

Habitat Suitability Modeling of Bombus affinis under Climate Change

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Abstract. The North American bumble bee *Bombus affinis* (*B. affinis*) is an important wild pollinator that has experienced severe population declines since the late 20th century. However, spatially explicit assessments of how climate change and human activities jointly shape its distribution remain limited, constraining forward-looking conservation planning. Here, we used a maximum entropy model (MaxEnt), integrating species occurrence records with multidimensional environmental variables, to characterize the historical distribution of *B. affinis* and project changes in potential habitat suitability under different climate scenarios for the mid- and late 21st century. The results show that mean temperature of the warmest quarter was the dominant predictor of its distribution, contributing 59.0% to the model. Moreover, our model indicated a highly restricted historical distribution, with medium- and high-suitability habitats (suitability > 0.7) accounting for only 7.9% of the study area and concentrated along the North Atlantic coast, the Great Lakes region, and the Appalachian Mountains. By the late 21st century, the SSP585 high-emission pathway would cut both the size and the quality of suitable habitats markedly; the range would also contract northward, shifting away from the south-central and northeastern United States toward higher latitudes and finally into southern Canada. This work gives a quantitative evaluation of *B. affinis* habitat suitability in both historical and future periods, points to the key role that global emission cuts play in easing the species' survival pressure, and supplies scientific support for identifying cross-border priority conservation zones and building a climate-resilient conservation framework.

Keywords: *Bombus affinis*, species distribution models, climate change, habitat suitability, conservation planning

1. Introduction

Climate change ranks among the leading forces behind biodiversity loss [1-3]. It reduces habitat area, alters food-resource structure, and shifts phenological rhythms, all of which deeply affect global biodiversity. The Sixth IPCC report confirmed the 2011–2020 average global surface temperature was 1.1°C higher than pre-industrial levels [4]. The global climate situation remains extremely grave. To address this, international ecological conservation organizations have already introduced several policies addressing climate change [5]. Still, conservation that relies solely on global-scale measures falls short, because regional climate change often combines with human

activities to produce stronger and more direct impacts on species. Within this group, endangered species that only live in certain local areas meet stronger climate-related influences than widely-spread species. Their small living space and limited living areas make them easier to be harmed by climate change [6]. So, to make special protection plans for certain endangered species, people badly need to measure different kinds of dangers and possible future risks on a regional level.

As one typical North American bumble bee, *B. affinis* has much ecological value. It is a pollinator that feeds on many kinds of plants, and it can visit plants from up to 65 different plant genera [7]. But its population number has dropped very fast after the end of the 20th century. This species used to live over large parts of the northeastern United States and nearby areas in Canada. Now scientists think its living area has become 87 % smaller than before [8, 9]. Some research work shows this living-area loss comes from both climate change and human activities. Higher temperatures may drive *B. affinis* to places with higher latitude and higher elevation [10]. At the same time, more intensive farming and simpler land environments have changed how many flowers exist and how long flowers can stay through seasons. These changes slowly make living conditions worse for some kinds of bumble bees [11]. Though the International Union for Conservation of Nature (IUCN) put this species into the "Critically Endangered" (CR) list in 2015 [12], real practical protection work moves at a slow speed. For example, the country-wide agreement for species protection advantages was still in the writing stage when this paper was being finished [13]. One big difficulty is that scientists do not have enough research results to tell how climate change and human activities will work together to change where this species can live in the future.

Species distribution models (SDMs) can help fill this lack of research information. These models use statistical ways or machine-learning tools to connect where species have been found with environmental factors. In this way, workers can work out what living conditions species require and guess where they may live in future [14]. Many researchers use this tool to judge how easily species get hurt by climate change and offer useful information for protection work [15]. Still, when people use SDMs to protect rare animals, several clear problems exist. These problems lower how helpful such models are for making real-world management choices. First, many guesses about future living areas do not fully use climate settings from the Shared Socioeconomic Pathways (SSPs). They also fail to add human-related factors such as land use in a complete way. Because of that, researchers cannot get full evaluations on existing dangers. Second, results given by these models often cannot connect with real-world protection steps that look ahead. People seldom turn such research results into clear practical advice. The advice should help mark possible protection zones or set up management rules which real-world protection workers can use.

Under such background, we set up one combined model system. It shows how living-place fitness for *B. affinis* changed in past time and how it may change later. At first, we used an improved MaxEnt model. This model mixed climate, land form, soil, land-use types and human-population density factors. We used it to draw maps showing where this species lived in history and find out major environmental factors that stop it from spreading. Next, we calculated where suitable living space may move for two time periods: 2041-2060 and 2081-2100, under several Shared Socioeconomic Pathways (SSPs). In the end, we use results from our model to talk about important ideas for flexible species protection. Our goal is to provide measurable research support for long-term management and protection of this endangered bee species.

2. Methods

2.1. Species records and environmental data

2.1.1. Occurrence data collection and cleaning

The occurrence records of *B. affinis* were obtained from the Global Biodiversity Information Facility (GBIF: <https://www.gbif.org/>) and the North American bumble bee dataset available through Dryad (<https://datadryad.org/dataset/doi:10.5061/dryad.c59zw3r8f>), published by Richardson et al. in 2022 [16]. The GBIF dataset contained occurrence records spanning 1881–2025, whereas the Dryad dataset covered 1805–2020 [16]. After combining the two datasets, a total of 37,591 raw occurrence records of *B. affinis* were obtained, spanning 1805–2025. To avoid record gaps and discontinuities caused by the Canada–United States border, this study focused on the region comprising southeastern Canada and the United States, bounded by 100°W–65°W longitude and 30°N–50°N latitude. Besides, to ensure data quality and reduce spatial sampling bias, we strictly screened the records using R (version 4.5.3) through the following steps: first, we excluded invalid and missing records; next, we removed records whose coordinates were located outside the study area; finally, using the spatial thinning method provided by the R package 'dismo' [17], we retained only one occurrence record within each grid cell at a 5-km spatial resolution to reduce potential spatial autocorrelation. Ultimately, a total of 2,616 independent occurrence points were obtained for subsequent model construction (Fig. 1).

