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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, the potentially suitable areas for *Z. glochidiata* and *A. pseudapricus* represent 54.84 and 36.17% of Senegal's total 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.

Keywords Fodder species, Climate change, Conservation, Species distribution modeling, Rangelands

1 Introduction

In Sub-Saharan Africa, rangelands constitute the backbone of pastoral and agro-pastoral livelihoods, providing essential ecosystem services such as forage production, soil protection, and biodiversity conservation [1]. In Sahelian regions, these rangelands



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are particularly sensitive to climate variability and increasing human pressures, which together threaten their sustainability and capacity to support livestock production [2].

Over recent decades, West Africa has experienced a marked increase in temperatures, greater rainfall variability, and more frequent extreme climatic events, all of which directly affect rangeland productivity and species composition [3]. In Senegal, rising temperatures and irregular precipitation patterns have been associated with reduced net primary productivity, altered phenological cycles, and declining forage quality in natural pastures [4]. These climatic pressures are further amplified by anthropogenic factors such as overgrazing, agricultural expansion, and unsustainable land-use practices, which collectively accelerate rangeland degradation and reduce the availability of grazing resources [3, 5].

Natural pastures remain the primary source of livestock feed in Sahelian systems, particularly during the rainy season, when herbaceous species dominate forage supply [6]. However, these ecosystems are characterized by strong seasonal contrasts [7]. During the dry season, the scarcity of herbaceous biomass forces livestock to rely more heavily on woody species, which also serve as key sources of fuelwood and non-timber forest products for rural households [8]. While woody species play a critical buffering role during feed shortages, herbaceous fodder species remain fundamental to livestock nutrition, pasture regeneration, and overall rangeland functioning [9]. Their high sensitivity to climatic variability and land-use pressure makes them particularly vulnerable to ongoing environmental change [10].

In the Sahel, ensuring a stable and sufficient fodder supply throughout the year is a major challenge for building resilient livestock systems [11]. Seasonal fodder shortages continue to constrain animal productivity and pastoral livelihoods, a situation expected to worsen under future climate change scenarios combined with increasing livestock densities and land-use transformation [12, 13]. Understanding how climate variability and human pressures jointly influence the distribution and persistence of key herbaceous fodder species is therefore essential for sustainable rangeland management and climate change adaptation.

Species Distribution Models (SDMs) provide a valuable framework for assessing the relationships between species occurrences and environmental drivers, and for projecting potential shifts in suitable habitats under changing climatic conditions [14, 15]. By linking species distributions to bioclimatic variables, SDMs allow the identification of areas at risk of habitat loss as well as potential refugia for conservation planning [16, 17]. Ensemble modeling approaches, such as those implemented in BIOMOD2, are particularly useful for reducing uncertainty by combining multiple algorithms, a key advantage when modeling climate sensitive species in highly variable rangeland environments [18]. Nevertheless, SDMs rely on assumptions such as equilibrium between species and climate and may not fully capture human-induced pressures, which must be carefully considered when interpreting results [19].

In West Africa, SDMs have been widely applied to woody and multipurpose tree species of ecological and socio-economic importance, including *Vitellaria paradoxa*, *Garcinia kola*, *Cordyla pinnata*, and *Parkia biglobosa* [20]. These studies have improved understanding of climate-driven distribution patterns for long-lived species [20]. In contrast, herbaceous fodder species, despite their central role in livestock feeding systems, remain largely underrepresented in SDM based assessments [21]. Their short life cycles

and strong dependence on rainfall variability make these species highly responsive to climatic fluctuations and grazing pressure [22, 23]. However, their spatial responses to climate change remain poorly documented in Senegalese rangelands.

Among the dominant herbaceous fodder species in the Ferlo rangelands of northern Senegal, *Andropogon pseudapricus* (a perennial grass) and *Zornia glochidiata* (an annual legume) are of particular importance due to their high pastoral value, palatability, and contribution to pasture productivity [24, 25]. These species play a key role in sustaining livestock during the rainy season and in supporting rangeland regeneration [11, 26]. However, their sensitivity to climatic fluctuations and land-use change raises concerns about their future persistence under projected climate scenarios [27].

Despite the growing body of literature on rangeland dynamics in Senegal, critical knowledge gaps remain regarding the climate sensitivity, spatial distribution, and future habitat suitability of herbaceous fodder species with high pastoral value [28, 29]. Addressing these gaps is essential to inform conservation strategies, pasture management, and climate-resilient livestock planning [30, 31].

The aim of this study was to assess the geographic distribution of *Andropogon pseudapricus* and *Zornia glochidiata* under current and future climatic conditions. Specifically, 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?

2 Methodology

2.1 Study areas

The current research study focused on the protected areas, rangelands, fallow lands and farmlands in Senegal. Senegal is located in West Africa, between latitudes 12°20'–16°20' N and longitudes 11°20'–17°30' W (Fig. 1) [32]. The country has a unimodal

