion of croplands and urban areas. Our results are consistent with those of Trisurat et al. [70] and Gbadamassi et al. [57], who reported that fodder species often occupy only a fraction of their potential ecological niche due to human activities, bushfires, and interspecific competition. Similarly, Saliou et al. [62] predicted a marked reduction in the habitats of three *Andropogon* species in Benin, highlighting the urgent need for targeted conservation actions. The projected shift of suitable habitats towards the Sudanian zone under future climate scenarios can be attributed to significant increases in temperature, particularly in the semi-arid regions of West Africa, which are likely to reduce areas suitable for plant biodiversity [71, 19, 72, 44]. Climatic changes are altering habitats, while human pressures such as agricultural expansion and infrastructure development continue to impact fodder species Gbadamassi et al. [57]. These combined challenges highlight the need for integrated management strategies that address both environmental and anthropogenic factors to ensure long-term conservation

4.5. Implications for management and conservation

Based on the results of this study, current management efforts should focus on monitoring areas identified as highly and moderately suitable habitats, with the aim of implementing timely and targeted conservation measures. In anticipation of future climate change, strategies should prioritize regions projected to remain suitable or become suitable for *Z. glochidiata* and *A. pseudapricus*. Concurrently, reducing human-induced pressures is essential to support the growth, regeneration, and expansion of these species within their potential distribution zones.

This study utilized Biomod2 simulations integrating six modeling algorithms to predict the geographic distribution of *Z. glochidiata* and *A. pseudapricus* across Senegalese rangelands under both current and future climate scenarios. Continuous monitoring and early warning systems for shifts in plant distribution can provide a scientific foundation for proactive conservation planning, enabling interventions at both local and regional scales. These insights have substantial theoretical and practical implications for guiding adaptive rangeland management and biodiversity conservation throughout the Sahelian region.

5. Conclusion

This study modeled the ecological niches of two forage species of high pastoral value in Senegal by combining six different algorithms. Our results identified precipitation during the wettest quarter, annual precipitation, and minimum temperature of the coldest month as the main environmental factors influencing their geographic distribution. Currently, favorable habitats for *Zornia glochidiata* cover approximately 54.4% of Senegal's total land area, including 22.29% classified as highly suitable. Similarly, potential habitats for *Andropogon pseudapricus* occupy about 43.17% of the country, but only 3.10% of these areas are highly suitable. Under future climate scenarios, these suitable habitats are projected to decline significantly. The models consistently predict a substantial reduction in the ecological niches of both species by 2070 and 2100, regardless of the climate scenario considered. Moreover, the spatial extent of suitable habitats varies according to the choice of climate model, scenario, and time horizon.

The study also reveals that many highly suitable habitats lie outside existing protected areas, indicating that current conservation zones may be insufficient for the long-term preservation of these forage species. To prevent the degradation of important forage resources in Sahelian rangelands, targeted strategies are essential. This includes implementing forestry policies aimed at endangered forage species and strengthening the protection of key habitats within and beyond protected areas.

Finally, to better safeguard forage biodiversity, ecological niche modeling should be expanded to include other forage species of high pastoral value in Sahelian rangelands. Incorporating additional environmental variables and utilizing a broader range of climate models could further improve the accuracy and effectiveness of future distribution predictions.

Declarations

Author contribution statement

Idrissa Sawadogo: Writing original draft, Visualization, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation and Conceptualization.

Jean Kouao Koffi: Visualization, Resources, Methodology, Data curation, Conceptualization and draft editing. **Sié Sylvestre Da:** Writing original draft, Visualization, Software, Methodology, Data curation, Conceptualization and draft editing. **Jean Baptiste Dembélé:** Visualization, Resources, Methodology, Data curation, Conceptualization and draft editing. **Innocent Charles Emmanuel Traoré:** Writing original draft, Visualization, Software, Methodology, Data curation, Conceptualization and draft editing. **Faustine Akossoua Kouassi:** Writing original draft, Visualization, Software, Methodology, Data curation, Conceptualization and draft editing. **Philippe Bayen:** Writing original draft, Visualization, Software, Methodology, Data curation, Conceptualization and draft editing. **Omonlola Nadine Worou:** Writing original draft, Visualization, Software, Methodology, Data curation, Conceptualization and draft editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Consent for publication

