



Range shifts of *Vigna* crop wild relatives under a climate change scenario in Mozambique

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Received: 10 April 2025 / Accepted: 8 June 2025 / Published online: 28 June 2025
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Abstract

Understanding how climate change affects crop wild relatives (CWRs) is crucial for both biodiversity conservation and food security. The present study assesses the current and future habitat suitability of six *Vigna* CWRs taxa in Mozambique using species distribution modelling. Our results show that *Vigna* CWRs occupy diverse habitats, primarily in southern and southeastern Mozambique, with coastal areas exhibiting the highest suitability. We identified key climatic factors shaping these taxa distributions, specifically focusing on the precipitation of the warmest month and driest quarter. Future projections indicate sizable habitat losses, ranging from 1 to 99% by 2090, with inland regions expected to experience the highest impact. Taxa with restricted distribution, such as *Vigna unguiculata* subsp. *pawekiae*, face the highest risk of extinction. By integrating land cover and land use (LULC) constraints with climatic models, we observed even higher declines in habitat suitability, highlighting the influence of anthropogenic pressures on *Vigna*'s diversity. Despite these challenges, our findings suggest that coastal habitats may serve as climate refugia in long-term conservation efforts for most *Vigna* CWRs taxa. However, Mozambique's protected areas network provides limited coverage of highly suitable areas for these taxa, underscoring the need for urgent implementation of in situ and *ex situ* conservation measures. Future research should refine habitat suitability models by incorporating additional environmental and anthropogenic factors, along with biotic factors. This research highlights the pressing need for proactive and innovative conservation strategies to protect *Vigna* CWRs, which are essential for enhancing agricultural resilience and ensuring global food security in the face of climate change.

Keywords Crop wild relatives · Environmental changes · In situ conservation · Leguminosae · Species distribution models

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Introduction

Climate change is widely recognised as a major global environmental challenge with profound implications for biodiversity, agriculture, and human livelihoods (Muluneh 2021). Projections for the 2030–2050 period indicate an increase in global temperatures of approximately 1.5°C, primarily due to insufficient progress in implementing the Sustainable Development Goals in the 2030 Agenda (IPCC 2023). However, recent data show that by 2024, global temperature increase has surpassed this threshold (Bevacqua et al. 2025). The conservation of biodiversity in a climate change scenario is challenging, with several current studies reporting significant shifts in the suitable habitats of many plant taxa by expansions and contractions (e.g. Hoveka et al. 2022; Manda et al. 2022; Varela et al. 2023), ecosystem

fragmentation (e.g. Parmesan and Yohe 2003; Aleman et al. 2016), biodiversity loss (e.g. FAO and Alliance of Bioversity International and CIAT 2021), and phenological changes (e.g. Lima et al. 2022; Bush et al. 2020). Furthermore, it is crucial to assess how climate change affects species' habitat suitability and identify the most vulnerable ones requiring immediate conservation measures (Zhao et al. 2021).

Sub-Saharan Africa (SSA) is expected to be highly impacted by climate change due to several factors, such as the high average temperatures, dependence on rainfed agriculture for income and subsistence, and ongoing socioeconomic issues (Ringler et al. 2010). According to the Intergovernmental Panel on Climate Change (IPCC 2023), temperature increases in SSA are predicted to be higher than the annual average, with certain regions also facing rainfall decreases. Besides the rising temperatures, the region faces challenges like fluctuating rainfall patterns and an increase in extreme weather events, affecting ecosystems, food security, and livelihoods (Collier et al. 2008). Mozambique, the region addressed in this study, is particularly susceptible to natural disasters, including droughts, floods, and cyclones, due to its location downstream of nine of Africa's largest rivers and its extensive coastline and lowland areas (Ministry for the Coordination of Environmental Affairs 2005). Over the past two decades, the frequency of such disasters has increased, driven by the adverse effects of climate change, resulting in drastic economic impacts, particularly on agriculture, a key source of income and livelihood for Mozambicans, as well as both public and private infrastructures (Manuel et al. 2021). For example, Cyclone Idai, one of the strongest and deadliest observed in the southern hemisphere, hit central Mozambique (Sofala) in 2019, resulting in a huge loss of human life, infrastructure destruction, economic recession, and severe environmental damage (Charrua et al. 2021).

Crop Wild Relatives (CWRs), which are wild plants closely related to cultivated species, are among the many species affected by changing climatic conditions. These plants are particularly important due to their genetic diversity, which can help enhance crop resilience (e.g. Wambugu and Henry 2022). CWRs preserve a wide morphological and genetic diversity since they have not undergone domestication and are adapted to diverse habitats (Heywood et al. 2007). The genus *Vigna* Savi (Fabaceae, Tribe *Phaseoleae*) comprises over 100 taxa, of which nine are domesticated (Mackinder et al. 2001; POWO 2024). *Vigna* crops, such as cowpea (*Vigna unguiculata*) and bambara groundnut (*Vigna subterranea*), are essential components of food security across several parts of the world, especially in Africa, where the genus (ca. 90 native taxa) is widely distributed (e.g. Catarino et al. 2021a). In Mozambique, as in many African countries, *Vigna* crops are a critical part of both subsistence

and commercial agriculture (Brilhante et al. 2023). These crops are an important food and nutritional security source, particularly in rural areas, where climate change effects are inevitable and more severe (e.g. Thornton and Herrero 2015; Sintayehu 2018). The genetic diversity within *Vigna* CWRs is a vital resource for breeding programs aimed at increasing crop resilience to biotic and abiotic stresses under changing climatic conditions (Maxted et al. 2010). However, the current and future impacts of climate change pose significant challenges for these taxa, potentially modifying their habitats and distribution, which may interfere with their future use in crop improvement (e.g. Aguirre-Gutiérrez et al. 2017). Indeed, Jarvis et al. (2008) predicted that by 2055, 16–22% of *Vigna* CWR taxa could be at risk of extinction, with many losing up to 50% of their suitable habitat. Therefore, understanding how *Vigna* CWRs respond to climate change is imperative for their conservation and sustainable use.

Species distribution models (SDMs) are numerical tools broadly used in spatial ecology, conservation, and land management that correlate the known occurrence data of species with the environmental variables that define them to predict where species are most likely to occur under current and future climate conditions (Guisan and Thuiller 2005). Recent studies have applied SDM methodologies to predict the distribution of species across Africa under both current and future climate scenarios (e.g. Ngarega et al. 2022; Shekede et al. 2018). However, studies involving distribution modelling of Mozambique's flora remain limited, mainly due to the scarcity and quality of occurrence data for certain areas and species (Charrua et al. 2020).

To date, and to the best of our knowledge, no study on the impact of climate change on the present and future distribution of *Vigna* CWRs has yet been done in Mozambique. In this study, we address this research gap.

The present study aims to assess the climatic niche of six *Vigna* CWR taxa occurring in Mozambique and the potential impacts of climate change on their distribution. Therefore, four main objectives were defined: (i) to identify the bioclimatic variables influencing the current distribution of suitable habitats for six *Vigna* taxa; (ii) to model their present and future distribution under two climate change scenarios (SSP2-4.5 and SSP5-8.5) and calculate changes in their ranges; (iii) to evaluate the impact of present land use and land cover (LULC) on the habitat suitability by integrating LULC data with SDMs results for all climate scenarios; (iv) to assess the effectiveness of protected areas in safeguarding suitable habitats for target taxa under both current and future conditions; and (iv) to discuss the implications of these findings for the conservation and sustainable use of *Vigna* CWR in Mozambique.

Methodology

Study area

Mozambique is located in the southeastern part of the African continent, between latitudes 10°20'S and 26°50'S, covering an area of approximately 801,590 km² (i.e. 784,090 km² of the mainland and 17,500 km² of inland water) (Ali et al. 2008). The country shares borders with Tanzania to the north, Malawi and Zambia to the north-west, Zimbabwe to the west, the Indian Ocean to the east, and Eswatini (formerly known as Swaziland) and South Africa to the southwest (Fig. 1). Politically, Mozambique is divided into 11 provinces, with Maputo City as the capital. It has an extensive 2800 km coastline along the Indian Ocean (Palalane et al. 2016). Moreover, the country has an estimated population of approximately 34 million in 2023, with an average population density of 43.6 inhabitants per km² (World Bank 2024).

Mozambique's ecological diversity is shaped by its geographical framework, geology, and topography, exhibiting several ecosystems, such as savannas and mangroves to lowland and montane humid forests and dry coastal forests (e.g., Joaquim-Meque et al. 2023). The country comprises 13 main ecoregions, hosting several plant communities, including miombo, mopane, undifferentiated woodland, Afromontane communities, halophytic and swamp vegetation, and coastal mosaic (Bandeira et al. 1996). This diversity makes Mozambique an important area of plant diversity, with over 6,000 native and naturalised plant taxa (Hyde et al. 2024) and a high level of endemism (Darbyshire et al. 2019). Nearly 70% of the country's land cover consists of forests or woody vegetation, with 26% established as protected areas (Ministry for the Coordination of Environmental Affairs 2014).

Mozambique experiences a predominantly tropical climate, except for the southernmost regions, which have a subtropical climate (Barbosa et al. 2001). The country has two well-defined seasons: a hot and humid season from November to March and a cold and dry season from April to October (Hoguane et al. 2007). The annual mean temperature varies across the country because of its wide extent. The coastal northern regions have an average temperature of 25.5 °C, whereas the inland northern regions average 18 °C. The coastal central regions average 25 °C, while inland central regions experience 20 °C. The coastal southern regions average 23 °C, and the inland southern regions average 25 °C. Annual mean precipitation is approximately 1,030 mm, varying from 300 mm in the southern region (particularly in Gaza inland) to 1,400 mm in the Zambezi valley (Uamusse et al. 2017).

Several centres of plant endemism have been identified in Mozambique (Darbyshire et al. 2019; Odorico et al. 2022), namely: Chimanimani-Nyanga (including the Manica and Sofala highlands), Mulanje-Namuli-Ribáuè (including the Nampula and Zambezia highlands), Maputaland [divided into three subcentres: Maputaland *sensu stricto* (including Maputo and Gaza), Lebombo Mountains (located in Maputo province only), and Inhambane Centre (including Gaza and Inhambane)], and Rovuma (including the Cabo Delgado coastal area, Nampula, and Zambezia).