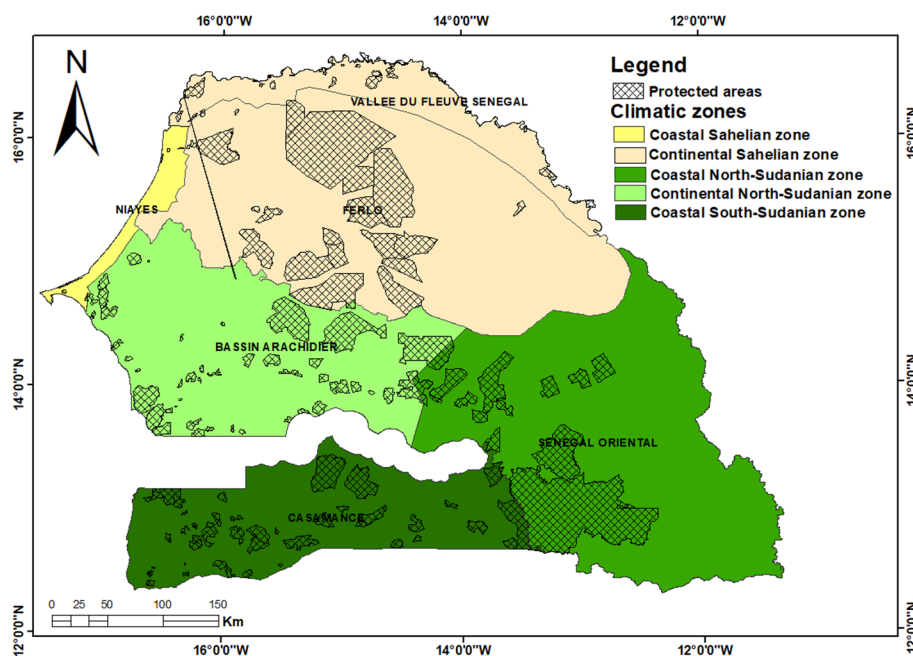


Fig. 1 Location of the study areas

rainfall pattern characterized by a short rainy season from June to September and a long dry season from October to May [33]. It is divided into three main climatic zones: Sahelian, North Sudanian, and South Sudanian [34]. In the Sahelian region, annual precipitation varies between 100 and 500 mm, while mean annual temperatures range from 23.3 to 29.6 °C [35]. In Senegal, the Wolof represent the largest ethnic group, followed by the Fulani [36]. Other ethnic groups are beginning to take their place in the composition of this population [37].

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 [38]. The plant provides good fodder when young and is grazed even when flowering [39]. This species is also appreciated as hay during the dry season by herding communities in Senegal. *A. pseudapricus* is an important component of savannah vegetation in areas with an average annual rainfall of 500–700 mm [38]. It grows on shallow, sandy or gravelly lateritic soils [39].

Zornia glochidiata is a leguminous herb in the Fabaceae family, widely distributed throughout the Sahelian zone of West Africa [40]. It is recognized as an important forage species in the region [41]. It is an annual herb, with erect stems and grows up to 45 cm tall [42]. Its leaves are compound, typically bifoliate, with broad leaflets, [41]. The stipules are lanceolate in shape and can reach up to 15 mm in length [43]. It is common in sandy areas with a mean annual rainfall of 300–600 mm or more during the rainy season and a dry season for up to eight months [42].

2.3 Data collection

2.3.1 Species occurrence data

Presence data for the two species were collected using a Global Positioning System (GPS) during field surveys conducted across their known distribution range in Senegal (Fig. 2). These field collected records were complemented with occurrence data obtained from the Global Biodiversity Information Facility (GBIF; www.gbif.org) to improve spatial coverage. Given the opportunistic nature of GBIF records, all occurrences were subjected to a rigorous data quality control process prior to analysis.

GBIF records were first temporally filtered to retain only occurrences recorded between 1990 and 2025, excluding older observations that may no longer reflect current species distributions due to climate variability and land-use change. Although the baseline climate data used for model calibration correspond to the 1970–2000 period, this time window was considered acceptable under the assumption of relative niche stability of perennial grass species over recent decades. Nevertheless, potential temporal mismatches between occurrence records and climate data are acknowledged as a source of uncertainty.

Additional quality control procedures included the removal of duplicate records, records with missing or obviously erroneous geographic coordinates, and points falling outside the known ecological range of the species. Records with high spatial uncertainty or imprecise georeferencing were excluded to minimize location errors commonly associated with large biodiversity databases.

To reduce spatial clustering and sampling bias, spatial thinning was applied to ensure that only one record per 1 km² grid cell remained, using the ENMTools package in R

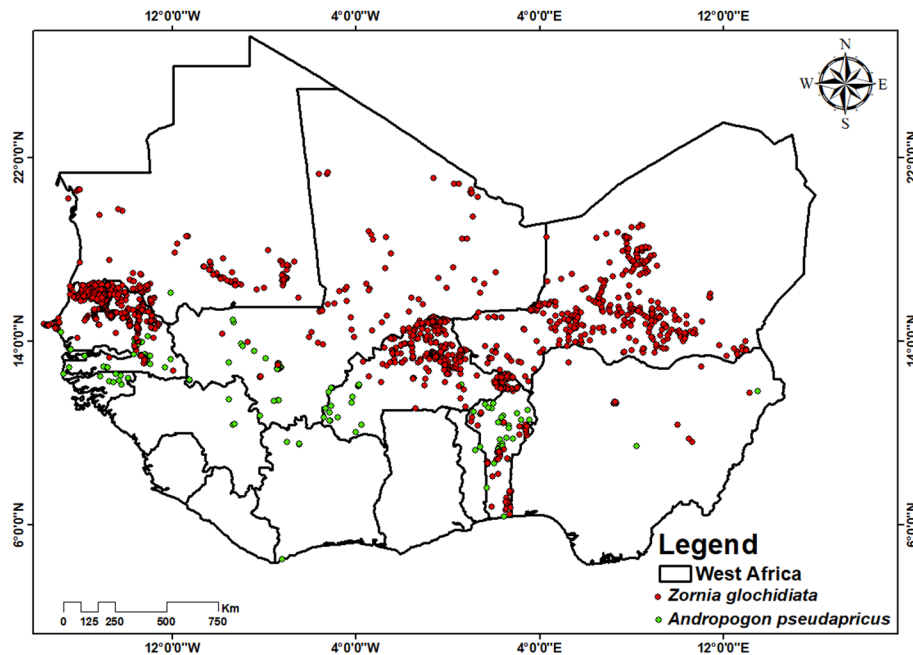


Fig. 2 Distribution map of two key herbaceous forage species with high pastoral value

