

Spatio-temporal distribution of native melliferous trees under climate change and their consequences for apiculture and pollinator conservation in the Republic of Benin

FELICIEN AMAKPE^{1,*}, CIKA ASTI AMALIA², BRICE SINSIN³, ADANDE BELARMAIN FANDOHAN⁴

¹Ecole Nationale des Eaux, Forêts et Chasse, General Directorate of Forests and Natural Resources Management. BP 388, Abomey, Republic of Benin. Tel.: +229-0195062997, *email: famakpem@hotmail.com

²Department of Biology, Faculty of Mathematics and Natural Sciences, Universitas Padjadjaran. Jl. Raya Bandung-Sumedang Km 21, Jatinangor, Sumedang 45363, West Java, Indonesia

³Laboratoire d'Ecologie Appliquée, Faculté des Sciences Agronomiques, Université d'Abomey-Calavi. BP 526, Cotonou, Republic of Benin

⁴Ecole de Foresterie Tropicale, Université Nationale d'Agriculture. BP 43, Ketou, Republic of Benin

Manuscript received: 20 July 2025. Revision accepted: 11 October 2025.

Abstract. Amakpe F, Amalia CA, Sinsin B, Fandohan AB. 2025. Spatio-temporal distribution of native melliferous trees under climate change and their consequences for apiculture and pollinator conservation in the Republic of Benin. *Asian J For* 9: 264-272. Climate change poses major threats to biodiversity, including the distribution of melliferous trees that sustain beekeeping and pollinator populations. In tropical regions such as the Republic of Benin (Benin), where dry-season bushfires destroy most herbaceous plants, honeybees rely heavily on perennial trees. This study assessed the impacts of climate change on the distribution of 87 native melliferous trees using the MaxEnt prediction model. The occurrence data were derived from nationwide forest survey plots. The environmental baseline data covered 1990 to 2021, and the predictive parameters covered 2041 to 2070. More than 50% of the country's territory was predicted to become unsuitable for melliferous trees by the 2070 horizon. The moderately suitable area that represented 22.92% of the country's territory will drop to 19.69% and the central parts will concentrate the highly suitable areas. The southern and northern extremities will remain unsuitable areas. The southward expansion of the unsuitable area in the Sudanian regions revealed the future bad beekeeping conditions in these areas, where deforestation is of great concern. The length of the dry season, potential evapotranspiration, and temperature seasonality were the most influential environmental variables shaping tree distribution. These shifts imply worsening conditions for apiculture and pollinator conservation, especially in northern Benin, where land degradation and deforestation are already severe. Strategic reforestation programs prioritizing native species, coupled with sustainable landscape management, will be essential for safeguarding pollinator services and ensuring the long-term viability of beekeeping in the region.

Keywords: Beekeeping, climate change, ecological niche, MaxEnt, melliferous plant

Abbreviations: Bio4: Temperature seasonality standard deviation over monthly values, Llds: Length of longest dry Season, Mimq: Moisture index moist quarter, Pet: Potential evapotranspiration

INTRODUCTION

Climate change is a top threat to biodiversity conservation through habitat loss and habitat fragmentation (Wambui et al. 2018; Jaureguiberry et al. 2022). It contributed to an estimated loss of 11.1 million hectares of tree cover in the tropics in 2021, and the situation is predicted to worsen in the future (Wang et al. 2022; Snyder et al. 2023; Abrha et al. 2024). Climate change also affects the honeybees, which are worldwide key pollinators (Filipiak et al. 2017; Hung et al. 2018). As bees collect pollens, nectar, and resin from a much-diversified plant species in the ecological patch, there is a complex bee-flora relationship that determines the ecosystem functions (Clarke and Robert 2018; Descamps et al. 2021).

The melliferous flora is made up of annual (herbaceous) and perennial plants from which the honeybees collect nectar and pollen (Amakpe et al. 2024; Mawussi et al. 2024). These plants are best valued when flowering seasons coincide with the periods of maximum bee

populations in the colony. In tropical areas, such a coincidence occurs during the dry season (Descamps et al. 2021). However, more than 87% of the territory of the Republic of Benin (Benin) lies in the Sudanian zone, where frequent bushfires burn most herbaceous plants in the dry season (Djidohonkpin et al. 2024). On the other hand, high pressures are put on the annual plants from agricultural pesticides, land clearing, and grazing (Felix et al. 2015; Rodopoulou et al. 2018). As such, the melliferous flora in Benin, as in most tropical African countries, is mainly based on exotic and native trees (Ahouandjinou et al. 2021; Mawussi et al. 2024). But the exotic trees are worldwide introduced and cropped beyond their natural origin, making their occurrence really challenging to fit a prediction model based on environmental modalities (Verchot et al. 2007). We, therefore, focused on native melliferous trees distributed in the different ecological areas of the country.

The impacts of climate change on the distribution of some socio-economic valued plant species are well documented in Benin (Ganglo et al. 2017; Dassou et al.