Target taxa

Vigna CWRs are distributed across several ecosystems, such as savannas, grasslands, open woodlands, and shrublands in subtropical and tropical regions (e.g., Mackinder et al. 2001). These herbaceous plants can be annual or perennial, showing prostrate, climbing or scrambling growth forms (e.g., Tomooka et al. 2011). Perennial taxa are characterised by woody rootstocks, which allow them to regenerate after seasonal dieback or burning (Maxted et al. 2004).

Our study focused on six *Vigna* CWRs taxa, which are considered a high priority for conservation in Mozambique based on their potential use for crop improvement, ethnobotanical uses, regional and global distribution, and the number of accessions in germplasm banks (Brilhante et al. 2023). These taxa include *Vigna unguiculata* (L.) Walp. subsp. *dekindtiana* (Harms) Verdc., *V. unguiculata* (L.) Walp. subsp. *pawekiae* Pasquet, *V. unguiculata* (L.) Walp. subsp. *pubescens* (R. Wilczek) Pasquet, *V. unguiculata* (L.) Walp. subsp. *stenophylla* (Harv.) Maréchal, Mascherpa and Stainier, *V. unguiculata* (L.) Walp. subsp. *tenuis* (E. Mey.) Maréchal, Mascherpa and Stainier, and *V. unguiculata* (L.) Walp. subsp. *unguiculata* (Table 1).

Taxa occurrence data records

The occurrence data for the six taxa of *Vigna* CWRs under study were primarily obtained from the Global Biodiversity Information Facility (GBIF) platform (GBIF.org 2024a, b, c, d, e and f). To enhance dataset quality, records from all SSA countries where the target taxa are native were included. Each record was assessed in terms of quality and accuracy, and the locations were confirmed using Google Earth Pro 7.3.4.8573 (Serea 2018). Duplicate records, identified by the same collector and collection number, were eliminated. Additionally, the dataset was complemented by the study of *Vigna* herbarium specimens collected in Mozambique and stored in the following institutions: Herbarium of the Institute of Tropical Scientific Research, University of Lisbon (LISC); Herbarium of the Royal Botanic Gardens, Kew (K); and Florence Tropical Herbarium (FT). Due to limited *Vigna*

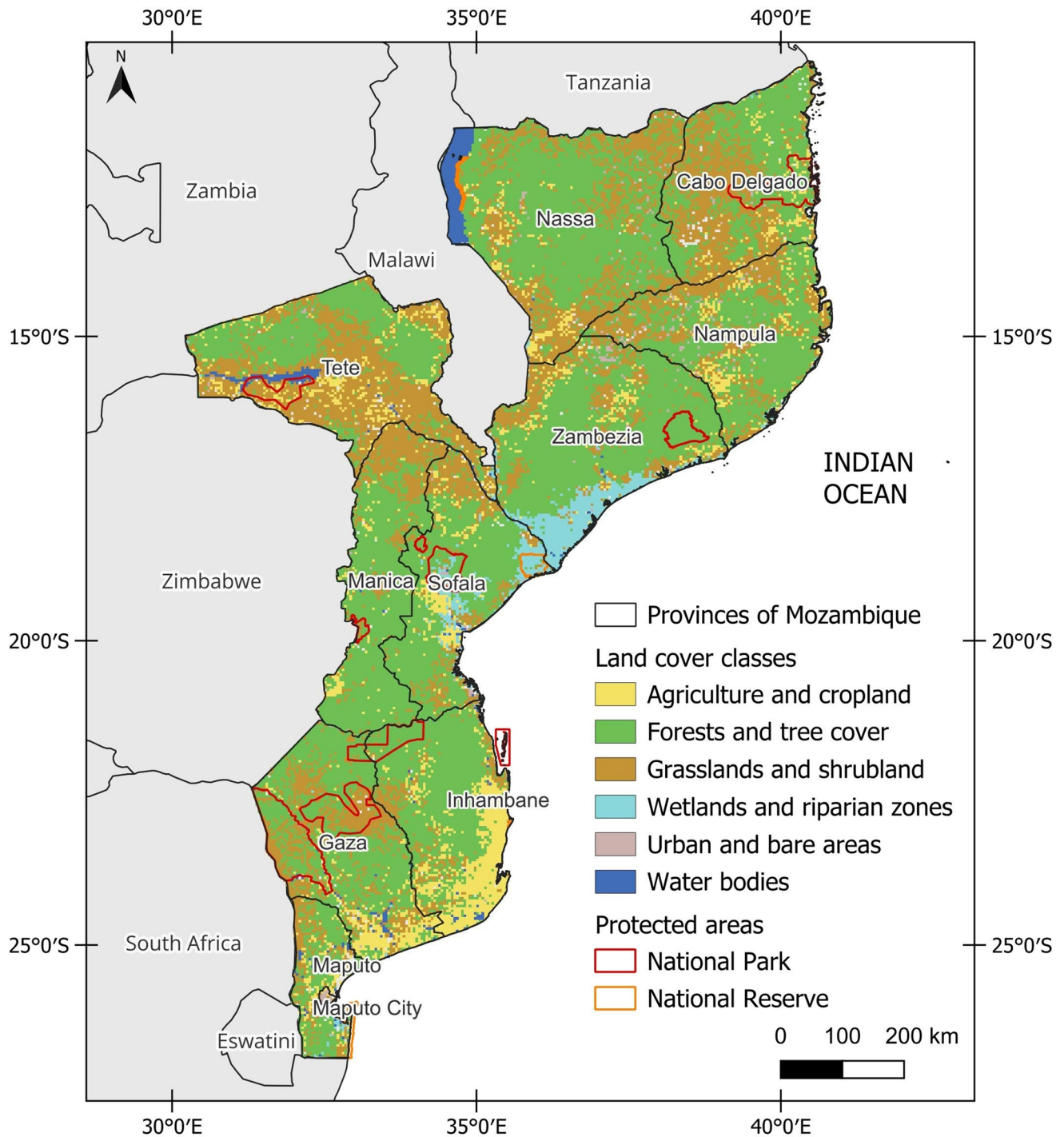


Fig. 1 Map showing Mozambique as the study area with details on provinces, protected areas and land cover categories

occurrence data from Mozambique, all the records from GBIF and herbarium specimens were analysed individually. Records without coordinates were geo-referenced based on the locality description according to guidelines described by Zermoglio et al. (2020). For records outside Mozambique,

only those with assigned geographical coordinates were considered.

The final dataset had 1,336 occurrence points (Table 2 and Figure S1) [i.e., *Vigna unguiculata* subsp. *dekindtiana* ($n=909$), *V. unguiculata* subsp. *pawekiae* ($n=35$), *V. unguiculata* subsp. *pubescens* ($n=40$), *V. unguiculata* subsp.

Table 1 Characterisation of the six studied *Vigna* CWR taxa in Mozambique

Taxa	Common name ¹	Life form	Native Distribution	Ecological preferences	LULC suitability scores					Refs ²
					Agriculture and croplands	Forests and tree cover	Grasslands and shrublands	Wetlands and riparian zones	Urban and bare areas	
<i>Vigna unguiculata</i> (L.) Walp. subsp. <i>dekindtiana</i> (Harms) Verdc.	nchanchin nhyemba (Mz)	Perennial climbing herb	Tropical & S. Africa	Grasslands (particularly if burnt seasonally), open woodlands, savannas, swamps, cultivated fields, riversides, riverine forests, littoral zones, and roadsides. Frequently associated with drier environments and sandy soils.	0.75	0.50	1.00	0.75	0.25	1, 3, 4, 5, 6
<i>Vigna unguiculata</i> (L.) Walp. subsp. <i>pawekiae</i> Pasquet	unknown	Perennial climbing herb	Kenya to S. Tropical Africa	Grasslands, tree and palm savannas, forest edges, gallery forests, swampy areas, fallow fields and roadsides.	0.75	0.75	0.75	0.25	0.25	1, 2, 3, 4, 6
<i>Vigna unguiculata</i> (L.) Walp. subsp. <i>pubescens</i> (R. Wilczek) Pasquet	niemboda (Mz)	Perennial climbing herb	South Sudan to Mozambique	Grasslands, savannas, coastal thickets, rocky outcrops, fallow fields and roadsides. Frequently near water.	0.75	0.50	1.00	0.75	0.50	1, 2, 3, 4, 5, 6
<i>Vigna unguiculata</i> (L.) Walp. subsp. <i>stenophylla</i> (Harv.) Märtschal, Mascherpa & Stainier	cowpea (En)	Perennial climbing herb, with rootstock	S. Tropical to S. Africa	Grasslands and savannas. Frequently associated with dry environments such as the Kalahari sands.	0.50	0.50	1.00	0.25	0.00	1, 2, 3, 4, 5, 6
<i>Vigna unguiculata</i> (L.) Walp. subsp. <i>tenuis</i> (E. Mey.) Märtschal, Mascherpa and Stainier	unknown	Perennial non-climbing herb, with rootstock	S. Tropical Africa to KwaZulu-Natal	Grasslands, miombo woodlands and sandy areas near the coast.	0.50	0.75	1.00	0.50	0.25	1, 2, 3, 4, 5, 6
<i>Vigna unguiculata</i> (L.) Walp. subsp. <i>unguiculata</i>	cowpea, black-eyed-pea (En); nhemba, nhumba (Mz);	Perennial climbing herb	Cape Verde, Tropical & S. Africa	Savannas, particularly in rough terrains and disturbed areas, and often as a weed in croplands. Frequently associated with dry environments and sandy soils.	1.00	0.50	1.00	0.50	0.25	1, 2, 3, 4, 6

¹English common name (En); Mozambican common name (Mz). ²Refs: **1**, Brilhante et al. (2023); **2**, Hyde et al. (2024); **3**, Mackinder et al. (2001); **4**, Maxted et al. (2004); **5**, Padulosi and Ng (1997); **6**, POWO (2024)

Table 2 Occurrence records and bioclimatic variables were used to model mozambique's six *Vigna* CWR taxa

Taxa	Occurrence records	Bioclimatic variables used in modelling ¹							
<i>Vigna unguiculata</i> subsp. <i>dekindtiana</i>	909	bio2	bio3	bio8	bio13	bio14	bio15	bio18	bio19
<i>Vigna unguiculata</i> subsp. <i>pawekiae</i>	40	bio2	bio4	bio8	bio14	bio15	bio18	bio19	
<i>Vigna unguiculata</i> subsp. <i>pubescens</i>	35	bio2	bio3	bio5	bio13	bio17	bio18	bio19	
<i>Vigna unguiculata</i> subsp. <i>stenophylla</i>	112	bio3	bio4	bio8	bio14	bio18			
<i>Vigna unguiculata</i> subsp. <i>tenuis</i>	36	bio2	bio4	bio8	bio12	bio14	bio18		
<i>Vigna unguiculata</i> subsp. <i>unguiculata</i>	204	bio2	bio3	bio8	bio13	bio14	bio18	bio19	

¹**Abbreviations:** bio2, mean diurnal range; bio3, isothermality; bio4, temperature seasonality; bio5, max temperature of warmest month; bio8, mean temperature of wettest quarter; bio12, annual precipitation; bio13, precipitation of wettest month; bio14, precipitation of driest month; bio15, precipitation seasonality; bio17, precipitation of driest quarter; bio18, precipitation of warmest quarter; and bio19, precipitation of coldest quarter

stenophylla ($n=112$), *V. unguiculata* subsp. *tenuis* ($n=36$), *V. unguiculata* subsp. *unguiculata* ($n=204$)].