[44]. A fixed random seed was used during this selection process to ensure workflow reproducibility [45]. After this thinning procedure, a total of 2327 occurrence records for *Zornia glochidiata* and 1306 for *Andropogon pseudapricus* were retained and used for the final modeling. This procedure aimed to limit overrepresentation of heavily sampled areas and reduce spatial autocorrelation among occurrence points [46, 47]. While spatial thinning reduces the influence of clustered sampling, it does not fully eliminate structured sampling bias, which is therefore considered in the interpretation of model outputs.

2.3.2 Environmental data

Environmental variables used in this study included bioclimatic variables, elevation, and the Human Footprint Index. A total of 19 bioclimatic variables representing current climate conditions (1970–2000) and future projections (2070 and 2100), together with elevation data, were obtained from the WorldClim database (<https://www.worldclim.org/>; accessed on January 9, 2025) at a spatial resolution of 30 arc seconds ($\sim 1 \text{ km}^2$) [48]. All environmental layers were harmonized to the same spatial resolution.

In addition to climatic predictors, the Human Footprint Index was obtained from the Wildlife Conservation Society (<https://wchumanfootprint.org/data-access>) and resampled to match the spatial resolution of the bioclimatic variables [49]. This index was included to represent anthropogenic influences on species distributions. The Human Footprint Index was included as a static predictor, held constant for future projections due to the lack of reliable future scenarios.

Future species distributions were projected using two Shared Socioeconomic Pathway (SSP) scenarios from the CMIP6 framework: SSP2-4.5 (moderate emissions) and SSP5-8.5 (high emissions), for two periods 2070 and 2100. These scenarios were selected to capture contrasting trajectories of greenhouse gas emissions and associated climate change impacts [48]. While these time horizons represent long-term projections that

may be less directly applicable to short-term pastoral management, they are commonly used in ecological niche modelling to assess potential long-term shifts in species distributions under climate change.

Climate projections were derived from two Global Climate Models (GCMs), HadGEM3-GC31-LL and MIROC6, which are widely used in CMIP6 experiments and ecological niche modelling studies, including in West Africa [17, 50, 51]. Although the use of only two GCMs does not encompass the full range of climate uncertainty, it allows for comparison between models with contrasting climate sensitivities, particularly regarding precipitation patterns that are critical for grassland ecosystems [52]. WorldClim CMIP6 climate layers, which are bias-corrected and downscaled, were used directly in this study.

2.3.3 Variable selection for fodder species modeling

To select relevant environmental predictors for ecological niche modeling, we conducted a variance inflation factor (VIF) analysis on 19 initial bioclimatic variables and the Human Footprint Index to assess multicollinearity [53]. We progressively eliminated variables with a Pearson correlation coefficient equal to or higher than $|0.7|$ ($r \geq |0.7|$) [54]. Then, the six least correlated environmental variables for *Andropogon pseudapricus* and seven 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 [55].

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 six machine learning algorithms implemented in the Biomod2 package [56]. Pseudo-absences were generated randomly across Senegal, assuming that the country represents the accessible area for both species. For each modelling run, the number of pseudo-absences was set equal to the number of presence records [46, 47]. Then, six algorithms commonly used for 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) [11, 46, 48]. These algorithms combine species occurrence data with current bioclimatic variables to generate maps of potential species distribution in the study area and future habitat suitability based on climate projections [59]. For each species, model calibration and evaluation were performed using a repeated split-sampling cross-validation design, in which 75% of the data were used for calibration and 25% for validation, with 10 repeated runs [60]. The final performance metrics, including the Area under the Curve (AUC), the True Skill Statistic (TSS), the Correlation Statistic (COR), and the Kappa [61], are reported as the mean $\pm$ standard deviation across all 30 replicates (3 PA sets $\times$ 10 evaluation runs). An AUC value close to 1 ($AUC > 0.75$) indicates a very good performance of the model [62].

To generate the final consensus maps, an ensemble modeling approach was used. Only individual models with a TSS score greater than 0.7 were retained for the ensemble to ensure high predictive accuracy, which led to the exclusion of poorly performing runs (notably from the ANN algorithm in certain scenarios). The final ensemble was

computed using a TSS-weighted mean, giving more influence to the most accurate models. The TSS value ranges from − 1 to + 1, and is calculated using the following formula [63]:

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

Suitable habitat distributions for the fodder species, both current and projected under future climate scenarios, were mapped based on logistic occurrence probabilities (*p*). Three suitability classes were defined as follows: low suitability (*p* ≤ 0.4), medium suitability (0.4 < *p* ≤ 0.6), and high suitability (*p* > 0.6), following the thresholds suggested by [64] and commonly used in similar SDM studies. These thresholds provide a simple and interpretable categorization of habitat suitability, and sensitivity analyses indicated that minor changes in the thresholds (± 0.05) did not substantially alter the spatial patterns of suitable habitats.