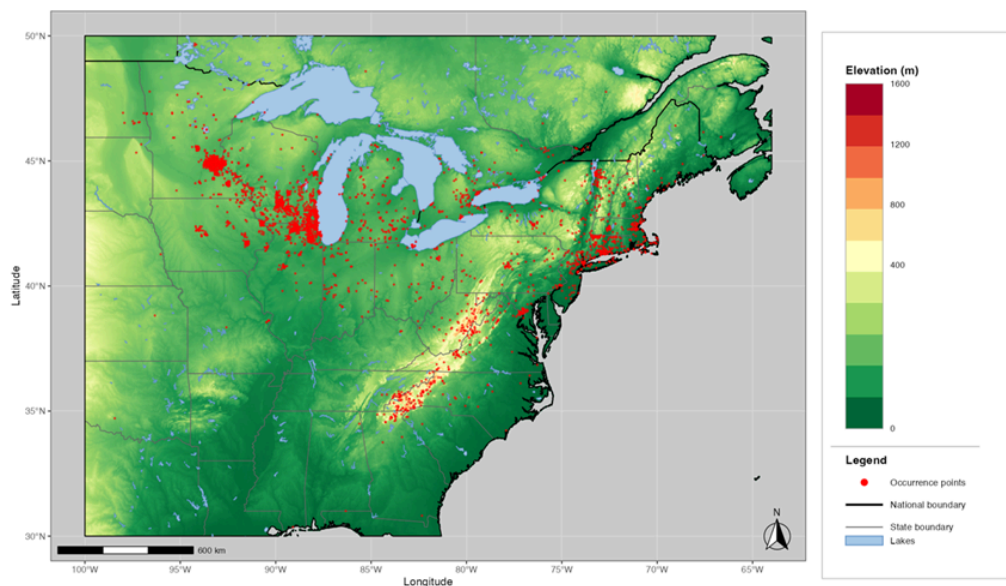


Figure 1. Geographic distribution map of *Bombus affinis* occurrence points

The map shows the terrain elevation of the study area (color from green to red represents terrain from low to high) and occurrence records of the species (red spots). Blue areas represent lakes. Occurrence points are mainly concentrated in the Great Lakes region and the northeastern United States. This map includes a total of 2,616 occurrence points of the species.

2.1.2. Environmental variables

To ensure the SDMs can reflect The species' habitat requirements accurately, this study integrated information on the ecological habits, characteristics of key developmental stages (such as nesting, hibernation, and foraging), major stressors affecting the population and the availability of variable data [18]. Finally, we analyzed four major categories of environmental variables (Table 1): (1) 19 bioclimatic variables obtained from the WorldClim database, which represented temperature and humidity conditions; (2) Four terrain variables (elevation, slope, roughness, Topographic Position Index (TPI)) obtained from EarthEnv, which represented topographic and geomorphological characteristics; (3) Two soil property variables (clay, bulk density) obtained from SoilGrids, which represented nesting suitability; (4) Land use and land cover (LULC) data obtained from ESA and anthropogenic stress (population) data obtained from WorldPop, which jointly represented the intensity of human activities. To reduce the redundancy of LULC patterns, we reclassified LULC variables into six categories (cropland, forest, grassland, barren land, urban land, and water; Table 2) and then calculated the percentage of each category at a coarser spatial resolution (e.g., 5 km) to better represent landscape composition at the modeling resolution.

Table 1. Initial environmental variables selected for the MaxEnt model of *Bombus affinis*, categorized into bioclimatic, topographic, soil, and human-influence groups

Class	Variable	Spatial resolution	Source	Future
Climate	BIO1-BIO19	~5 km	https://www.worldclim.org/data/worldclim21.html	https://www.worldclim.org/data/cmip6/cmip6climate.html
Terrain	Elevation/Slope/Roughness/Topographic Position Index (TPI)	~5 km	https://www.earthenv.org/topography	—
Soil	Clay/Bulk	~250 m	https://soilgrids.org	—
Land use and land cover	LULC class (cropland, forest, grassland, barren land, urban land, and water)	~300 m/1 km	https://maps.elie.ucl.ac.be/CCI/viewer/download.php	https://zenodo.org/records/4584775
Anthropogenic	Population density	~1 km	https://hub.worldpop.org/projects/categories?id=18	https://figshare.com/articles/dataset/Projecting_1_km-grid_population_distributions_from_2020_to_2100_globally_under_shared_socioeconomic_pathways/19608594/3

Table 2. Reclassification scheme mapping the original 37 ESA CCI LULC classes to 6 broad LULC categories used in this study

Original LULC ID	Original LULC Name	Reclassified LULC Name
10, 11, 12, 20, 30	Cropland rainfed, Herbaceous cover, Tree or shrub cover, Cropland irrigated or post-flooding, Mosaic cropland (>50%)/natural vegetation (<50%)	cropland
40, 50, 60, 61, 62, 70, 71, 72, 80, 81, 82, 90, 100, 120, 121, 122, 160, 170, 180	Mosaic natural vegetation (>50%)/cropland (<50%), Tree cover broadleaved evergreen, Tree cover broadleaved deciduous (closed to open/closed/open), Tree cover needle leaved evergreen (closed to open/closed/open), Tree cover needle leaved deciduous (closed to open/closed/open), Tree cover mixed leaf type, Mosaic tree and shrub (>50%)/herbaceous cover (<50%), Shrubland(evergreen/deciduous), Tree cover flooded (fresh or brackish/saline water), Shrub or herbaceous cover flooded	forest

Table 2. (continued)