2024; Yabi et al. 2025). As far as the honey-producing trees are concerned, most investigations are limited to sparse surveys with very poor temporal dynamics analysis (Amakpe et al. 2015; Ahouandjinou et al. 2021). At the regional and international levels, the impacts of climate change on many crops, trees, and invasive plants in the tropical areas are also analyzed (Abrha et al. 2024; Ramirez-Rodríguez et al. 2025). These investigations proved that climate change will shrink the distribution areas of most plant species, which will also shift to specific niches. In consequence, the impacts of climate change on the plant communities will hinder the available floral resources for the pollinators. But the international scientific community is lacking tangible investigations on the specific impacts of climate change on the melliferous trees in the spatio-temporal dynamics of environmental factors. This challenges the design and implementation of scientific decision tools to predict and adapt the beekeeping potential to the worldwide climate change. Modelling the distribution of melliferous trees in Benin will therefore help establish strategic scientific and political responses to the challenges of climate change on beekeeping development. We then set out to test whether the present and future environmental factors shape the distributions of the melliferous plants in Benin.

Many distribution models are developed and successfully used for single-species habitat prediction in Benin (Fandohan et al. 2015; Toffa et al. 2022). Although it was not specifically targeted on melliferous plants, the Maximum Entropy (MaxEnt) is widely used for predicting the potential distribution of particular agroforestry trees and key crops (Odeny et al. 2019; Favi et al. 2022). Using this model, we predicted for the first time in Benin and the West African regions, the impact of past and future environmental factors that determine the native melliferous trees. The implication of the suitable distribution areas for

beekeeping development and pollinator conservation was also analyzed.

MATERIALS AND METHODS

Study area

The study covered the entire Republic of Benin, a West African Country of 114,760 km² (Figure 1). The country lies in the Dahomey Gap, where the Savannah reaches the Atlantic Coast. More than 87% of the territory lies in the Sudanian ecoregion, characterized by recurrent bushfires that burn most annual plants from the landscape (Djidohonkin et al. 2024). The main nectar and pollen source for the bees during the honey season in these agroecosystems is mainly dominated by trees and shrubs (Amakpe et al. 2015). Regarding the climatic conditions, the littoral and sub-littoral climatic zone, the transitional tropical humid zone, and the dry tropical zone are the three main climatic areas that determine plant species distribution in the country (Bouko et al. 2025).

The vegetation varies from the Guinean forest in the south-east to the semi-arid vegetation in the extreme north (Adomou et al. 2006). Regarding the melliferous plants, the herbaceous species are poorly documented. The analysis of the melliferous trees helped determine three main honey zones, which were the southern honey zone, the central zone, and the northern honey zone (Amakpe et al. 2015; Ahouandjinou et al. 2021). The central zone benefits from the best beekeeping potential linked to its higher melliferous plant abundance and diversity, while the southern parts, dominated by pure industrial exotic species plantations of pollen-producing trees, are less suitable for beekeeping.