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* [65]. Maps of the species suitable areas were finally produced using ArcMap 10.8 under current and future climatic conditions for both scenarios and time horizons.

3 Results

3.1 Key environmental variables influencing species distribution

The relative importance of environmental variables influencing the potential distribution of the two fodder species is presented in Table 1. Variable contributions correspond to the mean importance derived from the ensemble modeling framework, based on internal Jackknife procedures applied after collinearity filtering. Only variables retained following correlation analysis were included, thereby reducing redundancy among predictors such as elevation and climate-related variables.

For *Zornia glochidiata*, elevation emerged as the most influential variable (21%), followed by minimum temperature of the coldest month (15.6%), isothermality (13.5%), precipitation of the coldest quarter (12.6%), and precipitation of the wettest month (10.6%). Precipitation of the wettest quarter (Bio16) showed a comparatively lower contribution (8.4%).

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

Species	Variables 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

For *Andropogon pseudapricus*, precipitation-related variables dominated, with precipitation of the wettest quarter (Bio16; 34.8%) and annual precipitation (Bio12; 26.6%) contributing the most, while precipitation of the driest quarter (Bio17) had the lowest influence (5.3%).

Although climatic variables were predominant, the Human Footprint Index also contributed to habitat suitability, accounting for 18.3 and 8.5% of the explained variation for *Z. glochidiata* and *A. pseudapricus*, respectively, highlighting the combined influence of climatic and anthropogenic factors.

3.2 Model accuracy and performance

Table 2 presents the predictive performance of the six algorithms (RF, MaxEnt, GLM, GBM, SRE, and ANN) for the two fodder species using AUC, TSS, COR, and KAPPA metrics. Overall, most algorithms exhibited good predictive ability (AUC > 0.8). In contrast, ANN showed weak performance, particularly for *Andropogon pseudapricus* (AUC = 0.59, TSS = 0.50), and moderate performance for *Zornia glochidiata* (AUC = 0.75, TSS = 0.63), indicating limited predictive reliability for this algorithm.

For *Zornia glochidiata*, RF achieved the highest predictive performance (AUC = 0.98, TSS = 0.91). Similarly, for *Andropogon pseudapricus*, RF also performed best (AUC = 0.98, TSS = 0.90). MaxEnt and GBM showed intermediate performance levels. SRE, an envelope-based approach, produced acceptable but generally lower performance compared to machine learning algorithms, reflecting its more constrained modeling framework.

3.3 Current and future distribution of two fodder species

3.3.1 *Zornia glochidiata*

Currently, highly suitable habitats for *Z. glochidiata* cover 22.69% (43,843.77 km²) of Senegal, while moderately suitable habitats account for 32.15% (63,161.36 km²). Unsuitable areas represent 45.16% (88,834.02 km²) of the national territory (Appendix A; Fig. 3), with suitable habitats primarily concentrated in the Sudano-Sahelian and Sudanian zones (Fig. 4).

Future projections across all scenarios and time horizons indicate a general trend of habitat contraction; however, the magnitude of this decline appears to be highly sensitive to the choice of Global Climate Model (GCM) and emission pathways. Under the HadGEM3-GC31-LL model, projected habitat losses remain relatively consistent, ranging from 47.9 to 50.2% by the end of the century. In contrast, when considering the

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

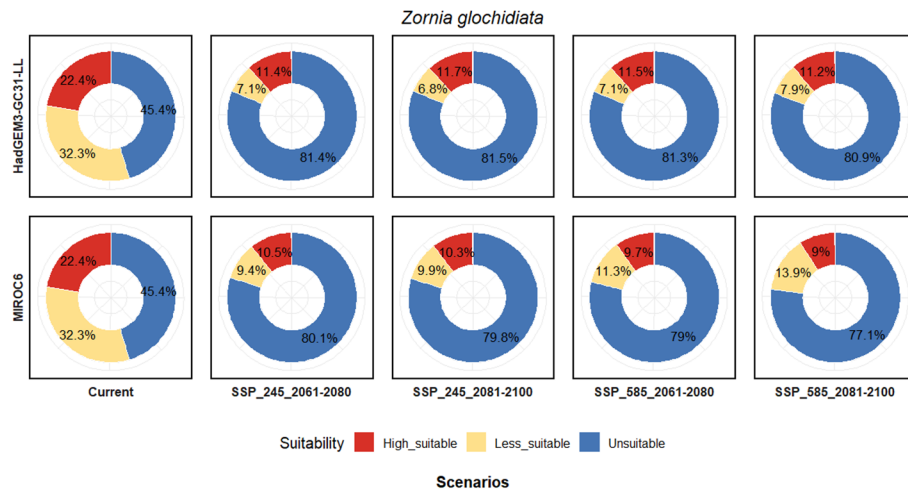


Fig. 3 Change in the range of suitable habitat areas for *Zornia glochidiata* under current and future climate scenarios based on SSP245; SSP585; HadGEM3-GC31-LL and MIROC6

MIROC6 model under the high-emission scenario (SSP585), projections yield a much more pessimistic outcome, where suitable areas could potentially decline to 9.65% by mid-century and 8.9% by 2100.