110, 130	Mosaic herbaceous cover (>50%)/tree and shrub (<50%), Grassland	grassland
140, 150, 151, 152, 153, 200, 201, 202	Lichens and mosses, Sparse vegetation (<15%), Sparse tree (<15%), Sparse shrub (<15%), Sparse herbaceous cover (<15%), Bare areas, Consolidated bare areas, Unconsolidated bare areas	barren land
190	Urban areas	urban land
210	Water bodies	water

To predict the future potential distribution of *B. affinis*, this study built a future projection model with the same structure as the historical (baseline) model. All the above-mentioned environmental variables have been retained. Among these, terrain and soil variables were regarded as time-invariant variables, but bioclimatic, land use and land cover (LULC) and population variables were replaced with the corresponding future scenario data. The prediction of future scenarios focused on two important timeframes, the middle of this century (2041–2060) and the end of this century (2081–2100). At the same time, to account for uncertainties regarding future economic development and climate policies, we integrated three representative Shared Socioeconomic Pathways (SSPs): SSP126 (low-emission scenario), SSP245 (middle-emission scenario), and SSP585 (high-emission scenario). Furthermore, to reduce the uncertainties associated with a single prediction model and to improve the accuracy of the results regarding future scenario climate data, we employed a multi-model ensemble averaging method, specifically, four Global Climate Models (GCMs) shown to have high accuracy for North America were selected, ensuring the completeness of the climate data for future scenarios [19]: ACCESS-CM2, CMCC-ESM2, EC-Earth3-Veg, and MRI-ESM2-0.

Moreover, to more clearly illustrate the spatial patterns of potential future habitat changes for *B. affinis*, this study calculated the latitudinal coordinate of the centroid of medium- and high-suitability areas in the historical scenario (1970–2000) and future scenarios (2041–2060, 2081–2100) separately to characterize spatial shifts in habitat location for comparison across scenarios [20].

2.2. MaxEnt modeling and model optimization

The maximum entropy model (MaxEnt) was used to predict the historical and future suitable habitats of *B. affinis*. MaxEnt uses presence-only records and does not require absence data to predict species distributions and has been shown to perform well even with small sample sizes [21]. It has been widely used to predict the suitable habitats of endangered species [22, 23].

To reduce the risk of overfitting of the MaxEnt model resulting from multicollinearity among environmental variables, environmental variables were screened prior to model construction. First, Spearman's rank correlation coefficient (r) was calculated among all pairs of environmental variables. For highly correlated variable pairs ($|r| > 0.7$), the variable with greater ecological relevance was retained. After that, Variance Inflation Factor (VIF) analysis was performed using the 'vifstep' function from the R package 'usdm'. This analysis iteratively eliminated environmental variables exhibiting high multicollinearity using a threshold of $VIF < 7$. Finally, 16 variables with VIF values below seven were retained for subsequent modeling: Mean Diurnal Range (BIO2), Mean Temperature of Wettest Quarter (BIO8), Mean Temperature of Driest Quarter (BIO9), Mean Temperature of Warmest Quarter (BIO10), Precipitation Seasonality (BIO15), Precipitation of

Warmest Quarter (BIO18), elevation, slope, TPI, water, grassland, barren land, clay, bulk density, urban land, and pop.

To improve model performance, we tuned the MaxEnt model with the R package 'ENMeval', searching for the best pairing of regularization multiplier (RM) and feature class (FC). We tested every RM value from 0.5 to 5.0 in steps of 0.5 against all seven FC settings (L, LQ, LQH, LQP, LQHP, LQHT, and LQHPT). We assessed performance with block cross-validation [24, 25]. Model selection relied mainly on the small-sample-corrected Akaike Information Criterion (AICc) and the test-data area under the receiver operating characteristic curve (AUC) [26, 27]. We preferred models with lower AICc and higher test AUC, seeing them as striking a better balance between complexity and predictive power. The selected settings were RM = 0.5 and FC = LQHP. With these parameters fixed, we ran the final model 10 times in cross-validation to reduce uncertainty, using 75% of the data for training and 25% for testing in each run. We summarized performance as the mean test AUC plus or minus its standard deviation across the 10 folds. We also applied the jackknife to rank variable importance and plotted response curves to visualize how key environmental variables relate to predicted suitability [28]. From this, we produced a historical habitat suitability map for *B. affinis*.

2.3. Statistical analysis

The continuous habitat suitability values (0–1) generated by the MaxEnt model were reclassified into three suitability levels for subsequent analysis: Low suitability (< 0.5), Medium suitability (0.5–0.7), and High suitability (> 0.7). The threshold values were selected based on the distribution characteristics of predicted suitability values and their widespread use in previous studies [29]. The percentage of the study area covered by each suitability level was calculated for comparison. To predict the future suitable habitat of *B. affinis*, the parameter-tuned model was run for three Shared Socioeconomic Pathway (SSP) scenarios (SSP126, SSP245, and SSP585) under four global climate models (GCMs). Moreover, for each SSP scenario, the ensemble means of predictions from the four GCMs were calculated, aiming to reduce the uncertainty inherent in individual climate models, thereby generating the final habitat suitability maps for the periods 2041–2060 and 2081–2100. For each SSP scenario and future period, the percentage of the study area covered by each suitability level and the percentage change relative to the historical scenario were calculated.

3. Results

3.1. Current habitat suitability

The MaxEnt model showed good predictive performance for the occurrence data of *B. affinis*. The final model (FC = LQHP, RM = 0.5) achieved high mean AUC values (0.840 ± 0.009 , Fig. 2A) under block cross-validation, indicating that the optimal model parameter settings effectively balanced model complexity and predictive performance, making the predictive accuracy substantially higher than random prediction. The low SD of the AUC further reflected relatively stable model performance across spatial subsets.