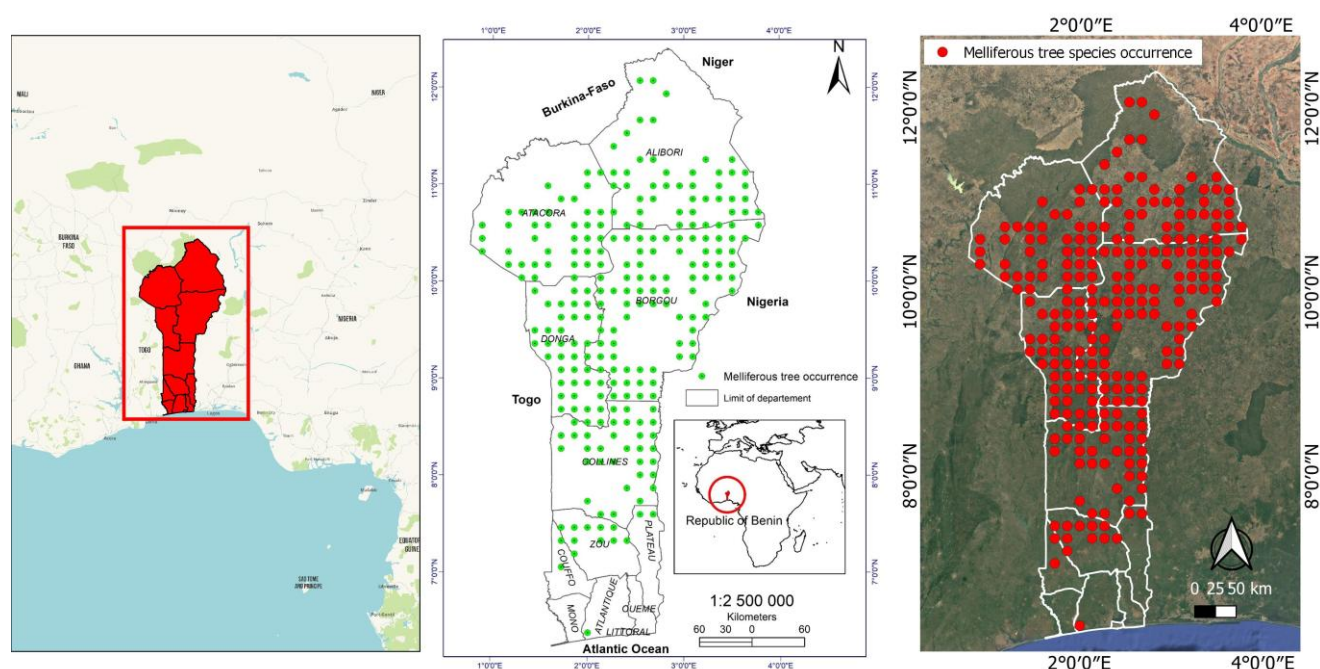


Figure 1. Native melliferous tree species occurrence in the Republic of Benin

Melliferous plant species occurrence data

The occurrence derived from the nationwide first and second national forest survey reports of 2010 and 2022 in Benin. These forest surveys used a systematic fixed area plot system of 18 m radius (1,017.3 m²) established at a regular distance of 15 km (Amakpe et al. 2015). Most of the large blank areas represented plots located in the center and the south, highly populated areas, and bush savannah regions in the north with no melliferous tree (Figure 1).

The native perennial plant species were made up of 87 "trees or shrubs, except exotic species, climbing plants and bamboos from which the honeybees collect pollen or nectar in Benin" (Amakpe et al. 2015; Ahouandjinou et al. 2021). A total of 250 survey plots that bore at least one of these species were considered as occurrence points. The specific melliferous tree diversity varied from 1 to 17, and 213 (85.83%) survey plots were located in the central parts. The richest families were the Combretaceae, Leguminosae, and Sapotaceae, which also bore the most frequent tree species. The targeted survey plots and plant species were extracted from the national forest survey data and saved in a Comma-Separated Value (CSV) format that served as presence-alone field data from which the environmental factors were analyzed (Figure 1). Supplementary material 1 presents the occurrence of each focused tree species and survey plot.

Baseline and future environmental spatial data

The environmental variables included estimates for 19 bioclimatic variables, derived from average monthly maximum and minimum temperature and precipitation data for Africa. They were based on the ensemble representative concentration pathways of IPCC-AR5 at 30' (1.0 km²/pixel) resolution, downloaded at www.york.ac.uk/environment-geography/research/kite/resources/ as GeoTIFF files of the African continent. They were cropped by extracting the data of Benin using ArcMap 10.1 at the same 30' pixel resolution.

The 19 environmental factors potentially impact the distribution of species in any ecological area. But data presenting discontinuity for Benin and those with high correlation or multicollinearity were discarded (Fandohan et al. 2015; Biaoou et al. 2023; Gahounga et al. 2025). The prevalence of the targeted set of plant species was finally determined by the following four key temperature and pluviometry environmental variables that are linked to aridity (Platts et al. 2014; Mwakapeje et al. 2019; Odeny et al. 2019). The temperature variables, which included the temperature seasonality standard deviation over monthly values (Bio4) and the potential evapotranspiration (PET); The pluviometry or moisture parameters, which included the Moisture index moist quarter (mimq) for any consecutive three (3) month periods, and the Length of longest dry Season (llds).

The historic baseline data covered an average term of 30 years, from 1990 to 2021. This period best describes the present prevailing environmental factors in which most plants are living in Benin (Toffa et al. 2022). For the future environmental data, SSP 1-2.6, SSP 2-4.5, SSP 3-7.0, and SSP 5-8.5 are the four scenarios of WorldClim. But in

accordance with the United Nations framework of global challenges in agriculture and food of the 2063 agenda for Africa (Zuza et al. 2021; Asamoah et al. 2025; Kabato et al. 2025), we chose the SSP 2-4.5 scenario (2041-2070). This corresponded to the mid-century 2055 term average period and is considered the most realistic and most reflective of the current political and economic trends in Africa (Arias et al. 2021).

Data analysis and suitable areas delineation

The environmental variables were all extracted and prepared to the same extent, same spatial resolution, and reported to the same WGS84 geodesic system using "crop", "resample", and "mask" functions of RStudio. Many previous studies validated the good and strong predictive power of the MaxEnt model, which was also commonly used for predicting the spatio-temporal distribution of species and diseases (Abrha et al. 2024; Ramírez-Rodríguez et al. 2025). We then used the MaxEnt model, which works perfectly from 30 occurrence records. The 250 occurrences served as "presence alone" of the set of the 87 plant species for a natural probabilistic interpretation in which there was a smooth gradation ranging from most to least suitable environmental conditions in the targeted geographic area (Phillips et al. 2006; Tesfamariam et al. 2022).