Environmental variables

Current climate

Climate is the abiotic factor that most influences and defines species distribution (Pearson and Dawson 2003). Bioclimatic variables, obtained from monthly precipitation and temperature values, play an important role in shaping the distribution patterns of African Fabaceae species (Burke 2006; Jinga and Ashley 2019). Therefore, to model the distribution of *Vigna* CWR taxa in Mozambique, we used bioclimatic variables sourced from WorldClim v2.1 (WorldClim 2020a) with a spatial resolution of 2.5 arc minutes (ca. 5 km) (Fick and Hijmans 2017). These global climate layers, derived from historical climate data (1970–2000), have been widely used in plant distribution modelling (e.g. Perri et al. 2020; Charrua et al. 2021; Varela et al. 2022). A detailed description of the bioclimatic variables is available in Supplementary Table S1.

The initial set of 19 bioclimatic variables was reduced to the most ecologically relevant ones for each taxon by using the Variance Inflation Factor (VIF; Dormann et al. 2013) in R v4.3.3 (R Core Team 2024). The variables with the highest VIF were iteratively removed until a final list with only those with a VIF lower than 10 was obtained, minimising multicollinearity and avoiding model overfitting, increasing model performance. This analysis was conducted exclusively using bioclimatic values extracted from each taxon's presence location. Data layers were processed using QGIS v3.4.15 software (QGIS Development Team 2024), ensuring the same projection to the Geographic Coordinate System (WGS84) with the nearest neighbour resampling method. The summary of bioclimatic variables used for each *Vigna* CWR taxon is represented in Table 2.

Future climate

Future climate projections for 2050 (2041–2060) and 2090 (2081–2100) were obtained from the Coupled Model Inter-comparison Project 6 (CMIP6; Eyring et al. 2016), available online on WorldClim (WorldClim 2020b). These Shared Socio-Economic Pathways (SSPs) and CMIP6 projections are in line with the IPCC's Sixth Assessment Report (AR6), representing the latest climate change assessment (IPCC 2023). The forecasted values of each bioclimatic variable were obtained as the mean of the five less correlated climate models (i.e. CMCC-ESM2, EC-Earth3Veg, HadGEM3-GC31-LL, MIROC-ES2L, MPI-ESM1-2-LR) to reduce bias and improve the model accuracy (Merrifield et al. 2023). Future climate projections were analysed under two Shared Socio-economic Pathways: SSP2-4.5 (optimistic scenario) and SSP5-8.5 (pessimistic scenario) (e.g. O'Neill et al. 2016).

Species distribution modelling

Modelling settings, calibration and training

To study the current and future distribution of *Vigna* CWRs in Mozambique, we used the 'biomod2' R package (Biodiversity MODelling) v4.2-5-2 (Thuiller et al. 2024) in R v4.3.3 (R Core Team 2024). BIOMOD is a tool widely used in modelling studies, in which it is possible to select or combine different statistical modelling methods to maximise the accuracy and reliability in predicting the distribution of species under present climate or future climate scenarios (e.g. Hao et al. 2019; Thuiller et al. 2009). Our approach combines five different modelling algorithms to fit the species models, as described by Catarino et al. (2021b). We applied, based on their higher performance and statistics, two regression techniques (i.e., generalised linear models [GLMs; Guisan et al. 2002] and multivariate adaptive regression splines [MARS; Friedman 1991]) and three machine learning methods (i.e., generalised boosted models [GBMs; Friedman et al. 2000], random forest [RF;

Breiman 2001], and maximum entropy modelling [MaxEnt; Phillips et al. 2006; Elith et al. 2011]). While MaxEnt requires only presence data, the other methods require both presence and absence data (e.g. Elith et al. 2006; Whitford et al. 2024). Then, we generated three random datasets of pseudo-absences, each with a number approximately equal to that of the presence data (Barbet-Massin et al. 2012). Pseudo-absences were randomly selected from the study region's background data using the "BIOMOD_Formating-Data" function of the "biomod2" package (Thuiller et al. 2024). The pseudo-absences were used solely for model training and evaluation in algorithms requiring absence data and did not influence the selection or exclusion of predictor variables, which was conducted independently using only presence data.

Model training was conducted using the presence and pseudo-absence data covering the whole African continent. Since an independent validation dataset was not available, we employed a cross-validation strategy, which consists of randomly splitting the dataset into training (70%) and testing (30%) subsets (e.g. Varela et al. 2023). The training subset was used to fit the models, while the testing subset was used to assess their predictive accuracy. This process was repeated ten times per pseudo-absence dataset and algorithm, yielding a robust set of model replicates. All models were implemented using the default settings of each algorithm within the "biomod2" framework, with a maximum of 10,000 interactions. Absence and presence data were weighted equally, and ten permutations were performed for each model run to estimate the relative importance of each predictor variable.

Model validation and evaluation

The model's performance and accuracy were evaluated using two quantitative metrics: the Area Under the Curve (AUC) of the Receiver Operating Characteristic (ROC) and the True Skill Statistic (TSS). AUC assesses the model's discriminatory capacity in distinguishing between the presence and absence of data based on environmental predictors (e.g. Fawcett 2004). AUC values ranged from 0.5 to 1, with values closer to 1 indicating good model performance and a strong correlation between the predictor variables and species distribution (Fielding and Bell 1997). Thus, the following prediction accuracy ranges can be distinguished: 'failure' ($0.50 < \text{AUC} < 0.60$), 'poor' ($0.60 < \text{AUC} < 0.70$), 'reasonable' ($0.70 < \text{AUC} < 0.80$), 'good' ($0.80 < \text{AUC} < 0.90$), and 'excellent' ($\text{AUC} > 0.9$) (Peterson et al. 2008). TSS measures the model's ability to detect true presences (sensitivity) and true absences (specificity), which translates into the following expression: $\text{TSS} = \text{sensitivity} + \text{specificity} - 1$. Its values vary between -1 and $+1$, with values closer to 1 indicating

better model performance; thus, models can be categorised as poor ($\text{TSS} < 0.4$), acceptable ($0.4 < \text{TSS} < 0.8$), and very good ($\text{TSS} > 0.8$) (Allouche et al. 2006).

Given the use of repeated cross-validation, the model evaluation metrics were averaged across the ten runs per algorithm per pseudo-absence set, allowing for the calculation of mean values and standard deviations for each model (e.g. Varela et al. 2022, 2023).

The importance of the bioclimatic variables was calculated using the 'get_variables_importance' function in the 'biomod2' R package. This method involves assessing how shuffling (or permuting) the value of each variable affects the model's predictive accuracy, as described in Thuiller et al. (2024). The results are presented as a correlation whose value varies between 0 (weak contribution/irrelevance) and 1 (strong contribution).

Ensemble models

An ensemble modelling approach was applied in our analysis to ensure more accurate predictions of species distribution. We performed the ensemble using the 'average' consensus method, an effective way of combining predictions from several models and more robust than other ensemble procedures (Marmion et al. 2009). This approach ensures that the overall model result reflects a balanced integration of the individual model contributions, thus reducing the potential biases of any model (Araújo and New 2007). To further improve the reliability of our ensemble forecasts, we implemented a selection criterion based on the ROC metric, specifically keeping only those models with an AUC value greater than 0.7 as employed by Catarino et al. (2021b). This threshold indicates strong model performance in differentiating between presence and absence data, ensuring that only the best-performing models were included in the final ensemble. The final ensemble models' performance was evaluated by AUC and TSS metrics as described above.

Model projections

Ensemble models of each *Vigna* CWR taxa for potential distribution under current and future climate conditions were projected using the 'BIOMOD_EnsembleForecasting' function of the 'biomod2' R package (Thuiller et al. 2024). Forecast projections for future climates were carried out for 2050 and 2090 under two different SSPs (i.e., SSP2-4.5 [optimistic scenario] and SSP5-8.5 [pessimistic scenario]). We, therefore, obtained continuous probability distribution maps of the projections of the ensemble predictions. Based on four probability classes, the continuous probability maps were classified according to their potential for occurrence as follows: unsuitable (< 0.25), low potential

(0.25–0.5), medium potential (0.5–0.75), and high potential (>0.75) (e.g. Charrua et al. 2020; Varela et al. 2022). The maps obtained that corresponded to the African continent were cropped based on the Mozambique shapefile (GADM 2023) using the ‘crop’ function of the R ‘raster’ package (Hijmans 2023).

Finally, changes in the suitable habitat of taxa under climate change scenarios compared to the current scenario were calculated using the ‘BIOMOD_RangeSize’ function of the R ‘biomod2’ package (Thuiller et al. 2024). For this analysis, binary presence-absence maps were used (i.e. classified as 0 or 1, corresponding to a probability of a pixel being a suitable habitat for taxa or not), obtained from the continuous probability maps by applying a threshold value that maximises the AUC values, ensuring an optimal balance between sensitivity and specificity. Specifically, we only considered as suitable habitats the areas with a probability above 50% (medium and high potential) by applying the threshold. Furthermore, this analysis assesses the extent of habitat loss and gain for each taxon, providing insight into how climate change may affect the spatial distribution of *Vigna* CWRs in Mozambique.