Not applicable

Ethics approval and consent to participate

Not applicable

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Figures

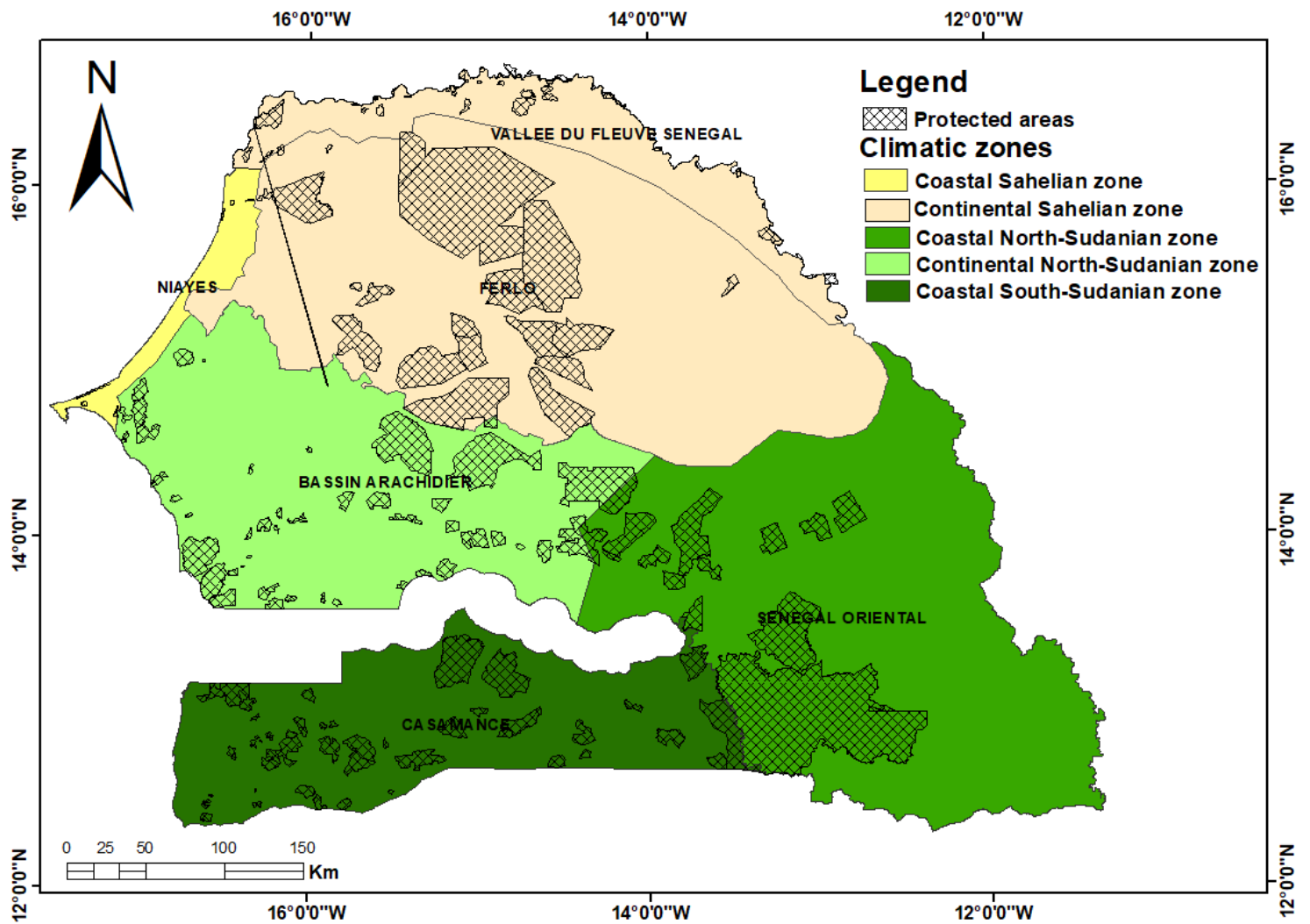


Figure 1