In order to delineate areas of suitable potential distribution from unsuitable ones, we set a 10th percentile training presence threshold (β). This represented the probability that 90% of the pixel centers is located in the delineated geographical area and helped not consider pixels with no occurrence as absences of the targeted object (Phillips et al. 2006; Dassou et al. 2024). The distribution maps were elaborated by dividing the distribution probabilities P into three classes related to the threshold β as follows (Fourcade et al. 2014; Dassou et al. 2024): (i) Highly suitable area for pixel centers with $P \geq \beta$; (ii) Moderately Suitable area for pixel centers with $\frac{1}{4}\beta \leq P < \beta$; (iii) Unsuitable areas for melliferous plants for pixel centers with $P < \frac{1}{4}\beta$.

The generated maps from RStudio were saved as GeoTIFF, which were projected in ArcMap. Using the "convert pixel to polygon" tools of ArcMap, a shapefile of each distribution area category was generated, and the corresponding covered area was calculated. The Algorithm converged after 240 iterations and 116988 background points for the MaxEnt distribution model. The dynamics from 1990 to 2070 were analyzed by the difference between the future and past covered area (D) in hectares (ha) and the corresponding proportion (%) over the total covered area of the Republic of Benin (D%) using the following equations.

$$D = F - P$$

$$D\% = (F/S) - (P/S)$$

Where:

D: Dynamic in the distribution of the considered suitable area between 1990 and 2070 (in ha)

F: Predicted value of the considered area (in ha) by 2041-2070 horizon

P: Value of the considered area (in ha) by 1990-1990 horizon

D%: Proportion of the distribution area over the national total area

S: Total covered area of the Republic of Benin (14760km²)

Model accuracy and performance

We first used the area under the Receiver Operating Characteristic (ROC) Area Under the Curve (AUC) for evaluating the model accuracy and performance. This varies from 1 for successful models to 0.5 for weaker ones (Phillips et al. 2006; Tesfamariam et al. 2022). The evaluation of the contribution of each environmental predictor in the model was performed by the jackknife test.

The response curves were also used for assessing the effect of each environmental variable on the MaxEnt prediction and how the prediction changes with each environmental average value when others are kept at their optimum. We also evaluated the MaxEnt model performance by the Test of omission rate curve, which is considered good when the "omission rate is close to the predicted omission line" (Ramírez-Rodríguez et al. 2025).

RESULTS AND DISCUSSION

Model quality and determining distribution factors

The average probability of presence over background sites was 0.657. The omission rate and predicted area as a function of the cumulative threshold (Figure 2.A) curves showed that the omission rate line was very close to the predicted omission, with an AUC equal to 0.658 (Figure 2.B). This value is low, but indicates that the MaxEnt model prediction of the suitable distribution areas of the perennial native melliferous plants in Benin is acceptable, and different from a randomized prediction.

The estimates of the relative contribution of the environmental variables to the MaxEnt model indicated that the Length of the longest dry Season (llds), the potential evapotranspiration (pet), and the temperature seasonality standard deviation over the monthly values (bio4) were the most important contributing environmental variables (Figure 3 and Table 1). Their synergetic actions lead to a better melliferous tree suitability in areas where the dry season lasts 4 to 5 months with cooler temperatures and low thermal amplitude throughout the year.

With a specific contribution of 59.1% for the llds, the occurrence probability of the native melliferous trees reached its highest value when the length of the longest dry season reached 5 months, followed by a rapid drop to its lowest values around eight dry months per year (Table 1). As far as the potential evapotranspiration was concerned, the occurrence probability reached its highest values between 1850 and 1950 mm and dropped beyond these values. The occurrence probability exponentially increased from 10 to 14°C for bio4, and from this value, an increase in the bio4 values leads to a drop in the occurrence probability till 23°C. Though the Moisture index moist quarter (mimq) had the lowest contribution (0.4%), the occurrence probability reaches its highest values around 180 mimq, followed by a high decreasing slope above this value.

Regarding the permutation influence of the environmental parameters (Table 1), the most significant values were the bio4 (42.7%), followed by the pet (33.8%) and the llds (17.5%). The llds which contributed to 59.1% to the MaxEnt model had the lower permutation contribution (17.5%) compared to Bio4 and pet.

The impact of each variable on the occurrence probability when the others are kept at their optimal values and when used alone in the MaxEnt model was similar. The environmental variables then strongly contribute to the model performance, whether considered alone or in synergetic actions with others, as it happens in the natural ecological conditions.