Land cover and land use (LULC) suitability maps

We created maps of Land Cover and Land Use (LULC) probabilities to assess the LULC impacts on habitat availability and suitability. LULC data were obtained from the Copernicus Climate Change Service (2019), specifically the Land cover classification gridded maps from 1992 to present, derived from the satellite observation dataset (version 2.1.1.). These data were reclassified to more accurately reflect the habitat suitability for *Vigna* CWRs (Fig. 1). Suitability scores, ranging from 0 to 1, were assigned to each LULC category according to the ecological preferences of each taxon as detailed in the literature (Table 1). These scores were applied individually to each taxon in terms of probability of occurrence as follows: 0 (no probability), 0.25 (low probability), 0.50 (moderate probability), 0.75 (high probability), and 1 (very high probability). Subsequently, we integrated the LULC suitability scores with the SDMs for the present and future climates by multiplying, for each cell, the respective LULC score with the habitat suitability value derived from the SDMs. This approach provided suitability maps for *Vigna* CWRs considering both land use limitations and climatic suitability for the current climate conditions.

Protected areas effectiveness

To evaluate how effective protected areas are in conserving *Vigna* CWRs under current and future climate scenarios,

considering also land use limitations, we used the geographic boundaries of protected areas extracted from the World Database on Protected Areas (WDPA) and World Database on Other Effective Area-Based Conservation Measures (WD-OECM) (UNEP-WCMC and IUCN 2025). This approach was focused solely on protected areas of total conservation (namely, National Parks and National Reserves), which aligns with Mozambique’s legislation (Diário da República de Moçambique, Law No. 5/2017, p. 183) (Fig. 1). Suitability maps were processed using QGIS (QGIS Development Team 2024) by clipping them to the boundaries of protected areas. We then employed QGIS’s Zonal Statistics tool to extract probability values for suitable habitats within each protected area.

Results

Model performance evaluation

The predictive performance of both single and ensemble models was assessed using AUC and TSS metrics for the six *Vigna* CWR taxa. These metrics were applied across five different modelling algorithms (GBM, GLM, MARS, MAX-ENT, and RF), revealing variation in performance between algorithms and taxa (see Supplementary Table S2 for further details). The RF algorithm performed best, showing AUC and TSS values close to or equal to 1 for almost all taxa. For GBM, the AUC values ranged from 0.920 (*Vigna unguiculata* subsp. *dekindtiana*) to 0.999 (*Vigna unguiculata* subsp. *stenophylla*), while the TSS values were 0.688 (*Vigna unguiculata* subsp. *dekindtiana*) and 0.982 (*V. unguiculata* subsp. *tenuis*). The minimum AUC value in MAXENT was 0.894 (*Vigna unguiculata* subsp. *dekindtiana*), while the maximum was 0.957 (*Vigna unguiculata* subsp. *tenuis*); the minimum TSS value was 0.604 (*Vigna unguiculata* subsp. *dekindtiana*), while the maximum was 0.915 (*Vigna unguiculata* subsp. *tenuis*). For MARS, AUC values ranged from 0.841 (*Vigna unguiculata* subsp. *dekindtiana*) to 0.999 (*Vigna unguiculata* subsp. *tenuis*), while TSS values ranged from 0.546 (*Vigna unguiculata* subsp. *dekindtiana*) to 0.992 (*Vigna unguiculata* subsp. *tenuis*). Finally, GLM showed the lowest performance, with AUC values ranging from 0.794 (*Vigna unguiculata* subsp. *dekindtiana*) to 0.994 (*Vigna unguiculata* subsp. *stenophylla*) and TSS values ranging from 0.487 (*Vigna unguiculata* subsp. *dekindtiana*) to 0.976 (*Vigna unguiculata* subsp. *tenuis*).

Considering the ensemble models, which combine the predictions of the best-performing models (AUC >0.7), the AUC values ranged from 0.890 (*Vigna unguiculata* subsp. *dekindtiana*) to 0.989 (*Vigna unguiculata* subsp. *tenuis*), while the TSS values were 0.663 (*Vigna unguiculata* subsp.

dekindtiana) to 0.973 (*Vigna unguiculata* subsp. *tenuis*) (Fig. 2). Thus, it is possible to emphasise that *Vigna unguiculata* subsp. *stenophylla* and *Vigna unguiculata* subsp. *tenuis* presented the best-performing models.

Environmental variables contributions

Of the 19 bioclimatic variables considered for modelling, seven were excluded after applying the VIF method, and only twelve were used in our study, as seen in Table 2. The six *Vigna* taxa under study responded differently to the different environmental variables (Supplementary Figure S2). Despite the different responses, the ones that generally showed the greatest predictive contribution across the six taxa analysed were bio3 (isothermality), bio4 (temperature seasonality), bio14 (precipitation of the driest month), and bio18 (precipitation of the warmest quarter). The bio18 had the highest contributions to three of the six taxa. Specifically, regarding the ensemble models, for *Vigna unguiculata* subsp. *dekindtiana*, bio18 showed the highest percentage of contribution, followed by bio3 and bio13 (precipitation of the wettest month). The *Vigna unguiculata* subsp. *pawekiae* exhibited bio4, bio8 (mean temperature of the wettest quarter), and bio18 as main contributor variables, while for *V. unguiculata* subsp. *pubescens*, the main contributor variables were bio17 (precipitation of the driest quarter) with the greatest contribution, bio2 (mean diurnal range), and bio3. For *Vigna unguiculata* subsp. *stenophylla*, bio18 displayed the highest percentage of contribution, followed by bio4 and bio14. Regarding the *Vigna unguiculata* subsp.

tenuis, bio14 was the main contributor, followed by bio18 and bio4. Finally, *Vigna unguiculata* subsp. *unguiculata* presented bio18 as the main contributor, followed by bio3 and bio14.

Potential distributions of habitat suitability

Current distribution

The habitat suitability predicted by the ensemble models for the six taxa of *Vigna* CWR under the current climate showed different distribution patterns across Mozambique. While some taxa exhibited broader distributions, others were more restricted (Table 3). Areas with a probability of occurrence equal to or higher than 50% are classified as suitable, representing medium to high potential.

Without considering LULC constraints, our results indicate that *Vigna unguiculata* subsp. *dekindtiana* has the largest potentially suitable area (705,697.541 km²) under the current climate scenario, followed by *Vigna unguiculata* subsp. *unguiculata* (582,985.284 km²), covering nearly 90% and 74% of Mozambique's land surface, respectively. *Vigna unguiculata* subsp. *stenophylla* (492,739.884 km²), *Vigna unguiculata* subsp. *pubescens* (453,074.882 km²), and *Vigna unguiculata* subsp. *tenuis* (449,228.708 km²) also exhibit relatively broad suitable ranges, covering approximately 63%, 58%, and 57% of Mozambique's land surface, respectively. In contrast, *Vigna unguiculata* subsp. *pawekiae* (104,899.534 km²) shows the smallest suitable area, representing only 13% of Mozambique's land surface.

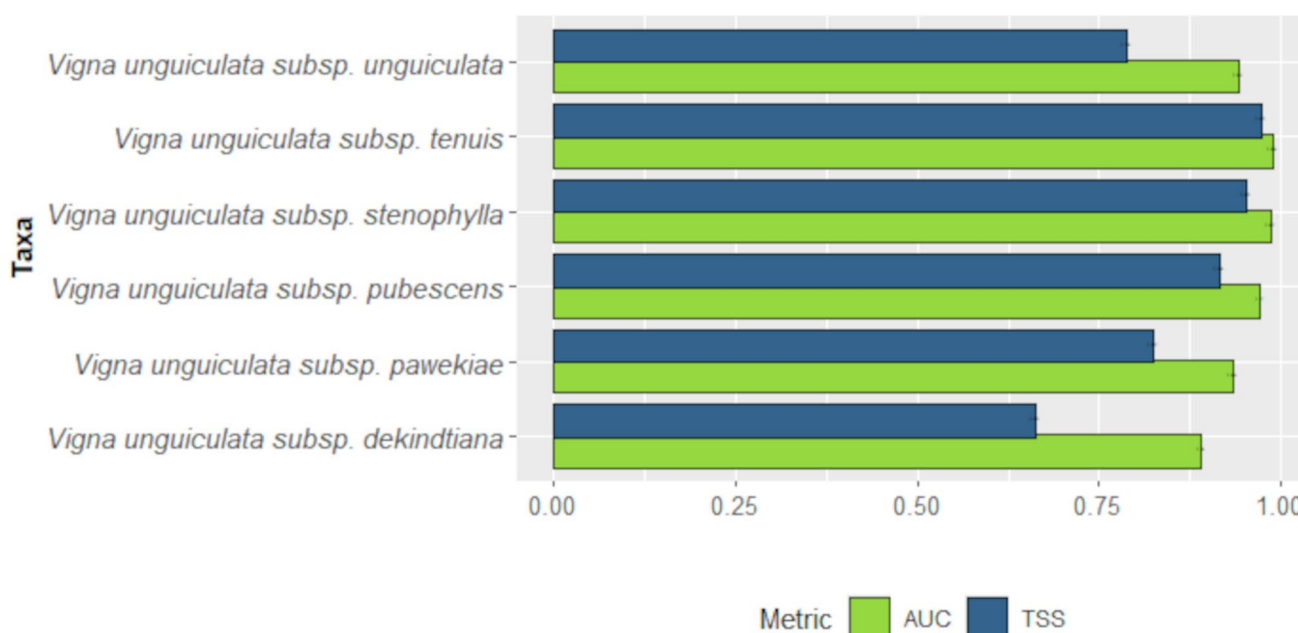


Fig. 2 Average values of the true skill statistic (TSS) and the area under the curve (AUC) of the receiver operating characteristic used to evaluate the six *Vigna* CWR taxa ensemble models

Table 3 Changes in suitable areas for *Vigna* CWRs taxa (probability of occurrence above 50%) changes under future Climatic scenarios compared to current conditions in mozambique, without considering LULC constraints