The analysis of environmental variables showed that the historical distribution of *B. affinis* was dominated by climate factors and modulated by human activity factors. Specifically, Mean Temperature of Warmest Quarter (BIO10) (BIO10) was the factor with the greatest impact (59.2%), highlighting the species' high sensitivity to summer temperature. Population density also showed a considerable contribution (12.3%), indicating its importance in predicting habitat suitability.

Precipitation Seasonality (BIO15, 10.1%) and Urban Land Cover Fraction (8.8%) also had considerable influence, reflecting the species' dependence on stable precipitation patterns and anthropogenic landscapes. These factors indicated that suitable microclimatic conditions and human-modified environments shaped habitat suitability (the remaining 13 variables showed relatively low contributions (<3%) and were not discussed further).

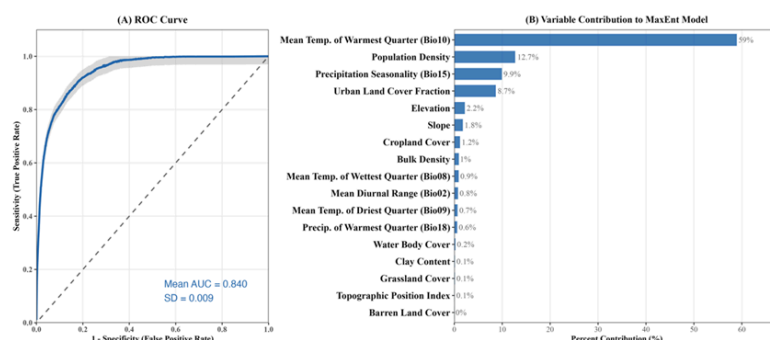


Figure 2. Receiver operating characteristic (ROC) curve and environmental variable contributions of the MaxEnt model for *Bombus affinis*. (A) ROC curve of the optimized MaxEnt model. The shaded area indicates the confidence interval across 10 replicate runs. The mean AUC was 0.840 ± 0.009 . (B) Percentage contribution of each environmental variable to the MaxEnt model. Variables are ranked in descending order of contribution

The historical (1970–2000) MaxEnt model results showed that the distribution of historical suitable habitat displayed strong spatial heterogeneity (Fig. 3). Under baseline climatic conditions, the area of moderately and highly suitable habitat was limited, accounting for only 7.9% of the total area of the study region. Although highly suitable (>0.7) habitat accounted for only 3.0% of the total area of the study region, it was distributed in an extremely concentrated manner along the western shore of Lake Michigan, the eastern North Atlantic coast, and the Appalachian Mountains, forming distinct clusters. Moderately suitable ($0.5–0.7$) habitat was distributed radially around the highly suitable habitat, accounting for 6.4%.

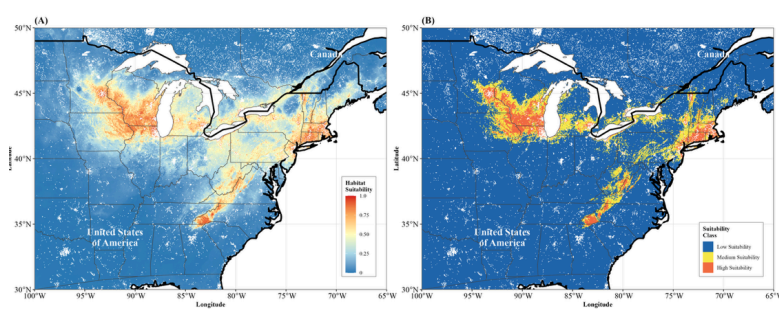


Figure 3. Habitat suitability map of *Bombus affinis* under the historical scenario (1970–2000).

Continuous habitat suitability was predicted by the MaxEnt model and classified into three suitability levels based on predefined thresholds (low suitability: < 0.5 ; medium suitability: $0.5–0.7$; high suitability: > 0.7). Colors ranging from blue to red indicate increasing habitat suitability, while white areas represent water bodies. (A) Continuous habitat suitability before threshold classification. (B) Habitat suitability after threshold classification

At the national scale, conservation priorities for *B. affinis* became clearer (Fig. 4). Within the United States, the core distribution centered on Connecticut along the North Atlantic coast and

stretched into the Northeast, covering Massachusetts and Rhode Island (Connecticut: 82.1%; Massachusetts: 57.6%; Rhode Island: 53.6%). Rhode Island served as the species' main refuge along the northeastern coast, since moderately or highly suitable habitat covered most of the state (high suitability: 53.6%; medium suitability: 46.4%). Connecticut stood out for habitat quality because it held the largest share of highly suitable habitat. West of the Great Lakes, Wisconsin, Minnesota, and Iowa formed the species' main stronghold in the plains, also showing broad areas of high- and moderate-suitability habitat (Wisconsin: 56.4%; Minnesota: 14.4%; Iowa: 27.1%). In North Carolina, moderately and highly suitable habitat appeared in separate, patchy clusters. Across Canada, the two provinces in the study area together held no more than 10% of highly or moderately suitable habitat, well below what *B. affinis* needs to survive. These results point to the need for targeted conservation strategies in the core states where highly suitable habitat is concentrated.