Despite these differences, both models agree on a general trend of range contraction, particularly in the central and northern parts of the current distribution. The extreme reductions projected by MIROC6 therefore represent a pessimistic scenario within the range of model uncertainty rather than a uniform outcome across all climate projections.

3.3.2 *Andropogon pseudapricus*

Under current climatic conditions, highly suitable habitats for *A. pseudapricus* represent 10.14% (19,942.38 km²) of Senegal's total area, while moderately suitable areas cover 26.03% (51,197.06 km²). Unsuitable areas account for 63.83% of the country (125,578.23 km²) (Appendix A; Fig. 5), with suitable habitats primarily concentrated in the northern Sahelian zone (Fig. 6).

Future projections indicate a general trend toward habitat reduction; however, the magnitude of change is highly sensitive to the choice of GCM. Under the HadGEM3-GC31-LL model, the total suitable area shows relatively limited variation, maintaining 88.11% (SSP245) and 88.37% (SSP585) of the current range by 2061–2080. In contrast, projections based on the MIROC6 model yield a much more extreme outcome under SSP585, where suitable habitat could potentially decline by 89.36% (5,448.75 km²) by 2061–2080. These contrasting results underscore that while a contraction is consistently projected, the most severe declines are model-contingent outcomes reflecting the specific climate sensitivity of the MIROC6 model.

Despite these discrepancies, both models converge on a declining trend in suitable habitats, particularly within the northern Sahelian zone, highlighting the species' sensitivity to future climatic conditions and the associated uncertainty in long-term projections.

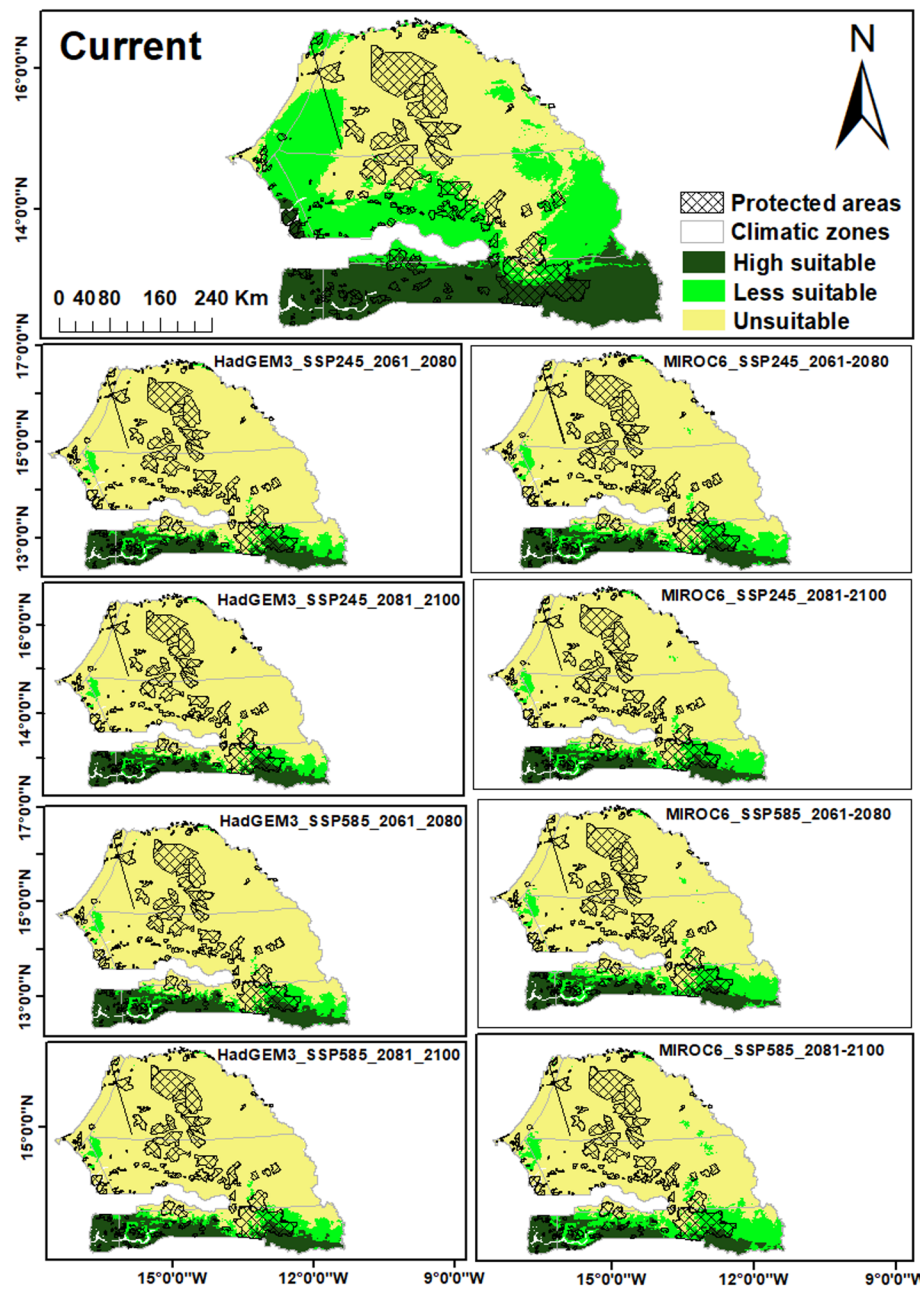


Fig. 4 Current and future distribution predictions of *Zornia glochidiata* under different climate scenarios (the upper bigger map is the current distribution and the small maps are the future distributions)

3.3.3 Trajectory of the two species under current and future climate conditions

Centroid shift analysis under future climate scenarios revealed contrasting trajectories between the two species (Fig. 7). For *A. pseudapricus*, the centroid consistently shifted northeastward, with displacement distances ranging from 150 to 230 km depending on the GCM and SSP scenario. The largest shift occurred under SSP585-2100 with HadGEM3 (≈ 230 km), indicating a progressive movement of suitable habitat toward cooler and relatively wetter eastern regions, consistent with the species' preference for sub-humid conditions.