Taxa	Current Range Size (km ²)	2050 SSP2-4.5 (km ²)	Δ (%)	2090 SSP2-4.5 (km ²)	Δ (%)	2050 SSP5-8.5 (km ²)	Δ (%)	2090 SSP5-8.5 (km ²)	Δ (%)
<i>Vigna unguiculata</i> subsp. <i>dekindtiana</i>	705,697.541	695,254.859	-1.480	635,349.103	-9.969	709,672.636	+0.563	574,411.971	-18.604
<i>Vigna unguiculata</i> subsp. <i>pawekiae</i>	104,899.534	24,430.719	-76.710	8,229.521	-92.155	21,143.208	-79.844	1,353.681	-98.710
<i>Vigna unguiculata</i> subsp. <i>pubescens</i>	453,074.882	363,581.527	-19.752	315,364.699	-30.395	360,229.555	-20.492	280,620.22	-38.063
<i>Vigna unguiculata</i> subsp. <i>stenophylla</i>	492,739.884	406,684.449	-17.465	379,352.985	-23.012	485,498.765	-1.470	449,056.813	-8.865
<i>Vigna unguiculata</i> subsp. <i>tenuis</i>	449,228.709	354,449.552	-21.098	325,656.972	-27.508	407,350.546	-9.322	367,470.674	-18.200
<i>Vigna unguiculata</i> subsp. <i>unguiculata</i>	582,985.284	616,139.725	+5.687	594,588.264	+1.990	587,927.294	+0.848	553,161.328	-5.116

Most taxa show a wide current distribution with medium to high suitability, particularly along coastal areas, with some taxa extending to inland regions (see Figure S3 for further details). *Vigna unguiculata* subsp. *dekindtiana* presents higher suitability across the Maputo, Gaza, Inhambane, and Sofala coastal regions, extending inland to Manica, nearly all of Zambezia, and parts of Niassa near Lake Niassa. Conversely, *Vigna unguiculata* subsp. *pawekiae* has the most restricted distribution, occurring in small, isolated patches, particularly in the north and centre of Mozambique, with higher potential in the interior of Manica, Sofala, Tete, Zambezia, and Niassa. *Vigna unguiculata* subsp. *pubescens* is most distributed along the Maputo, Gaza, and Inhambane coastal regions, with additional suitable areas inland in Manica, Zambezia, the coast of Nampula, and the extreme north of Cabo Delgado near Palma. *Vigna unguiculata* subsp. *stenophylla* and *Vigna unguiculata* subsp. *tenuis* exhibit higher suitability along Maputo, Gaza, Inhambane, and Sofala coastal regions, as well as inland together with Manica, part of Tete, the coast of Zambezia, and the strip up to the border with Malawi near Milange, as well as Niassa near Lake Niassa. Finally, *Vigna unguiculata* subsp. *unguiculata* shows higher suitability along both the coast and inland regions of Maputo, Gaza, and Inhambane, with additional suitable areas, though to a lesser extent, in Manica, Tete, and Zambezia.

Future distribution

The future habitat suitability distribution for the six *Vigna* CWR taxa is significantly impacted by climate change, as shown by distribution models under the SSP2-4.5 and SSP5-8.5 scenarios for 2050 and 2090. Our results demonstrate varying expansion and contraction trends of suitable areas (probability of occurrence above 50%) across the studied taxa, with more than half of the taxa expected to face habitat loss ranging from 1 to 92% under the SSP2-4.5 scenario and from 1 to 99% under the SSP5-8.5 scenario (Table 3). Inland regions are projected to experience the highest declines in habitat suitability, while coastal regions remain moderately stable but still exhibit a notable decrease in highly suitable areas. Under the SSP5-8.5 scenario, even more significant losses in habitat suitability are predicted by 2090.

The responses of the different taxa vary considerably, as shown in Table 3 (see Figure S3 for further details). *Vigna unguiculata* subsp. *dekindtiana*, *Vigna unguiculata* subsp. *stenophylla*, and *Vigna unguiculata* subsp. *unguiculata* exhibit relatively stable high suitability areas near the coast, whereas *Vigna unguiculata* subsp. *pawekiae* and *Vigna unguiculata* subsp. *pubescens* face significant decreases, with large parts of their current distribution areas becoming unsuitable by 2090. *Vigna unguiculata* subsp. *tenuis* shows

a mixed trend, maintaining areas of high suitability in some places and experiencing declines in others. Under the SSP2-4.5 scenario, *Vigna unguiculata* subsp. *dekindtiana* remains relatively stable, with a slight decrease of 1.480% in 2050 and a more pronounced reduction of 9.969% in 2090. However, under the SSP5-8.5 scenario, the taxon presents an increase of 0.563% in 2050 and a substantial decline of 18.604% in 2090. *Vigna unguiculata* subsp. *pawekiae* faces the most severe reductions, with an estimated habitat loss of 76.710% in 2050 and 92.155% in 2090 under the SSP2-4.5 scenario. The contractions are even more pronounced under the SSP5-8.5 scenario, with losses of 79.844% in 2050 and 98.710% in 2090. *Vigna unguiculata* subsp. *pubescens* experiences significant habitat contractions in both scenarios, with reductions of 19.752% and 30.395% in 2050 and 2090, respectively, for the SSP2-4.5 scenario, and even more dramatic declines of 20.492% and 38.063% for the SSP5-8.5. For *Vigna unguiculata* subsp. *stenophylla*, range contractions under the SSP2-4.5 scenario are moderate, with decreases of 17.465% in 2050 and 23.012% in 2090. The losses are less pronounced under the SSP5-8.5 scenario, with a reduction of 1.470% in 2050 and 8.865% in 2090. *Vigna unguiculata* subsp. *tenuis* shows range size losses with 21.098% and 27.508% reductions in 2050 and 2090, respectively, under SSP2-4.5. Under the SSP5-8.5 scenario, the losses are comparatively lower, at 9.322% in 2050 and 18.200% in 2090. Conversely, *Vigna unguiculata* subsp. *unguiculata* follows a different trend, with an expansion in habitat of 5.687% in 2050 and 1.990% in 2090 under the SSP2-4.5 scenario. However, under the SSP5-8.5 scenario, the expansion is minimal at 0.848% in 2050, followed by a slight contraction of 5.116% in 2090.

Refining suitability with LULC constraints

Figure 3 illustrates the predicted current and future (SSP2-4.5 and SSP5-8.5) habitat suitability for Mozambique's six *Vigna* CWR taxa, integrating climatic models and LULC constraints. The results present a significant reduction in suitable habitat across all taxa when considering LULC constraints. These changes were only assessed for suitable areas (i.e., medium and high potential), referring to areas with a probability of occurrence above 50%.

Under the current climate scenario, habitat suitability decreases by an average of 65.338%. Future projections indicate even higher declines, with suitability losses reaching 68.490% under SSP2-4.5 for 2050 and 73.018% by 2090. Under the SSP5-8.5 scenario, suitability decreases by 68.827% in 2050 and 69.769% by 2090.

Among the six taxa studied (Fig. 4), *Vigna unguiculata* subsp. *stenophylla* shows the most substantial decline, with suitability decreasing by 81.434% for the current climate

scenario. The trend is the same under future projections, with reductions of 85.111% by 2050 under SSP2-4.5 and 82.538% under SSP5-8.5. By 2090, *Vigna unguiculata* subsp. *pawekiae* is the most impacted taxon, experiencing reductions in the suitability of 93.734% under SSP2-4.5 and 82.540% under SSP5-8.5. Conversely, *Vigna unguiculata* subsp. *tenuis* exhibits the lowest decrease in habitat suitability, with a reduction of 43.749% after applying LULC constraints.

Protected areas effectiveness and conservation

The habitat suitability of *Vigna* CWRs across 14 protected areas of total conservation is illustrated in Fig. 5 as a spatial overlay and in Fig. 6 as average values of probability of occurrence for the six studied taxa under current and future climate scenarios (i.e., SSP2-4.5 for 2050 and 2090, and SSP5-8.5 for 2050 and 2090). Under the current climate scenario, only the Pomene (PE) National Reserve exhibits habitat suitability with values exceeding 50%. Comparing current and future scenarios reveals an overall decline in habitat suitability for most protected areas. However, Chimanimani (CH) and Serra da Gorongosa (SG) National Parks stand out as exceptions, showing significant increases.

A detailed analysis of individual taxa reveals distinct trends across protected areas (Supplementary Table S3). Among protected areas, only Magoé National Park (50.625%), Marromeu (59.832%), and Pomene (65.300%) National Reserves currently exceed 50% of the probability of occurrence for *Vigna unguiculata* subsp. *dekindtiana*. Future climate scenarios reveal a general decline in suitability, except in Chimanimani, Magoé, and Serra da Gorongosa National Parks, where suitability is projected to increase significantly. For *Vigna unguiculata* subsp. *pawekiae*, only Chimanimani (57.527%) and Serra da Gorongosa (57.029%) National Parks show a probability of occurrence above 50% under the current climate scenario. Under future climate scenarios, an overall decline is projected across most protected areas. For *Vigna unguiculata* subsp. *pubescens*, only Marromeu (56.739%) and Serra da Gorongosa (60.325%) National Reserves exhibit a probability of occurrence above 50% under the current climate scenario. Future projections show a general decline; however, Serra da Gorongosa National Park and Ponta do Ouro National Reserve show significant increases in suitability under both SSP2-4.5 and SSP5-8.5. Also, slight increases are observed for Bazaruto and Chimanimani National Parks and Pomene National Reserve under the SSP2-4.5 for both 2050 and 2090. *Vigna unguiculata* subsp. *stenophylla* currently exhibits a probability of occurrence below 50% across all protected areas. However, future projections indicate significant increases in Bazaruto, Quirimbas, Serra da Gorongosa National Parks,