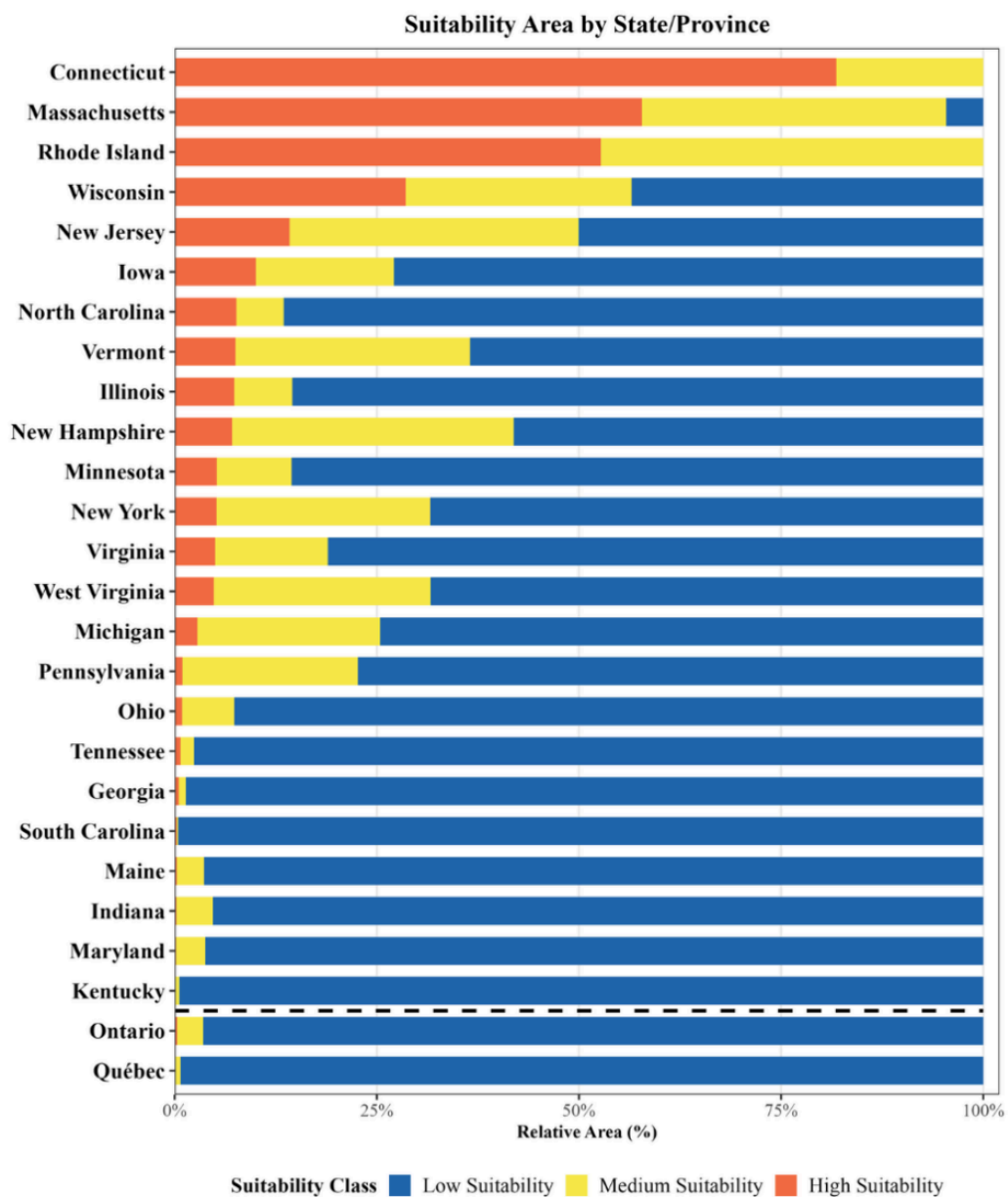


Figure 4. Proportion of historical suitable habitat areas for *Bombus affinis* across states and provinces within the study region

Canadian provinces are displayed above the black dashed line, and U.S. states are displayed below. Colors indicate low suitability (<0.5), medium suitability (0.5–0.7), and high suitability (>0.7). States and provinces are ranked by the proportion of highly suitable habitats in descending order.

3.2. Future habitat suitability under climate change scenarios

Climate-change scenario projections indicated that suitable habitat for *B. affinis* would move geographically and shrink sharply in area. The degree of range contraction and migration tracked future economic development and carbon-emission pathways closely (Fig. 5). Geospatial forecasts pointed to a clear shift of suitable habitats toward higher latitudes. Comparing the latitudinal position of the core of moderately and highly suitable habitats between the historical period (1970–2000) and the future periods (2041–2060 and 2081–2100) showed that, with rising emissions, this core would move northward to 45.37°N, 45.98°N, and 46.52°N under SSP126, SSP245, and SSP585 in 2041–2060, respectively, from the historical core at 42.16°N in the United States. The corresponding latitudinal offsets were 3.21°, 3.83°, and 4.37°. By 2081–2100, the northward shift would grow even larger under the persistent high-emissions scenario (SSP585), with offsets reaching 4.26°, 5.53°, and 6.48°. Future distribution maps (Fig. 5) illustrated this pattern as 'retreat along the southern margin and expansion at the northern margin': under SSP585, suitable habitats in the United States would nearly disappear by the end of the 21st century, with the remaining range withdrawing strongly into southern Canada and becoming fragmented and segmented.