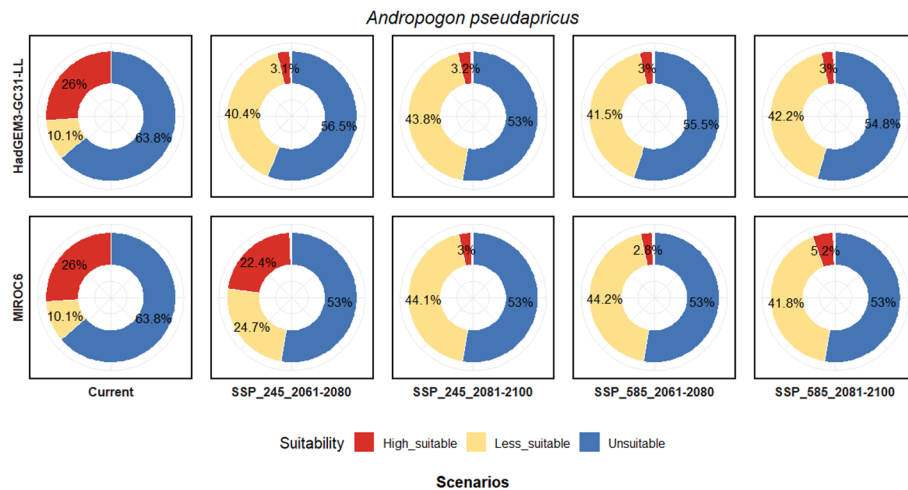


Fig. 5 Change in the range of suitable habitat areas for *Andropogon pseudapricus* under current and future climate scenarios based on SSP245; SSP585; HadGEM3-GC31-LL and MIROC6

In contrast, *Z. glochidiata* exhibited southwestward centroid shifts, with distances ranging from 100 to 140 km, particularly pronounced under MIROC6 projections. This pattern reflects displacement toward drier low latitude and western areas, in line with the species' tolerance to arid environments.

Although the magnitude of shifts varies among GCMs and SSPs, the directional trends are consistent, highlighting species-specific responses to climate change.

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 [66]. 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, 55], reinforcing the role of temperature and rainfall in determining the ecological niches of tropical species [68]. According to O'Donnell and Ignizio [70], 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* [74] and *Carapa procera* [58] in Burkina Faso, as well as for other multipurpose species in Benin [67]. The present findings are consistent with previous research on the spatial distribution of fodder species in West Africa [66]. Numerous studies have emphasized that precipitation and temperature are the dominant climatic factors influencing the distribution patterns of woody vegetation throughout the region [59, 62].

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 [66]. The growing intensity of human use of rangelands has