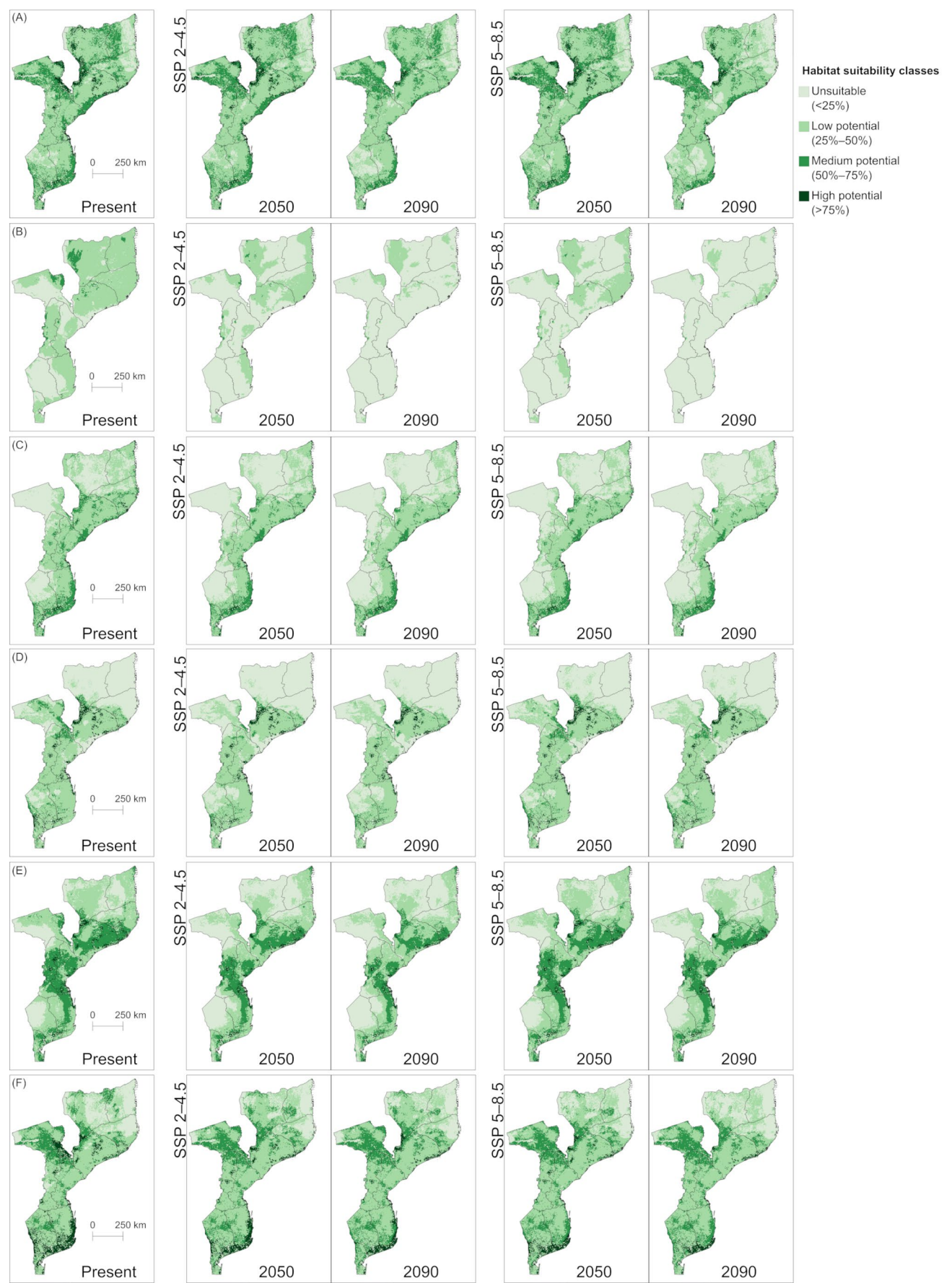


Fig. 3 Predicted potential current and future (SSP2-4.5 and SSP5-8.5) habitat suitability for Mozambique's six *Vigna* CWR taxa based on climatic models and constraints derived from different LULC categories. (A) *V. unguiculata* subsp. *dekindtiana*; (B) *V. unguiculata* subsp. *pawekiae*; (C) *V. unguiculata* subsp. *pubescens*; (D) *V. unguiculata* subsp. *stenophylla*; (E) *V. unguiculata* subsp. *tenuis*; and (F) *V. unguiculata* subsp. *unguiculata*

and Marromeu National Reserves. Currently, only Chimanimani (65.736%), Gilé (65.142%), Gorongosa (58.227%), and Serra da Gorongosa (54.176%) National Parks, and Ponta do Ouro National Reserve show a probability of occurrence above 50% for *Vigna unguiculata* subsp. *tenuis*. Future projections indicate that Chimanimani and Serra da Gorongosa National Parks experience significant increases in habitat suitability. However, Magoé and Quirimbas National Parks show slight increases under the SSP5-8.5 scenario in both 2050 and 2090. For *Vigna unguiculata* subsp. *unguiculata*, the probability of occurrence currently exceeds 50% in Banhine (53.464%) and Limpopo (57.704%) National Parks, and Pomene (86.667%) and Ponta do Ouro (51.530%) National Reserves. Under future scenarios, Chimanimani, Gorongosa, Magoé, and Serra da Gorongosa National Parks, and Lago Niassa and Marromeu National Reserves exhibit significant increases in suitability.

Discussion

Our study aimed to evaluate the habitat suitability of six taxa of *Vigna* CWRs in Mozambique under current and future climate conditions using ensemble modelling techniques. The results offer valuable insights into how climate change impacts the distribution of these taxa, directly informing conservation and management efforts and sustainable use of these important plant genetic resources.

The assessment of the individual models showed that the RF algorithm generated the highest quality models, as evidenced by achieving the highest AUC and TSS values. These results are in line with previous studies (e.g. Varela et al. 2023; Dogbo et al. 2025), which highlight the efficiency of RF in species distribution modelling due to its ability to deal with complex interactions and non-linear relationships between variables (Kumari et al. 2024). Combining the predictions from best-performing individual models (AUC > 0.7; e.g. Catarino et al. 2021) resulted in more accurate and reliable ensemble models for the six studied taxa, reducing inconsistencies often associated with models with lower AUC values.

Our analysis identified key climatic variables, including the precipitation of the warmest month and the driest quarter, which play a decisive role in determining the distribution of *Vigna* CWRs. The diverse responses of the taxa to specific climatic variables indicate that environmental factors shape

each one's climatic niches uniquely. This aligns with the findings of Jarvis et al. (2008) and Manda et al. (2022), who reported that different taxa of *Vigna* CWRs respond differently to diverse environmental variables. Similarly, studies on other African Fabaceae CWRs, such as those by Idohou et al. 2025; have reported similar patterns.

The precipitation of the warmest month (bio18) emerged as the most important predictor variable for *Vigna unguiculata* subsp. *dekindtiana*, *Vigna unguiculata* subsp. *stenophylla*, and *Vigna unguiculata* subsp. *unguiculata*, whereas the precipitation of the driest month (bio14) played a crucial role for *Vigna unguiculata* subsp. *tenuis*. Similar trends have been reported for other Fabaceae taxa in Africa. For example, the study by Semu et al. (2021) considered the precipitation of the warmest month and that of the driest month to be the variables with the greatest predictive power in the distribution of *Vachellia negrii* (Pic.Serm.) Kyal. & Boatwr. in Ethiopia, while Ngarega et al. (2022) described the precipitation of the driest month as being the most important in the distribution of *Cynometra webberi* Baker f., *Dalbergia vacciniifolia* Vatke, *Newtonia paucijuga* (Harms) Brennan and *Sesbania speciosa* Taub. ex Engl. on the coast of East Africa. Additionally, Cassamo et al. (2023) described the precipitation of the warmest month as one of the most important variables in the distribution of *Coffea arabica* L. in Mozambique. For *Vigna unguiculata* subsp. *pubescens*, the precipitation of the driest quarter (bio17) stood out as the most important factor, a finding cogent with studies on *Vigna* CWRs in Benin (Manda et al. 2022) and other Fabaceae species across Africa (Salako et al. 2021). In contrast to the other taxa, the mean temperature of the wettest quarter (bio8) was significantly important for *Vigna unguiculata* subsp. *pawekiae*, possibly indicating a unique adaptation or sensitivity to this climatic factor. Our data show that most *Vigna* CWR taxa thrive with lower precipitation requirements, as reported by Manda et al. (2022) for *Vigna* CWRs in Benin, reflecting their ability to persist in arid environments. This adaptation may be due in part to their absorbent root systems or tuberous rootstocks (Maxted et al. 2004). Studies indicate that wild *Vigna* with higher root dry weight have better water status, probably due to lower vegetative biomass and, consequently, lower water consumption (Iseki et al. 2018). In addition, precipitation during the driest or warmest periods of the year seems to influence its reproductive success and its ability to thrive in arid and semi-arid regions, playing a crucial role in pod development (Nadeem et al. 2019).

Current distribution predictions reveal that the majority of *Vigna* CWR taxa exhibit a wide array of suitable habitats throughout Mozambique, particularly concentrated in the southern and southeastern regions, with heightened suitability observed near coastal areas. *Vigna unguiculata* subsp.

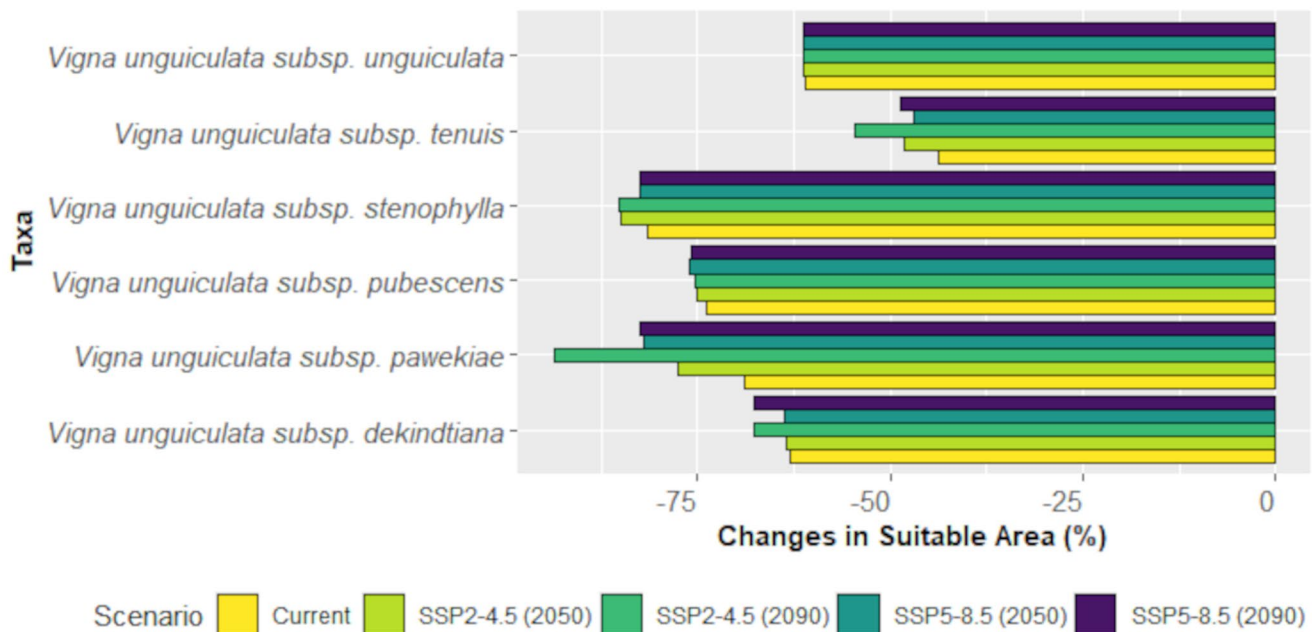


Fig. 4 Changes in suitable areas for *Vigna* CWR taxa (probability of occurrence above 50%) under current and future climatic scenarios in Mozambique, considering constraints from different LULC categories