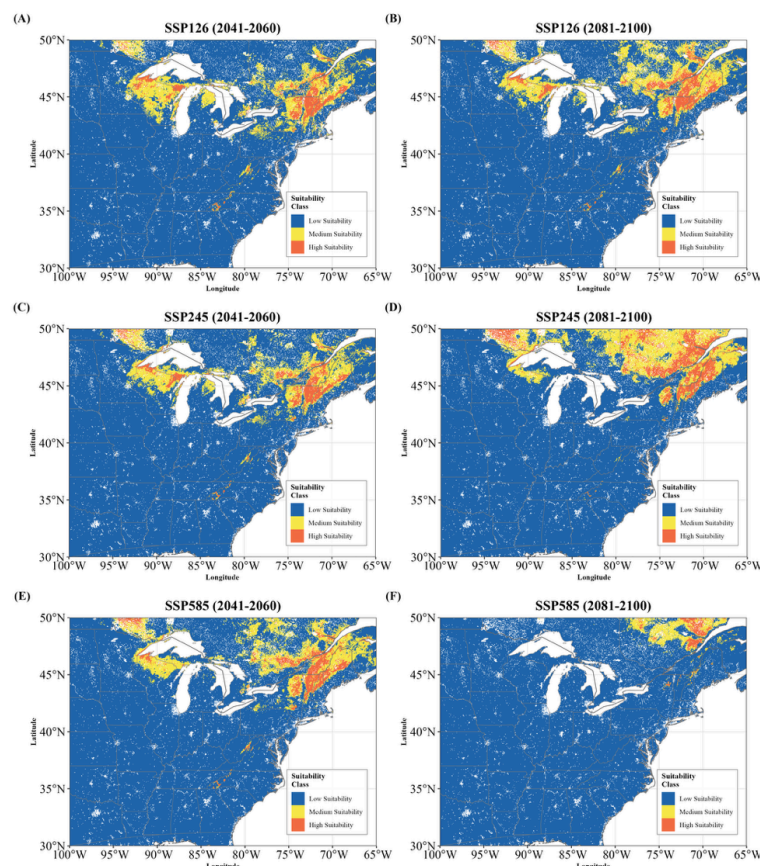


Figure 5. Predicted habitat suitability of *Bombus affinis* under different SSP scenarios and future periods

Panels A–F represent SSP126 (2041–2060), SSP126 (2081–2100), SSP245 (2041–2060), SSP245 (2081–2100), SSP585 (2041–2060), and SSP585 (2081–2100), respectively. Color schemes are consistent with Fig. 4. White areas represent water bodies.

By the middle of this century (2041–2060), under the three SSP scenarios, the area of suitable habitats for *B. affinis* showed limited change compared to the historical scenario (Fig. 6). Although the area of moderately and highly suitable habitats showed a certain trend of expansion (SSP126: 24.5%, SSP245: 17.6%, SSP585: 27.9%), the area of highly suitable habitats showed a downward trend (SSP126: 11.5%, SSP245: 14.1%, SSP585: 2.4%, Fig. 7), which demonstrated that the main habitats still face the risk of reduction, and the moderately and highly suitable habitats under the high-emissions scenario (SSP585) were lost massively, mainly concentrated in the northeastern United States and the Great Lakes region.

By the end of this century (2081–2100), climate change is projected to have a profound impact on the suitable habitat of *Bombus affinis*. In particular, under the high-emission scenario (SSP585), the proportion of the study area occupied by moderately and highly suitable habitats is projected to decline sharply to 3.3%, from 12.8% under SSP126 and 14.9% under SSP245 (Fig. 6), representing a 60.9% reduction relative to the historical period. The area of highly suitable habitat will be reduced by 74.2%, the area of moderately suitable habitat will be reduced by 61.3%, and the area of low-suitability habitat will expand by 6.7% (Fig. 7), which shows that the suitable habitat of the species will suffer extreme threats; not only will the area be greatly reduced, but the quality will also decline.

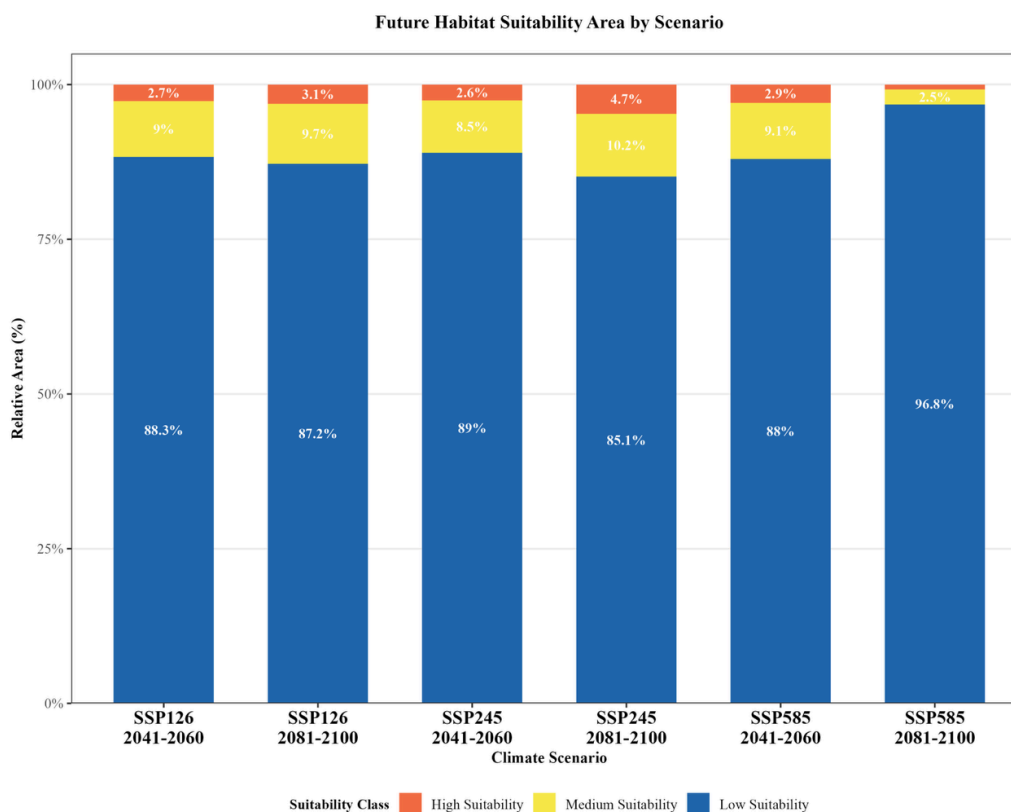


Figure 6. Stacked bar chart showing the proportions of different suitability levels under future climate scenarios

The proportions of each suitability level occupied by habitat suitable for *Bombus affinis* relative to the total study area under different SSP scenarios and future periods. Color scales are the same as in Figure 4.