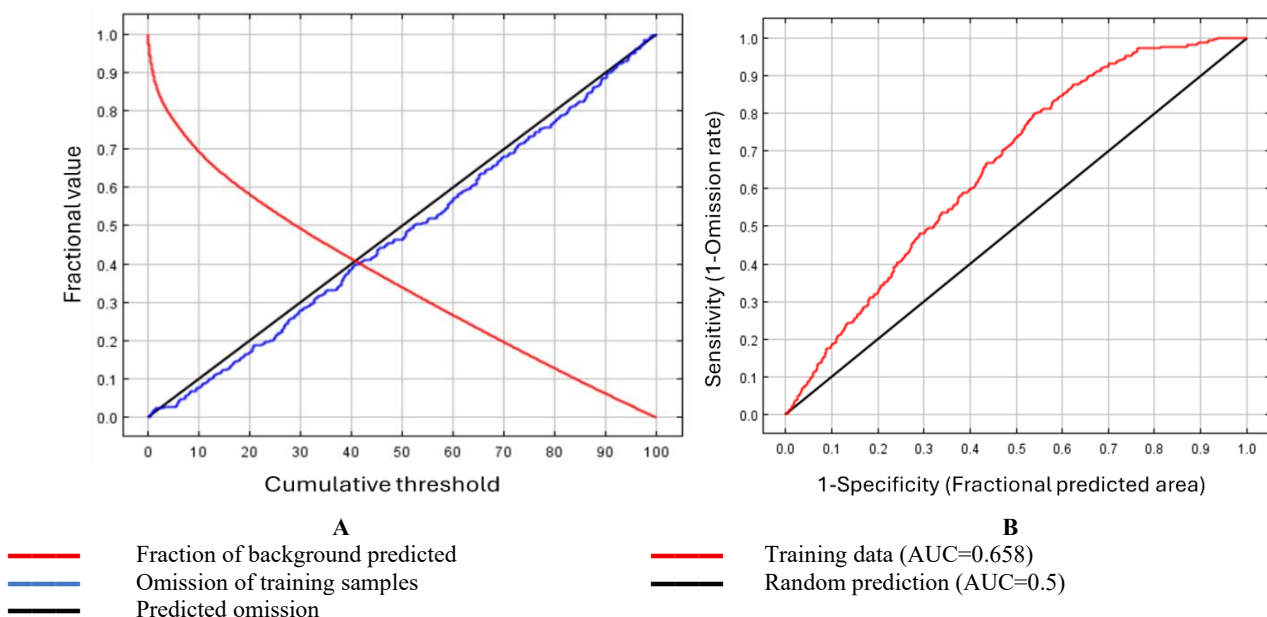


Figure 2. Maxent model performance analysis. A. Test of mission rate, B. AUC analysis

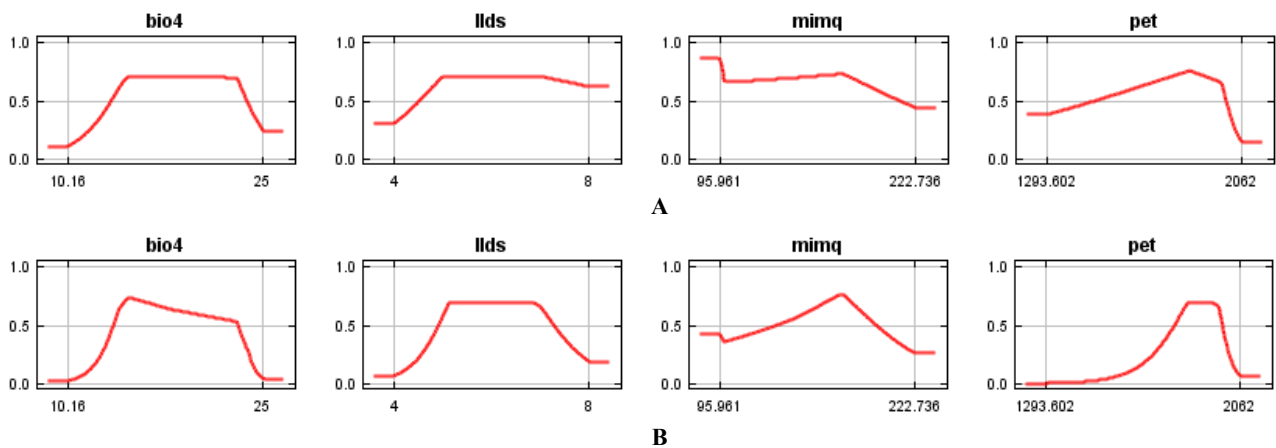


Figure 3. Species response to environmental factors. A. Impact of each variable on the occurrence probability when the others are kept at their optimal values, B. Impact of each variable on the occurrence probability when used alone in the model, Bio4: Temperature seasonality standard deviation over monthly values, Llds: Length of longest dry Season, Mimq: Moisture index moist quarter, pet: potential evapotranspiration

Table 1. Analysis of variable contributions

| Variable | Percent contribution | Permutation importance |
|----------|----------------------|------------------------|
| Llds | 59.1 | 17.5 |
| Bio4 | 27.4 | 42.7 |
| Pet | 13.1 | 33.8 |
| Mimq | 0.4 | 5.9 |

Note: Bio4: Temperature seasonality standard deviation over monthly values, Llds: Length of longest dry Season, Mimq: Moisture index moist quarter, Pet: Potential evapotranspiration

Past distribution areas

The south and north extremities were unsuitable distribution areas for native melliferous trees (Figure 4.A and Table 2). The unsuitable area covered 2,978,050.10 ha (25.95% of the national territory). In the south, this covered the Guineo-Congolian zone that stood from the Atlantic Ocean coast to the 7th parallel and an elongated north-west area bordering the Republic of Togo. In the north, it is a line that shares borders with the Republics of Burkina-Faso and Niger, in the Sudanian ecoregion.