dekindtiana and *Vigna unguiculata* subsp. *unguiculata* stand out with the largest suitable areas, while *Vigna unguiculata* subsp. *pawekiae* has a more restricted distribution, occurring in small patches further north and inland. Our results showed that the potential distribution area of *Vigna* CWR taxa ranges between 104,899.534 km² and 705,697.541 km², suggesting considerable variation in the adaptation of these taxa to temperature and precipitation conditions in Mozambique. The same has been reported for Fabaceae species distributed along the east coast of Africa (Ngarega et al. 2022). Nevertheless, the forests of the East African coast have been classified as one of the top biodiversity hotspots in the world based on their high level of endemism (e.g., Ngumbau et al. 2020).

Future climate projections indicate that many *Vigna* CWRs taxa could face significant decreases in their suitable habitats, with anticipated losses ranging between 1% and 92% in the SSP2-4.5 scenario by 2090. In more extreme climate conditions, potential habitat losses could be as high as 99% in the SSP5-8.5 scenario, depicting the vulnerability of these taxa. Similar impacts of climate change on the distribution of Fabaceae taxa in Africa have been reported by several recently published studies, e.g., for the *Vigna* genus in Benin by Manda et al. (2022) and the *Dalbergia* genus in Madagascar by Rakotonirina et al. (2024); however, with smaller losses than those shown by our data. At the global level, Warren et al. (2013) projected that 57% of plant species would lose a minimum of 50% of their suitable natural habitat by 2080. Considering the loss of suitable habitat by

Vigna CWRs in Mozambique, in fact, the precipitation of the driest quarter, a determining variable in the distribution of these taxa, is expected to decrease significantly by 2090 (Fick and Hijmans 2017). Nevertheless, there are variations in responses among taxa and regions of Mozambique. The inland areas appear particularly vulnerable to loss of suitable habitat, while coastal regions, though relatively more stable, are also expected to experience significant declines. However, the coast is more exposed to climatic shocks and faces increased pressure from ongoing infrastructure development (e.g. Charrua et al. 2021). Brilhante et al. (2023) projected the pressures imposed by climate change on the effective distribution of *Vigna* CWR taxa, finding that the inland country, where some of the centres of diversity of these taxa are currently located, will be the most affected by increases in average annual temperature above 5°C by 2080; in contrast, coastal areas in the centre and southeast will experience more moderate temperature increases and reduced precipitation. These data, along with our general future forecasts, confirm the resilience of *Vigna* CWRs in arid climates, where they can thrive by tolerating lower precipitation levels.

Our projections suggest, as expected, that taxa with already restricted distributions, such as *Vigna unguiculata* subsp. *pawekiae* and *Vigna unguiculata* subsp. *pubescens*, will be the most affected, facing a higher risk of extinction. Conversely, taxa like *Vigna unguiculata* subsp. *dekindtiana* and *Vigna unguiculata* subsp. *unguiculata* demonstrated higher stability, mainly in the coastal areas to the southeast

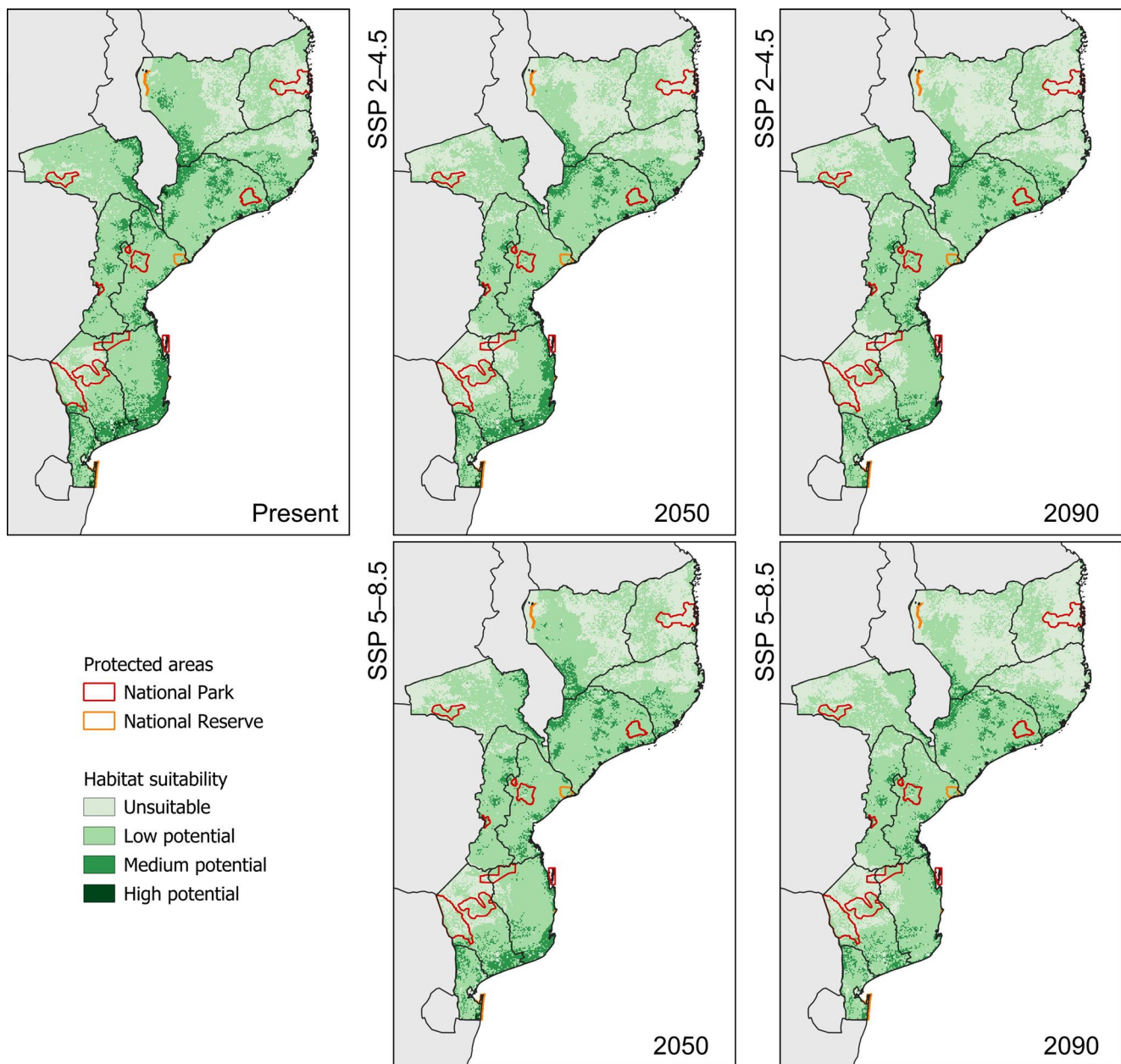


Fig. 5 Spatial distribution of predicted habitat suitability for six *Vigna* CWRs across Mozambique under current and future (SSP2-4.5 and SSP5-8.5) conditions and their overlap with protected areas under total conservation. Suitability values are averaged across taxa

and south. Notably, *Vigna unguiculata* subsp. *unguiculata* could even register a slight expansion of its distribution in certain scenarios, such as in SSP2-4.5, where a small expansion is expected, followed by a slight contraction by 2090. These differences underline the variability in the response of each taxon to climate change, influenced by factors such as local environmental conditions, adaptive capacity and propagation strategies (e.g. DeMarche et al. 2019). These observed variations further reinforce the complexity of climate change impacts, highlighting the critical

need for localised conservation and management planning that considers taxon-specific responses and regional climate dynamics.