Location of the study areas

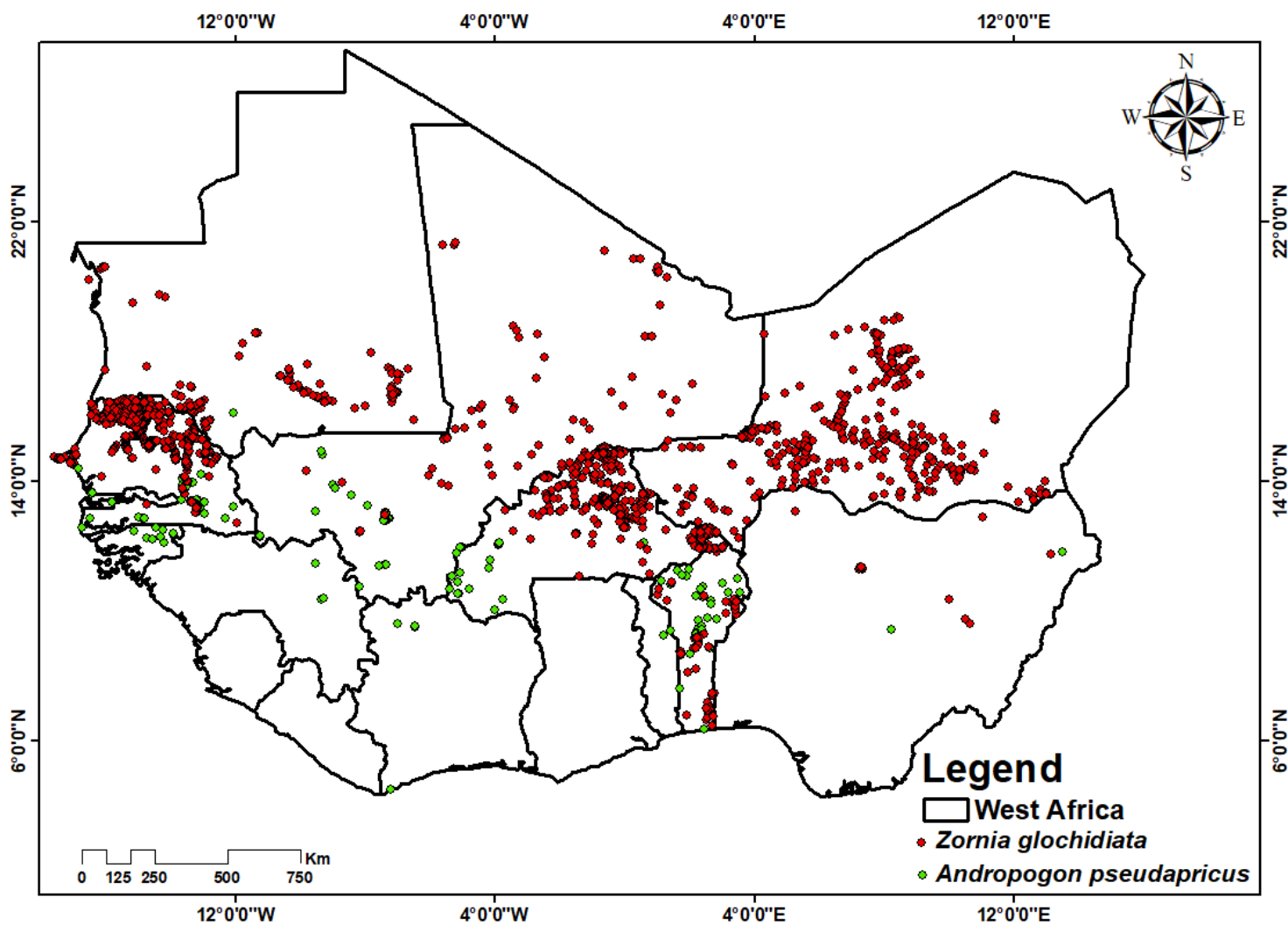


Figure 2

Distribution map of two key herbaceous forage with high pastoral value

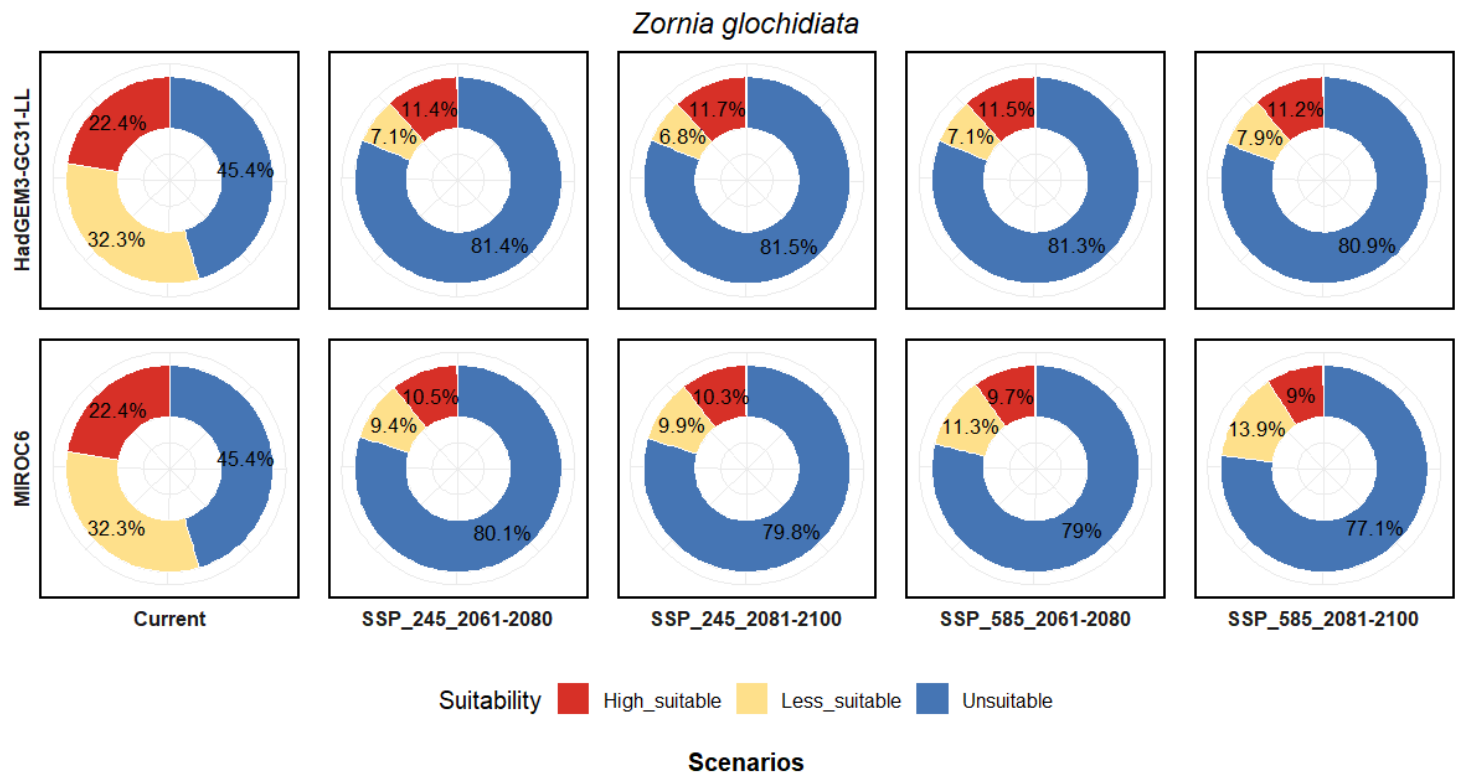


Figure 3

Change in the range of suitable habitat areas for *Zornia glochidiata* under current and future climate scenarios based on SSP245; SSP585; HadGEM3-GC31-LL and MIROC6