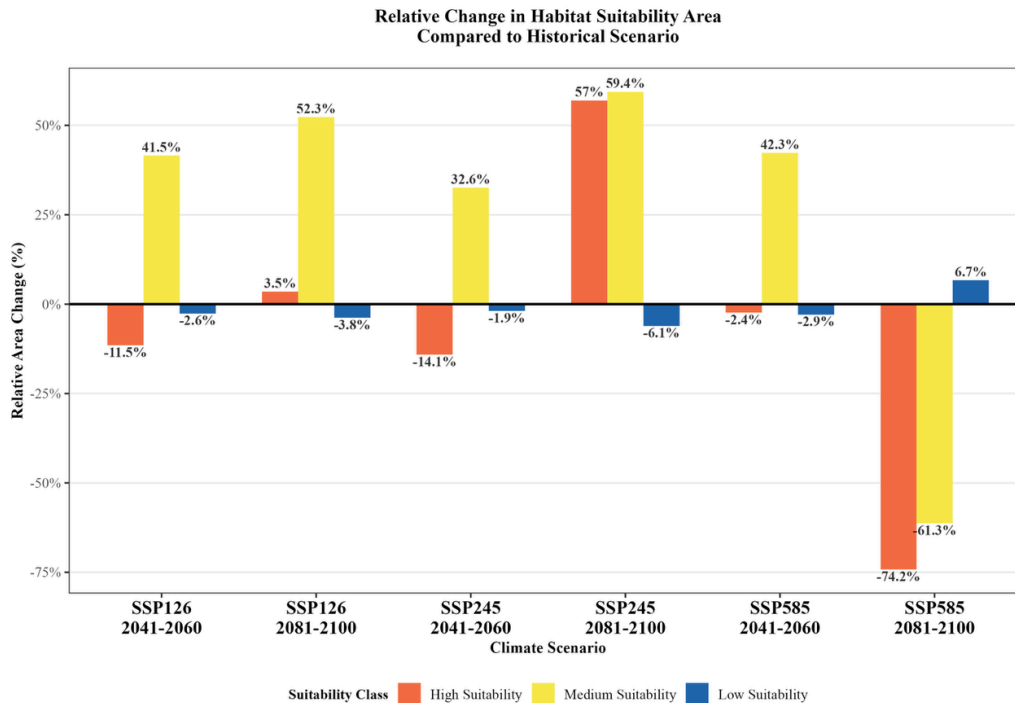


Figure 7. Bar chart showing the relative changes in suitability levels under future climate scenarios compared with the historical scenario

The relative changes in the area of each suitability level for *Bombus affinis* were calculated under different SSP scenarios and future periods. Positive values indicate increases, whereas negative values indicate decreases. The relative change rate was calculated as: $(\text{future area} - \text{historical area}) / \text{historical area} \times 100\%$. Color scales are the same as in Figure 4.

4. Discussion

4.1. Driving factors and current distribution patterns

This study revealed the mechanisms underlying the historical habitat distribution of *B. affinis*. The results showed that for this species, the area of medium and high suitability habitats was limited and of generally poor quality; the habitats exhibited high spatial heterogeneity and were highly concentrated in the Great Lakes region, the northeastern North Atlantic coast, and the Appalachian Mountains. Important climate limits and particular human activities together produced this outcome.

Climate-related factors work as one basic screen for ecological conditions. BIO10 played a bigger part than all other variables, and it took up the largest proportion (59.2 %). Its response curve showed an obvious single-peak shape. The highest value appeared close to 21 °C, and its proper temperature range was about 18-23 °C (Fig. 8). This relationship tells us how good a living place is for this bee largely relies on a small summer-temperature window. The best condition happens when summers are not too hot. This rule agrees with past distribution records collected from woodlands, wetlands, lake edges and mountain low-hills [12]. These places provide more steady small-scale

climate for bee groups to live and keep their nests at proper temperatures. Tree cover, cool water areas and high-land landforms can ease the harm from hot summer weather. BIO15 (Precipitation Seasonality, 10.1 %) had two obvious high points on its response curve. The peaks appeared at $CV \approx 8$ and $CV \approx 54$ (Fig. 8). Such a trend may show how rainfall change across seasons shapes habitat quality, and it probably works by changing how many flower-based food sources exist [30]. If the change of rainfall in different seasons cannot keep enough nectar-rich plants all year round [31], or cannot fit the body features this bee has formed through long-time evolution [32], bee groups will produce fewer new individuals. This will slow group development and lower their breeding performance.

Human activities affect *B. affinis* in many mixed ways. Some related bumble bees like *Bombus occidentalis* get hurt when human disturbance happens [33], but *B. affinis* shows a positive link with Precipitation Seasonality (BIO15) and Urban Land Cover Fraction (Fig. 8). This finding means *B. affinis* can stand some human-changed land environments, and it may even get some advantages from them. We can use several reasons to explain this fact. First, city building creates the heat-island effect and pushes up average yearly temperature. Compared with old natural conditions, queen bees may wake up from winter sleep earlier [18]. Then they will have more time to look for food, produce new bees and finish other activities to keep their groups alive. Second, *B. affinis* can get food from many different flowering plants, such as Asteraceae, *Melilotus* spp., and *Sonchus* spp [30]. These plants can offer rich and various food sources in local areas [34-36]. Third, man-built green areas like city parks and suburban gardens put nest-building spots and food-rich flowers nearer to each other. From April to September when bees stay active, they like nests surrounded by many kinds of plants, with flower resources within one kilometer [12, 18]. Such environments satisfy the bees' nesting demands and greatly reduce the energy they spend searching for food.