Integrating land use and land cover (LULC) constraints in the models revealed a significant reduction in potential habitats for *Vigna* CWRs, with average declines exceeding 65%. *Vigna unguiculata* subsp. *stenophylla* and *Vigna unguiculata* subsp. *pawekiae* could lose more than 80% of its suitable habitat by 2090. These results highlight that, although Mozambique's climate is adequate for the occurrence of these taxa, anthropogenic activities, such as

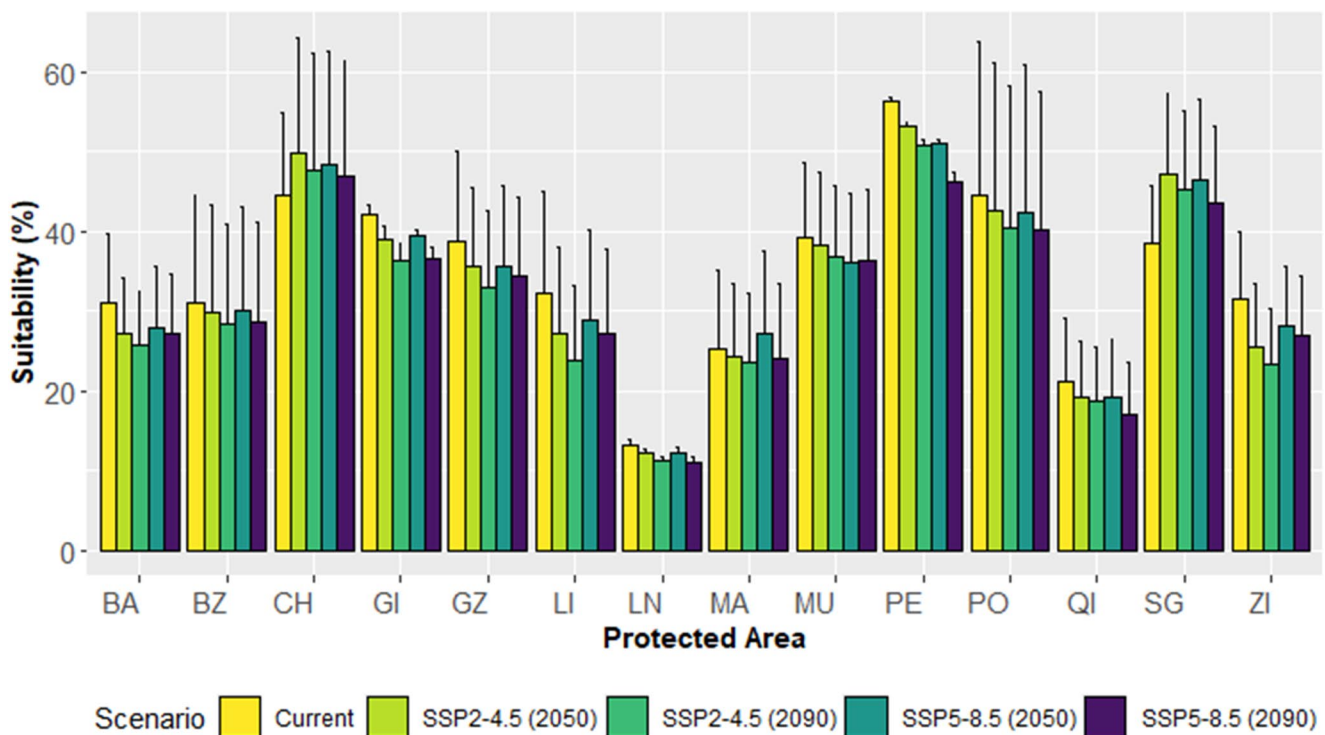


Fig. 6 Average predicted potential current and future (SSP2-4.5 and SSP5-8.5) habitat suitability for the six *Vigna* CWR taxa in Mozambique's Protected Areas network based on climatic models and constraints derived from different LULC categories. Acronyms: National Parks (BA, Banhine; BZ, Bazaruto; CH, Chimanimani; GI, Gilé; GZ, Gorongosa; LI, Limpopo; MA, Magoé; QI, Quirimbas; SG, Serra da

Gorongosa; ZI, Zinave) and National Reserves (LN, Lago Niassa; MU, Marromeu; PE, Pomene; PO, Ponta do Ouro). Only Protected Areas of total conservation were considered as described by Mozambique's legislation (*Diário da República de Moçambique, Law No. 5/2017, p. 183*)

agricultural expansion and urbanisation, may impose significant restrictions on their distribution and conservation, especially when combined with the expected impacts of climate change. Coherent with our results, Varela et al. (2023) demonstrated that by integrating LULC constraints into climate models for *Faidherbia albida* (Delile) A.Chev. in Cabo Verde, the area of high suitability was reduced from 49% to less than 20%.

According to our approach, grasslands and shrublands are the most suitable LULC types for the occurrence of *Vigna* CWRs, followed by agriculture and croplands, forests and tree cover, wetlands and riparian zones, while urban and bare areas and water bodies show low suitability (e.g. Mackinder et al. 2001; Maxted et al. 2004). Despite the constraints imposed by LULC, most *Vigna* CWRs are herbs or early colonisers that thrive in environments with occasional, low-intensity disturbance, and are often found along croplands, roadsides, and built-up areas (Peters et al. 2005). Thus, sustainable land management and agroecological practices can help mitigate habitat loss and fragmentation. Furthermore, infrastructures, such as road networks, can act as migration corridors, helping the dispersion of these taxa to more suitable habitats, and increasing the distribution

area, in a scenario of habitat fragmentation resulting from climate change (Kirchner et al. 2003).

The protection of remaining suitable habitats is critical to ensuring the preservation of genetic biodiversity and ecological resilience of the *Vigna* CWRs, especially those expected to remain stable in the future. Mozambique's terrestrial protected area network, covering approximately 26% of the country (excluding recent additions such as the Palma National Reserve), represents a significant conservation effort (Ministry for the Coordination of Environmental Affairs 2014). However, the effective protection of *Vigna* faces several obstacles. While national coverage of protected areas is relatively high, the absence of adequate management measures limits the effectiveness of these areas. Particularly, grasslands and shrublands, many located outside protected areas and often supporting low population densities, require further assessment and documentation to better inform conservation planning. Despite these challenges, the ongoing expansion of the protected areas network, especially in areas overlapping with Key Biodiversity Areas (KBAs), offers a promising opportunity to strengthen and refine conservation strategies for *Vigna* CWRs (Malatesta et al. 2023). Currently, among the existing protected areas, only the Pomene National Reserve has

habitat suitability above 50% for all taxa studied. However, future projections indicate a generalised decline in suitability in most protected areas, with exceptions in Chimanimani and Serra da Gorongosa National Parks, where suitability is predicted to increase. These results indicate that, although there are areas with potential for conservation, many face significant challenges, reinforcing the need to adapt in situ conservation strategies.

Our results demonstrated the resilience of *Vigna* CWRs in coastal habitats, suggesting that they can act as climate refugia, which increases their relevance for long-term conservation initiatives. Given the increasing fragmentation of habitats and the loss of suitable areas in the future, taxa with more restricted distributions, such as *Vigna unguiculata* subsp. *pawekiae* and *Vigna unguiculata* subsp. *pubescens*, are particularly vulnerable to climate change, loss of genetic diversity and even extinction, and should be a priority in conservation actions (Jarvis et al. 2008). In general, but especially for these taxa, it is crucial to combine *ex situ* conservation strategies, such as seed banking, with in situ measures, such as the creation of genetic reserves in highly suitable regions (e.g. Brilhante et al. 2023).

Despite the advantages of ensemble modelling in improving predictive reliability by combining outputs from multiple algorithms, several sources of uncertainty remain in our study and should be considered when interpreting the results. First, structural uncertainties arise from differences in algorithmic assumptions and model architecture, which can influence predictions even within ensembles (e.g. Araújo and New 2007). Second, potential biases or gaps in species occurrence records and environmental variables may affect model accuracy, particularly for taxa with limited or uneven sampling (e.g. Booth 2018). Lastly, the use of static LULC data assumes no future changes in land use, which may underestimate habitat loss or fragmentation under changing socio-economic conditions (e.g. Synes et al. 2016).

Future research should consider additional factors, such as land use changes and human impacts, when developing habitat suitability models. Incorporating biotic variables such as pollination and dispersal, as well as edaphic, topographic and anthropogenic factors, will help to better understand the distribution and threats to *Vigna* CWRs (e.g. Ngarega et al. 2022). Furthermore, integrating multi-scale climate impact assessments with socio-ecological dynamics improves conservation planning under climate change, as shown by Kiribou et al. (2024). Therefore, it is imperative to adopt an integrated approach that combines ecological modelling, conservation planning and environmental policies and strategies to ensure the preservation of these valuable genetic resources. This study strongly emphasises the urgent need for proactive conservation strategies to safeguard the

genetic diversity of *Vigna* CWRs, which are essential for promoting climate-resilient agriculture and ensuring global food security—key priorities aligned with United Nations Sustainable Development Goals, particularly SDG 2 (Zero Hunger), SDG 13 (Climate Action), and SDG 15 (Life on Land) (United Nations 2015).

Conclusions and recommendations

To the best of our knowledge, this is the first study focused on the modelling impact of climate change in the distribution of *Vigna* CWRs in Mozambique, providing valuable insights into their potential future distribution under changing climatic conditions. Our analysis revealed that climate change, per se, represents a severe threat to these genetic resources, with predicted losses of suitable habitat ranging between 1% and 99%, depending on the scenario and taxon. When land cover and land use data are integrated with climate models, the effects on habitat suitability become even more pronounced, emphasising the influence of anthropogenic pressures on these taxa.

Our findings highlight the important role of the resilience of *Vigna* CWR in coastal habitats, which can serve as climate refugia in a changing future climate. Taxa with restricted distribution, such as *Vigna unguiculata* subsp. *pawekiae*, are particularly at risk of losing their suitable habitat and genetic diversity and should be prioritised in conservation efforts. Although Mozambique's protected areas network currently covers 26% of the country, it offers limited coverage of highly suitable areas for *Vigna* CWRs. As such, urgent action is required to implement both in situ and *ex situ* conservation strategies to ensure the long-term preservation of these essential genetic resources.

Expanding the network of protected areas, particularly in alignment with identified Key Biodiversity Areas (KBAs) will be crucial, alongside strengthening national germplasm banks to safeguard genetic material.

In addition, future research should consider further ecological factors, such as biotic interactions, in habitat suitability models to improve their predictive capacity and better inform conservation strategies. This will further provide a clearer picture of the challenges facing these taxa.

A comprehensive conservation approach that integrates ecological modelling, conservation planning, effective monitoring of *Vigna* CWRs, and the development of robust environmental policies will be essential for protecting the genetic diversity of these taxa. The preservation of these plant resources is not only crucial for maintaining biodiversity but also for supporting climate-resilient agricultural systems and contributing to global food security.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s40808-025-02493-x>.

Acknowledgements The authors would like to acknowledge the research unit LEAF: UID/AGR/04129/2020 (LEAF), which is supported by the Portuguese National Funds through FCT, Portugal, as well as Fundação para a Ciência e Tecnologia (FCT). Also, the authors would like to acknowledge Professor Luís Silva at the Department of Biology, University of Azores, Portugal who has reviewed the results in the early stages of this manuscript.

Author contributions MB and MMR: conceptualisation. MB, SC, and AC: methodology. MB: formal analysis. MB: writing—original draft preparation. MB, SC, AC, MM, SB, and MMR: writing—review and editing. MM, SB, and MMR: supervision. All authors have read and agreed to the published version of the manuscript.

Funding Open access funding provided by FCT|FCCN (b-on).

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest There is no conflict of interest to declare.

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