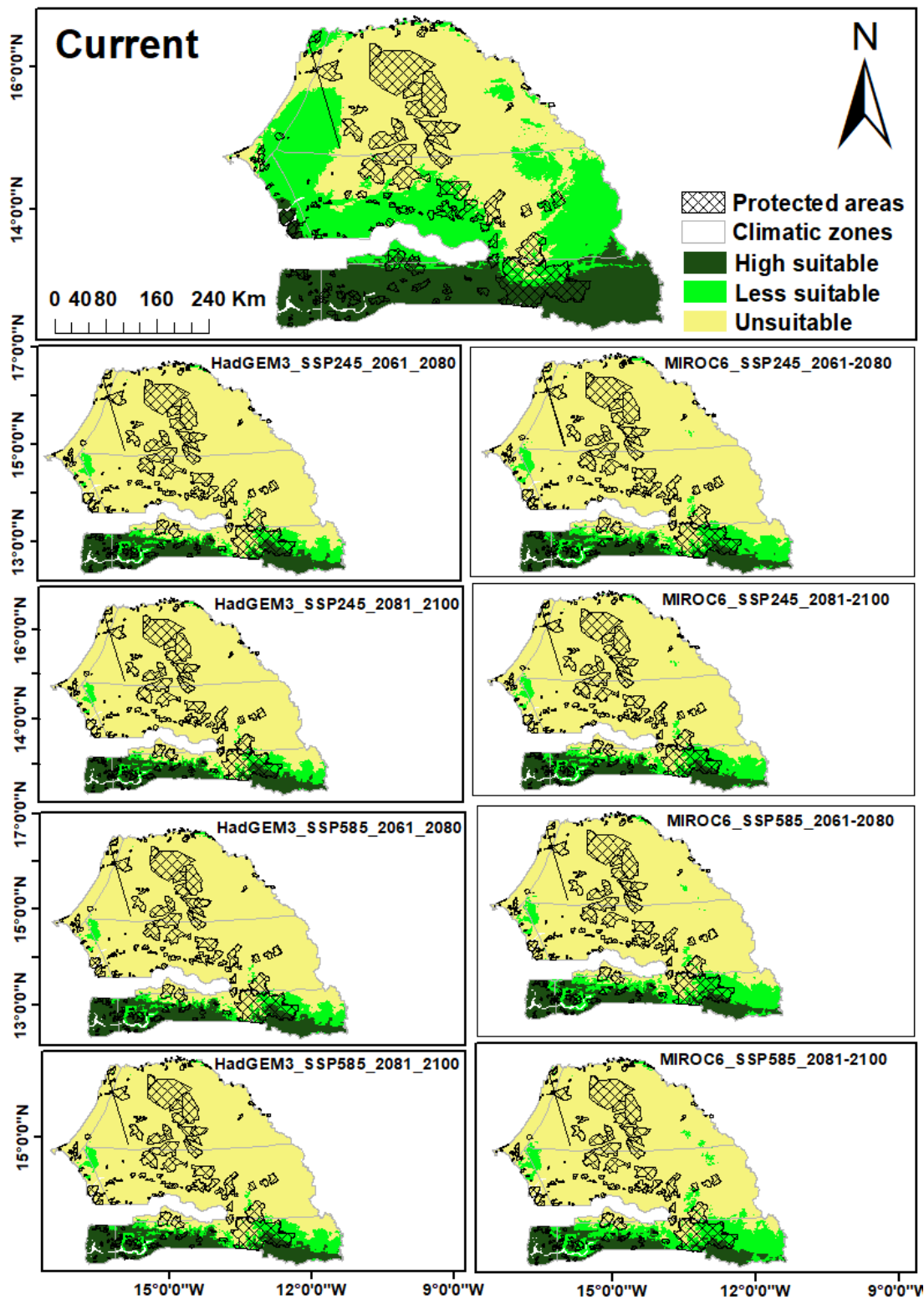


Figure 4

Distribution predictions under current and future climate conditions (the upper bigger map is the current distribution and the small maps are the future distributions)