The past predicted moderately suitable area covered 22.92% of the country's total area. In the south, it stood from the 7th parallel to the 8th parallel. In the north, it is made up of scattered blocks located in the south Sudanian ecoregion. The past potential highly suitable areas constituted a compact block located in the Sudanian and Sudano-Guinean ecoregion. It covered 51.13% of the country's total area between the 8th and the 11th parallels.

Predicted future potential distribution areas

The predicted future distribution areas at the 2070 horizon indicated a drastic loss in the suitable areas, in which the northern parts are totally unsuitable (Figure 4.B and Table 2). The highly suitable area dropped from 51.13% to 29.94% followed by a slight drop in the moderately suitable area (22.96% to 19.69%). There was a shrink and shift of the highly suitable block towards the

south till the 7th parallel in the Sudano-Congolian ecoregion.

The unsuitable areas almost doubled, covering 50.37% of the country's total area. In the south, it covered the marshy strip of the Atlantic coastal ecosystems and the Mono River basin in the southwest. In the north, it was a large block covering the entire Sudanian region.

The future moderately suitable areas, on the other hand, were made up of two narrow bands of 2260048.95 ha (19.69%) in the south and the central north. The central north block stood from the north borders of the Republic of Togo to the border of Nigeria between the Sudanian unsuitable block and the Sudano-Guinean suitable block. The south moderately suitable area was restricted to the Oueme and Mono rivers basins in the Guineo-Congolian regions.

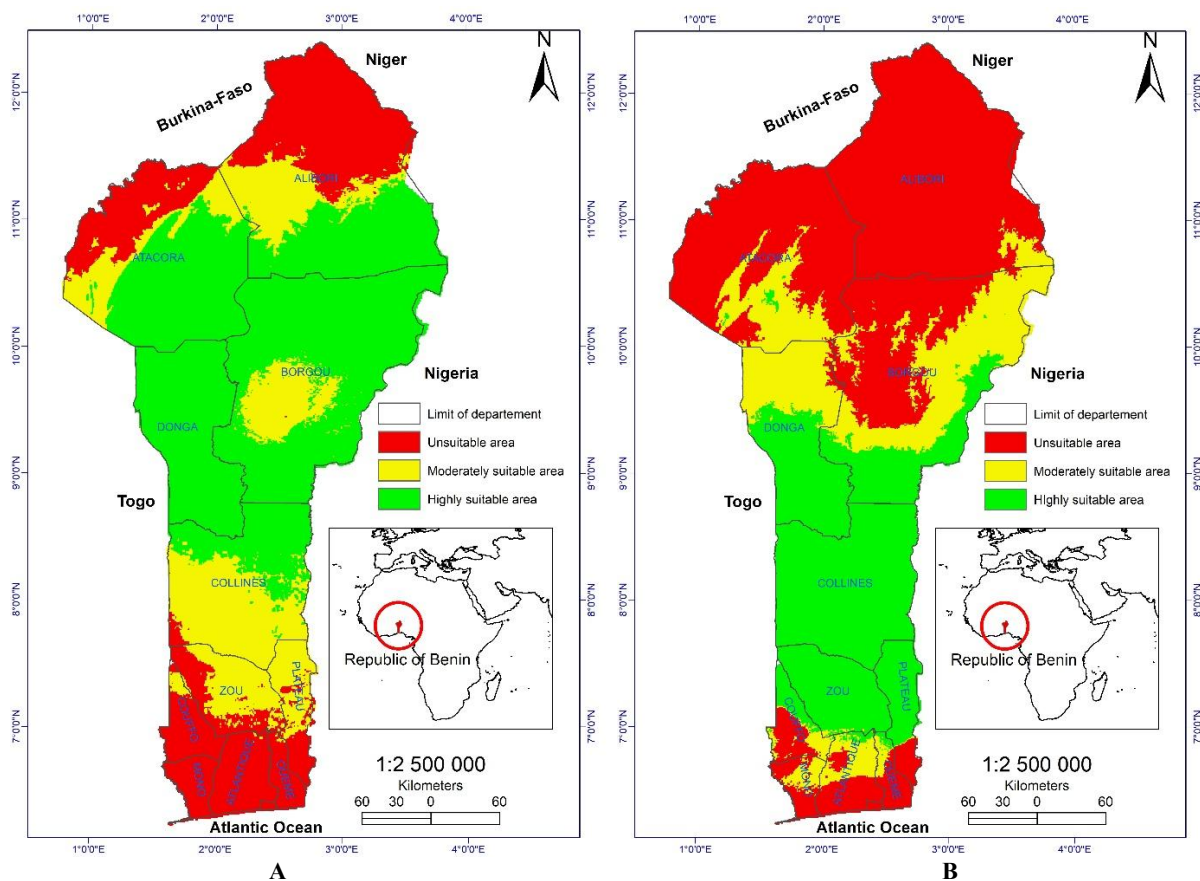
Spatio-temporal dynamics of the potential distribution area of native melliferous trees