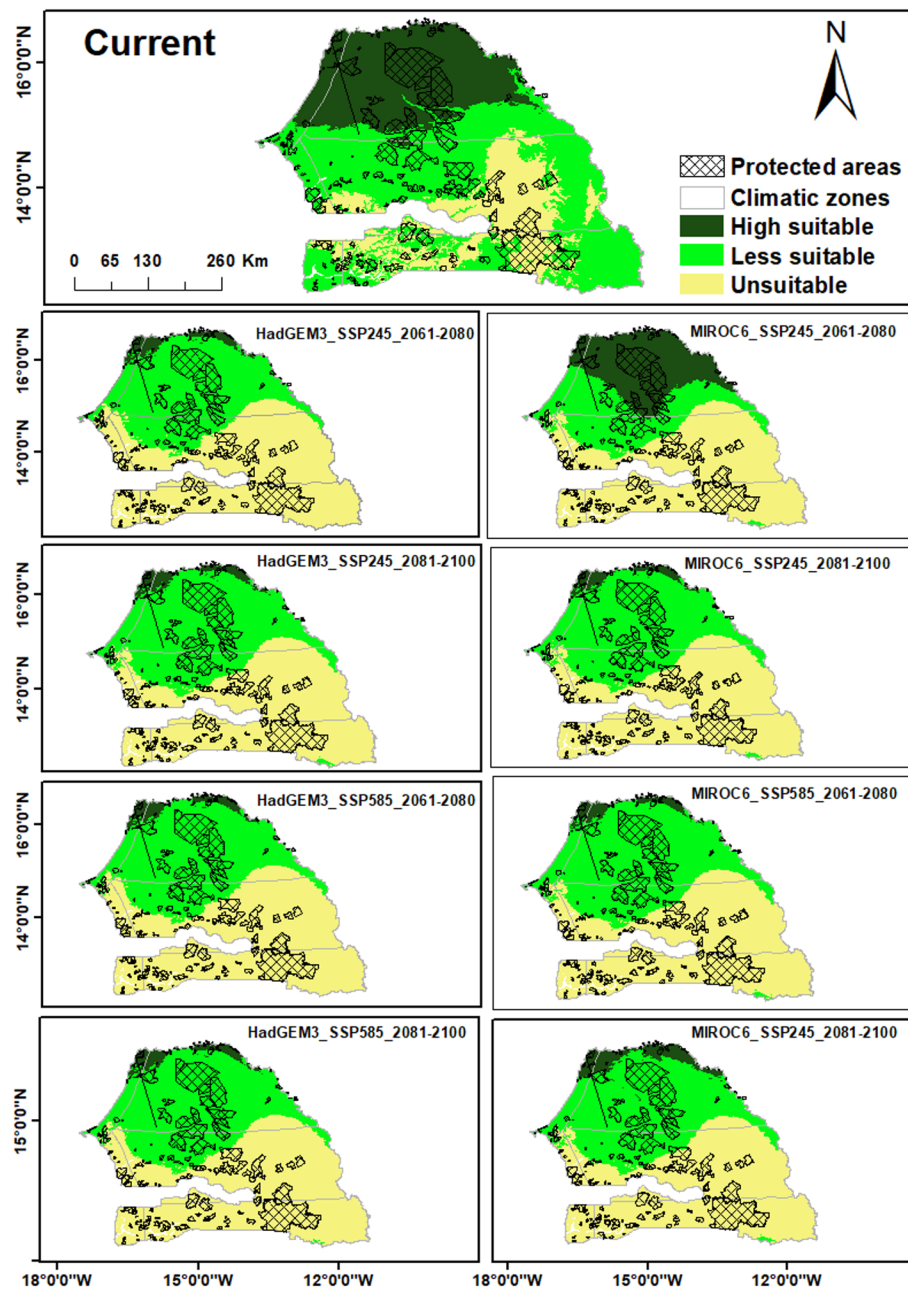


Fig. 6 Current and future distribution predictions of *Andropogon pseudapricus* under different climate scenarios. (The upper bigger map is the current distribution and the small maps are the future distributions)

been identified as a major driver of the widespread degradation of fodder vegetation in recent years [66].

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, RE, 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. [56] Coulibaly et al. [59],

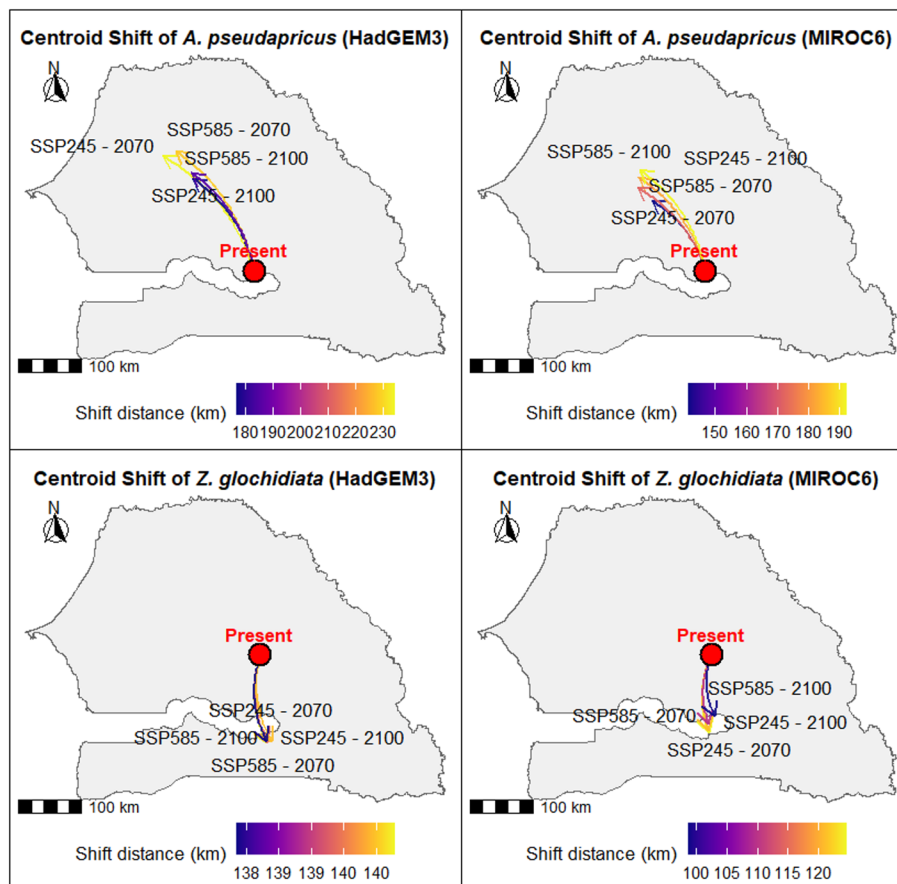


Fig. 7 Maps illustrating the directional shifts of the centroids for *A. pseudapricus* and *Z. glochidiata* from the current distribution to future SSP scenarios

and Sambou et al. [34], which also identified RF as the most effective method for species distribution modeling. Similarly, recent studies by Dogbo et al. [67] and Gbadamassi et al. (2025)[59] 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 [67]. Rausell-Moreno [72], 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 [73, 57].