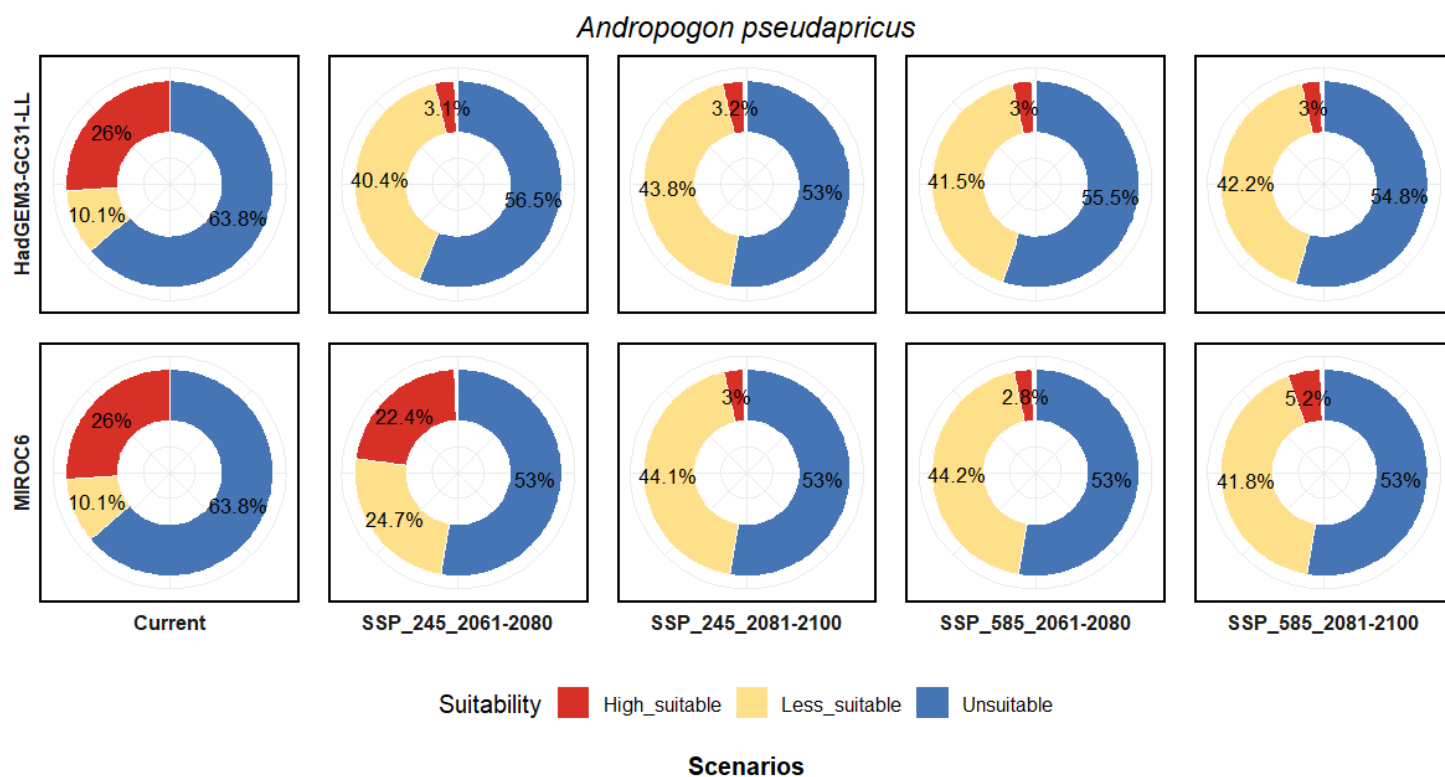


Figure 5

Change in the range of suitable habitat areas for *Andropogon pseudapricus* under current and future climate scenarios based on SSP245; SSP585; HadGEM3-GC31-LL and MIROC6