The challenging environmental conditions of the future lead to a shift of the different distribution areas (Figure 4 and Table 2). The dynamics in the distribution showed the following types of zones: (i) The first zones included areas predicted to register a regression in their suitability. These were the highly suitable zones located in the northern Sudanian regions. They will lose more than 50% of their total present suitable area between 1990 and 2070. (ii) The second zones were expected to register an improvement in their suitability. A global loss of suitable areas was predicted. But most Sudano-Guinean region will evolve from unsuitable or moderately suitable areas to highly suitable zones. (iii) The third area was made up of unchanged highly suitable areas in the future. These zones are located in the southern Sudanian regions. They represented an area with more stable environmental conditions in the country. A small area located in the mountain chains of Atacora belonged to this highly suitable area in the north-west.

Table 2. Dynamics in the distribution of the melliferous trees' suitable areas in the Republic of Benin

| Distribution area | Area variation | | | | | | Annual Lost or gained (ha) |
|--------------------------|-------------------|-------|-------------------|-------|---------------|---------|----------------------------|
| | From 1970 to 2021 | | From 2041 to 2070 | | 1970-2070 | | |
| | P (ha) | % | F (ha) | % | D Ha | D(%) | |
| Unsuitable area | 2,978,050.10 | 25.9 | 5,780,088.50 | 50.37 | 2,802,038.40 | 94.09% | 28,020.38 |
| Moderately suitable area | 2,629,875.73 | 22.92 | 2,260,048.95 | 19.69 | -369,826.79 | -14.06% | -3,698.27 |
| Highly suitable area | 5,868,074.17 | 51.13 | 3,435,862.55 | 29.94 | -2,432,211.62 | -41.45% | -24,322.12 |

Note: D: Dynamic in the distribution area between 1990 and 2070, F: 2070 predicted value, P: 1990 value, D%: Proportion of the distribution area over the national total area

**Figure 4.** A. Past and B. Future potential distribution areas of the native melliferous trees in the Republic of Benin

Discussion

Environmental variable contribution to the native melliferous trees' distribution

Our findings supported that the temperature and pluviometry parameters we used for predicting the present and future potential distribution of the melliferous plants are effective, as also found for a set of 15 species of the *Vigna* genus and for many other species' distribution (Ganglo et al. 2017; Dassou et al. 2024; Ramírez-Rodríguez et al. 2025). The Receiver Operating Characteristics (ROC) Area Under the Curve (AUC), which is widely used for model evaluation, was in the range of most prediction models based on presence alone data (Phillips et al. 2006; Favi et al. 2022). Values of the AUC below 0.7, as in our case, confirmed that the melliferous plants had very large distribution areas and a broader range of environmental conditions (Anderson et al.

2003; Phillips et al. 2006). This also occurs when considering numerous species, as the suitable environmental conditions of some species may affect others (Fandohan et al. 2015; Gahounga et al. 2025).

The increase in the average surface temperature is projected to be much higher in Africa, where extreme values are projected for Sub-Saharan Africa by the middle century (Platts et al. 2014). These temperature variations will affect the other environmental variables, leading to specific responses of species or populations to climate change at local and regional scales (Odeny et al. 2019). The differences in the observed past suitability of the melliferous plants per zone, as we found, were then a consequence of the diversity in the baseline environmental conditions, which already showed a strong south-north gradient in Benin (Bouko et al. 2025).

The distribution of the past and future unsuitable areas in the southern and northern parts of Benin also conforms to many other previous research studies that classified these two extremities as poor melliferous areas. In fact, the southern areas are dominated by industrial pollen-producing plants with limited honey production capacity, while the extreme north is dominated by small-sized shrubs under land clearing and bushfire pressures (Amakpe et al. 2015; Ahouandjinou et al. 2021). The specific contribution of each environmental factor also highlighted the particular distribution pattern of the melliferous plants in the south and northern zones with their opposite environmental conditions (Bouko et al. 2025).

As for other species (Ganglo et al. 2017; Favi et al. 2022), the low suitability of the south was linked to the low values of pet and llds in these areas, which negatively impacted the occurrence probability of native melliferous tree species. But such a poor status is also determined by the high population density with limited forest cover. The honeybees also perform less in high humidity conditions, and our findings proved that the coastal region in Benin may really be considered as an unsuitable beekeeping area (Amakpe et al. 2015; Ahouandjinou et al. 2021).

In contrast to the low values of pet and llds in the south, their maximal values in the northern parts supported the lower suitability of these areas due to herbaceous plants dominance. But this didn't include mountainous areas located in the Department of Atacora with their specific edaphic and ecological conditions that favor tree species (Amoussou et al. 2016; Nambima et al. 2023). On the other hand, the longer daylight time in the Sudanian regions will compensate for a better foraging time for the bees (Ouattara et al. 2012; Satta et al. 2024). These zones will then stay more favorable to beekeeping than the southern area, even though the two regions bear the same bad floral potential for the honeybees and pollinators.