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 [41]. 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 and Vuill. [59]. 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. [59], and for *Combretum glutinosum* Perr. ex-DC. in Burkina Faso, documented by Dembélé et al. [44]. 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. [62] 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* [58] and *Parkia biglobosa* (Jacq.) R.Br. ex G. Don [67], 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* [43] and *Adansonia digitata* under changing climatic conditions in the region [59]. 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 [71]. By 2100, under the specific projections of the MIROC6 model (SSP2-4.5), *Z. glochidiata* could potentially lose approximately 69.25% (19,419.32 km²) of its less suitable habitats, while *A. pseudapricus* is projected to lose about 56.81%. This difference may reflect species-specific ecological sensitivities to climate forcing. Furthermore, while not explicitly quantified in our spatial models, this decline could be further exacerbated by anthropogenic factors such as the expansion of croplands and urban areas, which often reduce the available niche in rangelands. Our results are consistent with those of Trisurat et al. [67] and Gbadamassi et al. [59], 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. [59] 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 [19, 43, 68, 69]. Climatic changes are altering habitats, while human pressures such as agricultural expansion and infrastructure

development continue to impact fodder species Gbadamassi et al. [59]. 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 to 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.

From a policy perspective, these findings can inform climate-smart rangeland planning by identifying priority areas for conservation, restoration, and sustainable grazing under future climate scenarios. The projected shifts in suitable habitats provide valuable inputs for national adaptation strategies, land use planning, and pastoral development policies. Incorporating these findings into decision making frameworks can help improve the resilience of rangeland systems and pastoral livelihoods in the face of ongoing climate change.

5 Conclusion

This study provides clear evidence that climate change, in interaction with topographic and anthropogenic factors, will strongly reshape the future availability of key fodder resources in Senegalese rangelands. The strong dependence of *Zornia glochidiata* and *Andropogon pseudapricus* on precipitation- and temperature related variables indicates a high sensitivity of these species to ongoing and projected climatic changes. The consistent contraction and spatial displacement of suitable habitats under future scenarios suggest that climate change may exacerbate forage scarcity, with direct implications for pastoral livelihoods and rangeland resilience.

The projected decline and redistribution of suitable areas, combined with the limited overlap between future suitable habitats and existing protected areas, highlight gaps in current conservation and land-use planning frameworks. These findings underscore the need to integrate climate-informed species distribution projections into rangeland management, conservation planning, and pastoral adaptation strategies. Proactive measures such as habitat protection, sustainable grazing management, and the prioritization of climate-resilient forage species will be essential to sustain pastoral systems under future climatic uncertainty.

Appendix A

Dynamics of suitable areas of *Zornia glochidiata* and *Andropogon pseudapricus* under current and future climatic conditions.

		Unsuitable			Less suitable			High suitable		
		Area (Km2)	Trend (%)	%	Area (Km2)	Trend (%)	%	Area (Km2)	Trend (%)	%
Z. glochidiata	HadGEM3-GC31-LL	Current		45.16	63,161.36		32.15	43,843.77		22.69
		SSP_245_2061-2080	79.21	80.93	13,927.69	-77.95	7.08	22,364.17	-48.99	11.37
		SSP_245_2081-2100	79.38	81.01	13,323.36	-78.91	6.77	22,815.99	-47.96	11.60
		SSP_585_2061-2080	78.96	80.82	13,964.85	-77.89	7.10	22,543.28	-48.58	11.46
	MIROC 6	SSP_585_2081-2100	78.03	80.40	15,501.84	-75.46	7.88	21,844.18	-50.18	11.10
		SSP_245_2061-2080	76.28	79.61	18,394.38	-70.88	9.35	20,500.71	-53.24	10.42
		SSP_245_2081-2100	75.63	79.31	19,419.32	-69.25	9.87	20,061.23	-54.24	10.20
		SSP_585_2061-2080	73.79	78.48	22,133.09	-64.96	11.25	18,977.71	-56.72	9.65
A. pseudapricus	HadGEM3-GC31-LL	SSP_585_2081-2100	69.78	76.67	27,159.99	-57.00	13.81	17,514.96	-60.05	8.90
		Current		63.83	19,942.38		10.14	51,197.06		26.03
		SSP_245_2061-2080	395.29	56.12	79,028.19	-60.37	40.17	6088.30	-88.11	3.10
		SSP_245_2081-2100	364.59	52.65	85,618.66	-57.07	43.52	6339.11	-87.62	3.22
	MIROC 6	SSP_585_2061-2080	386.55	55.13	81,111.58	-59.33	41.23	5955.05	-88.37	3.03
		SSP_585_2081-2100	380.48	54.45	82,560.46	-58.60	41.97	5856.29	-88.56	2.98
		SSP_245_2061-2080	364.59	52.65	48,227.98	-75.82	24.52	43,729.66	-14.59	22.23
		SSP_245_2081-2100	364.59	52.65	86,135.21	-56.81	43.79	5820.55	-88.63	2.96
A. pseudapricus	MIROC 6	SSP_585_2061-2080	364.59	52.65	86,510.47	-56.62	43.98	5448.75	-89.36	2.77
		SSP_585_2081-2100	364.59	52.65	81,822.04	-58.97	41.59	10,136.97	-80.20	5.15

Acknowledgements

We express our gratitude to the Ferlo population for their cooperation and to the people who helped collect this data.

Author contributions

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.

Funding

This work was supported by the Partnership for Skills in Applied Sciences, Engineering, and Technology (PASET) Regional Scholarship Innovation Fund (RSIF) awarded to Mr Sawadogo Idrissa.

Data availability

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

Declarations

Ethics approval and consent to participate

Not applicable.

Consent to publication

Not applicable.

Competing interests

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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Received: 4 October 2025 / Accepted: 8 April 2026

Published online: 30 April 2026

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