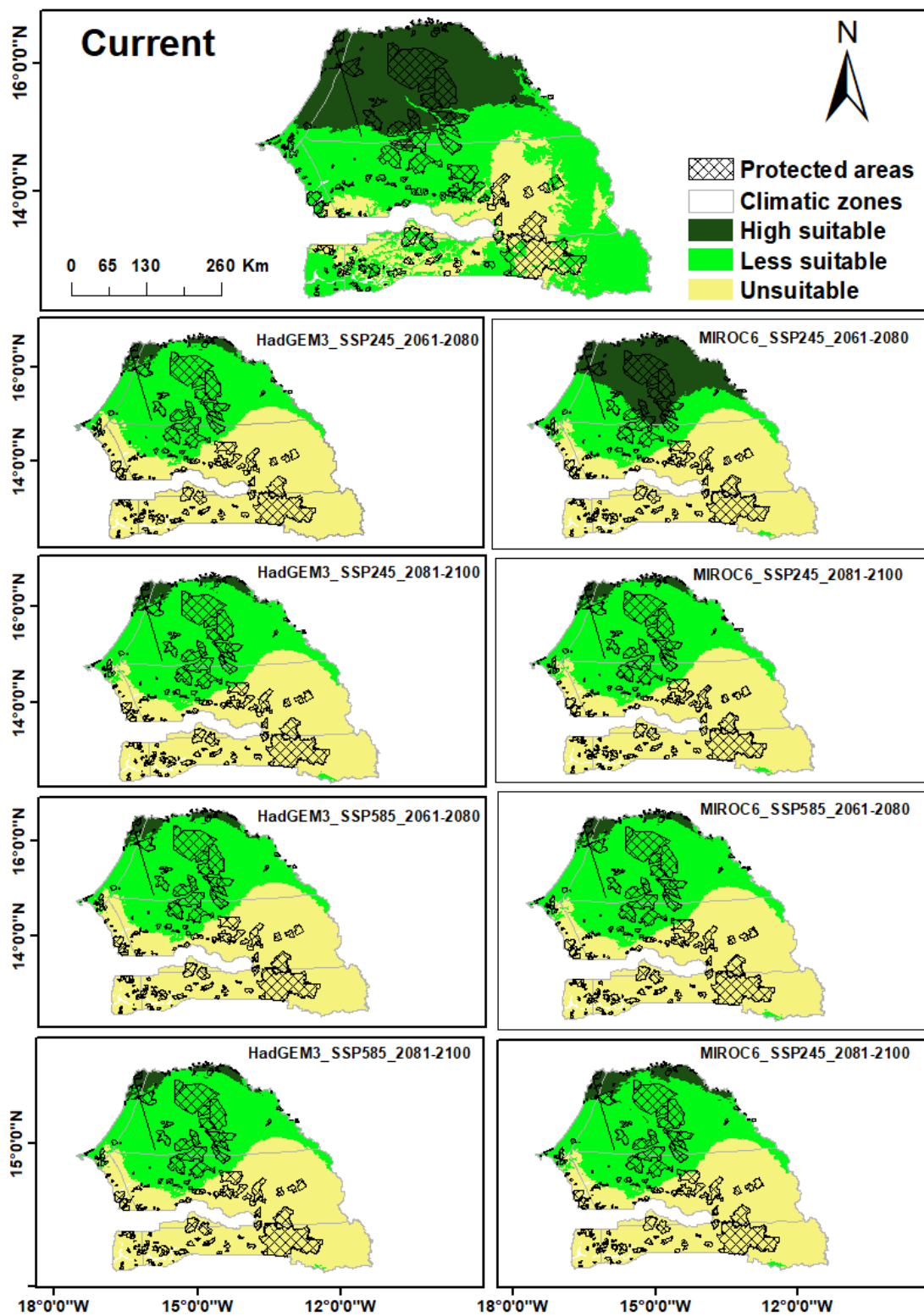


Figure 6

Distribution predictions under current and future climate conditions (the upper bigger map is the current distribution and the small maps are the future distributions)