The study revealed a steady suitability in the Sudano-Guinean regions, particularly the Departments of Collines, Donga, and South Borgou. Such stability was also found for many other plant species in these areas, which are transition zones between the dry Sudanian and the Guineo-Congolian climates (Ganglo et al. 2017; Favi et al. 2022). With the best plant species diversity in Benin, these areas also benefit from very low amplitude in most of the climatic parameters (Adomou et al. 2006). They have the best beekeeping and pollinator conservation potential in Benin in the face of global climate change.

Implications for beekeeping and biodiversity conservation in Benin

The southward shift of the favorable areas confirmed that climate change impacts species and population distribution by pushing them to their ecological limits, leading to a significant shift in their geospatial ranges (Scheffers et al. 2016; Abrha et al. 2024). The predicted shift of the suitable areas to the south implies that the climatic conditions in the future will lead to potential niches for savannah species of the Sudanian and Sudano-Guinean ecoregion. But the south of Benin is the area of high demographic pressure (Adechian et al. 2015). The

improved future melliferous suitability of this zone will then be highly challenged by the induced industrialization (Hou et al. 2023). Specific investments will then be required for greener cities that guarantee shelters and melliferous plants for pollinators (Daniels et al. 2020).

The stability of the most suitable areas in the Sudano-Guinean regions was conclusive to the present beekeeping status of these zones, which belong to the best melliferous zones with the highest well-trained beekeeper population (Ahouandjinou et al. 2021). Strategic investment would then be required in these zones in terms of capacity building. These areas also host many protected areas with valuable reforestation programs that support potential melliferous trees. The challenges of these areas lie in the governmental promotion of exotic trees such as *Acacia auriculiformis* and *Tectona grandis* for domestic energy and timber products. Their suitability should then be supported with more diversified native species plantations to ensure the required diversity in nectar and pollen sources for bees and pollinators (Hung et al. 2018; Descamps et al. 2021).

The Sudanian regions presented a particular situation of expansion of the unsuitable area towards the south. These unsuitable areas corresponded to the present distribution areas of *Vitellaria paradoxa* and *Parkia biglobosa* parks in Benin (Kakpo et al. 2024). Our results then supported that the environmental conditions will be extremely unsuitable to these two species of great socio-economic values, in addition to the high pressure through agriculture land clearing, firewood harvesting, and limited regeneration (Descamps et al. 2021; Ayeko et al. 2023). Reforestation programs should then target these two native species for their promotion and conservation towards sustainable apiculture and pollinator conservation for poverty alleviation.

The predicted lower suitability of more than 50% of the country's territory for native melliferous trees in the future supports the proliferation of herbaceous plants, including invasive plant species (Amakpe et al. 2025). This will exacerbate bushfires in the dry season as a consequence of Poaceae species dominance (Alvarado et al. 2018; D'onofrio et al. 2020). The ecological conditions will then be particularly detrimental to the honeybees' diet in terms of pollen and nectar sources. In addition to the predicted global worsening climatic conditions, the future widespread pesticide-polluted landscape (Arpaia et al. 2021) will severely challenge beekeeping in the entire Benin. Operational beekeeping strategic plans that ensure diversified and abundant melliferous plants in a cleaner agro-ecosystem are then crucial for sustainable apiculture and pollinator conservation.

In conclusion, this study demonstrates that climate change will significantly alter the distribution of native melliferous trees in Benin, with more than half of the national territory projected to become unsuitable by 2070. The analysis of the specific impacts of bio4, llds, mimq, and pet on the distribution of the native melliferous trees supported a clear regionalization of native melliferous trees in the country, where the central region will remain the best beekeeping zone. Apiculture and pollination service

sustainability in Benin requires relevant reforestation programs focused on native trees. Such special reforestation programs are particularly crucial in the northern parts, where the melliferous plants will be highly impacted by the widespread deforestation, pesticides, and land degradation from agriculture, in addition to climate change. Native tree species are certainly key for sustainable beekeeping in the tropical area, but the honeybees also forage herbaceous and even invasive plant species. The analysis identified the length of the dry season, potential evapotranspiration, and temperature seasonality as the key drivers of distribution shifts. These findings suggest that apiculture and pollinator conservation in Benin will require proactive measures, including large-scale reforestation programs prioritizing native melliferous species, sustainable land management, and the integration of pollinator-friendly practices into agricultural systems.

While this work focused on native tree species, future research should also model the contributions of herbaceous and exotic melliferous plants to provide a more complete picture of floral resources. Long-term monitoring and the inclusion of socio-economic drivers, such as land-use change and pesticide pressures, will be critical for strengthening predictive accuracy and guiding policy. Overall, native melliferous trees remain essential for sustaining honey production and pollinator diversity, and their conservation should be a cornerstone of climate adaptation strategies in Benin.

ACKNOWLEDGEMENTS

The authors thank the foresters of the General Directorate of Forest and Natural Resources of Benin, for their contribution to field data building.

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