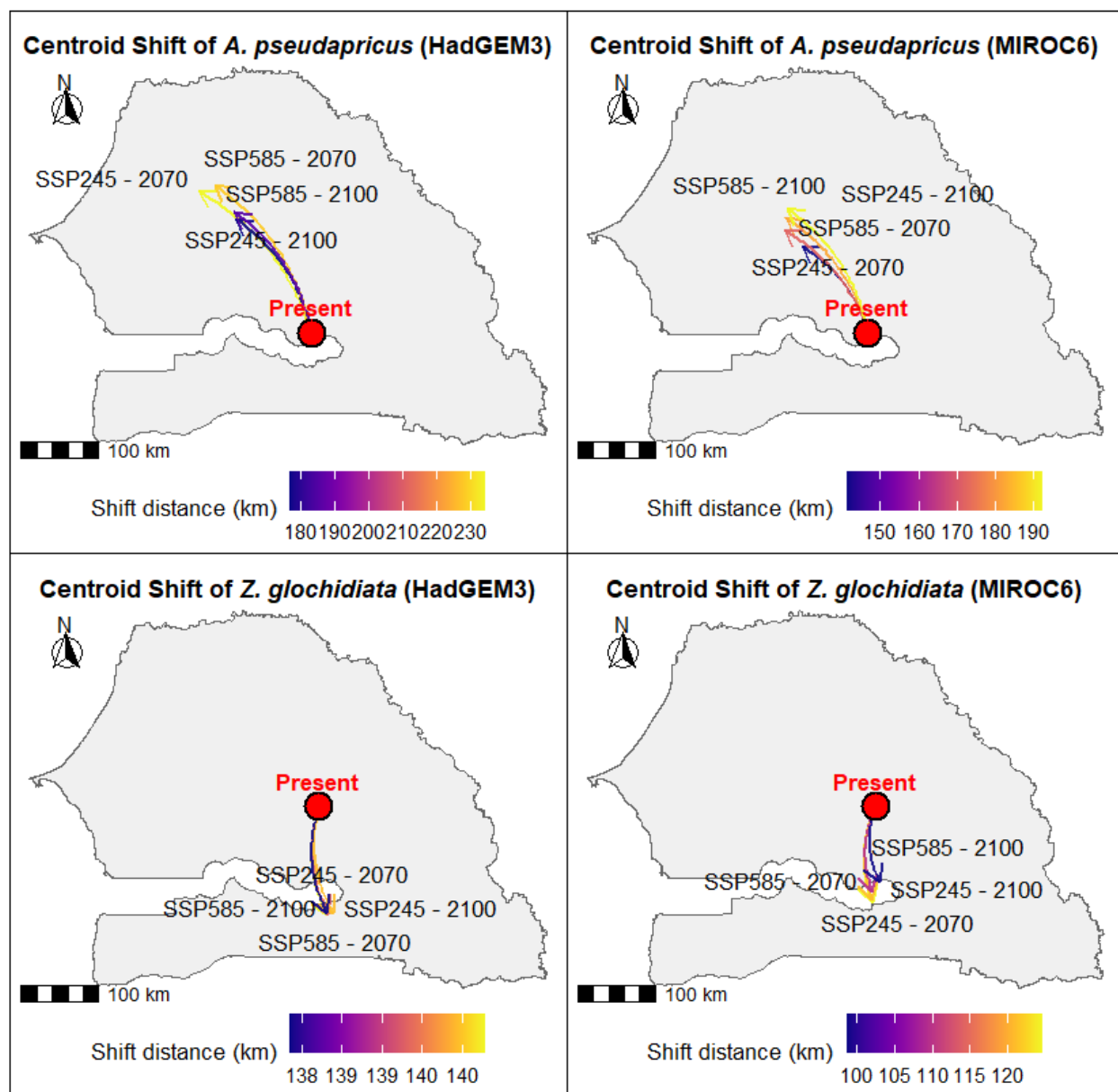


Figure 7

Maps illustrating the directional shifts of the centroids for *A. pseudapricus* and *Z. glochidiata* from the current distribution to future SSP scenarios

Supplementary Files

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- [AppendixA.docx](#)