Still, the positive response of *B. affinis* to human activity needs careful interpretation. The species can use particular features of artificial landscapes-open microclimates, concentrated nectar sources, and close spatial arrangement of resources-but its tolerance of urban settings is not unlimited. This relationship is double-edged. Urbanization-driven habitat fragmentation has created artificial landscapes that support fewer species than historical habitats did [37]. Together with pesticide exposure, including neonicotinoids [38], this has emerged as a significant stressor for bumble bees. A reduction in nectar plants linked to agricultural intensification [39], along with greater pathogen exposure such as *Nosema bombi* infection, has also been tied to bumble bee declines [40]. Thus, *B. affinis*' use of anthropogenic landscapes mainly reflects exploitation of specific structural features, and this use can be quickly undermined by unfavorable shifts in land use.

Thus, the core distribution of *B. affinis* (the Great Lakes region, northeastern coast, and Appalachian Mountains) can be understood as the region capable of simultaneously meeting its core needs: a cool summer climate (satisfying temperature constraints), relatively stable precipitation patterns (ensuring resource supply), and environments modified by moderate human activity (providing food resources and some suitable habitat components). The spatial coupling of these factors defines the historical, highly heterogeneous, and limited key distribution areas of this species.

These key distribution areas also reveal the key areas and internal conflicts of current conservation efforts. Northeastern coastal states such as Rhode Island, Connecticut, and Massachusetts, as well as Great Lakes states such as Wisconsin and Minnesota in the United States, carry most of the highly suitable habitats of *B. affinis* and constitute the zones of absolute priority for protection. However, the continued existence of these key areas relies heavily on current human

land-use patterns. This means that conservation actions cannot remain limited to designating protected areas but also need to actively manage these human-dominated landscapes, such as connecting green spaces and planting native nectar plants during urban planning [41] and promoting pollinator-friendly agricultural practices in agricultural zones [42]. Meanwhile, for the natural habitats in the Appalachian Mountains that experience relatively little human disturbance, emphasis should be placed on preventing habitat loss and fragmentation. The historical scenario suitability distribution map is not only a conservation priority map but also suggests the potential vulnerability of *B. affinis* due to its reliance on human activity patterns.

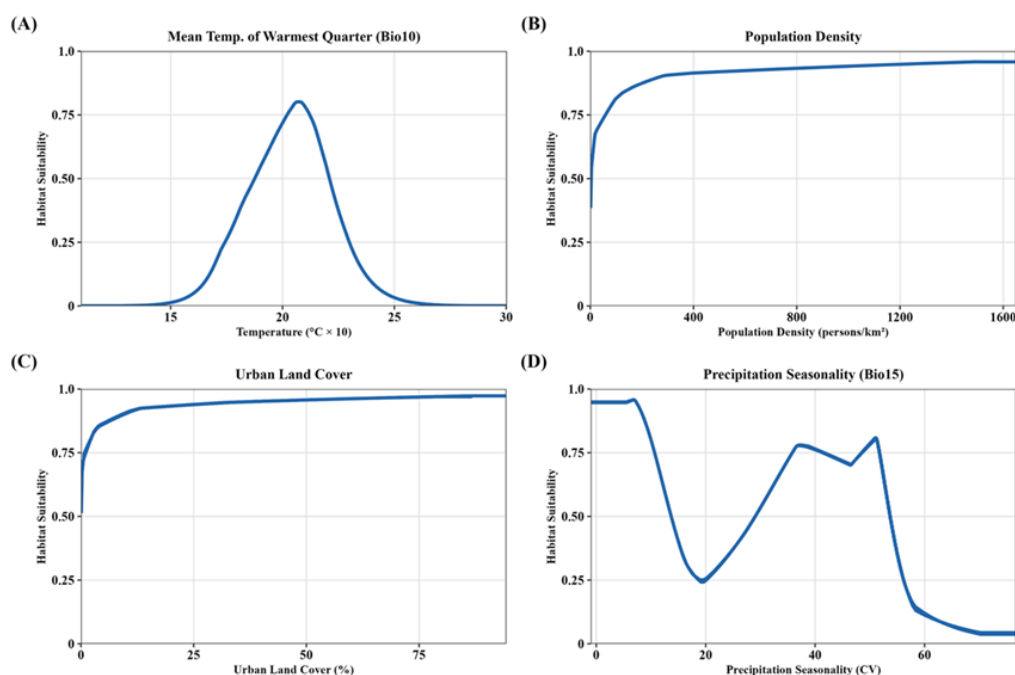


Figure 8. The response curves for key environmental variables illustrate the effect of changes in a single environmental variable on suitability while holding other environmental variables at their mean values

4.2. Future distribution projections under climate change scenarios

Projections under different Shared Socioeconomic Pathways (SSPs) showed that future suitable habitat for *B. affinis* would depend heavily on global greenhouse gas levels. Under high-emission scenarios, the potential suitable habitat area would shrink markedly and severely by the end of this century (Fig. 5), while habitat quality would also deteriorate increasingly (Fig. 7). Core highly suitable habitats would be lost more sharply than the overall decline in suitable habitat area. This means that any surviving populations would probably be restricted to marginal, lower-suitability habitats, severely limiting their ability to grow and persist over the long term.

This downward trend likely connects directly to greater summer heat stress from climate change. The BIO10 response curve showed that *B. affinis* has fairly low heat tolerance but can tolerate some cold. Observations suggest that the species may remain active at temperatures down to about 4°C [43]. By the end of this century, global temperatures are projected to rise by roughly $2.4\text{--}4.8^{\circ}\text{C}$ above the historical period (1970–2000) because of human-caused greenhouse gas emissions [4]. Such warming may push beyond the species' thermal tolerance, lower physiological performance, and eventually kill individuals or populations. Heat stress affects not only adult bees-workers,

drones, and queens-but also harms larvae and eggs in the hive. Because bumble bees are social insects, colonies keep hive temperatures within a narrow range to support normal larval development. When outside temperatures pass the colonies' thermal limit, maintaining an optimal nest temperature becomes harder, which can damage larval development and colony persistence [44]. High-temperature stress can therefore reduce both adult survival and the colony's capacity to keep a stable brood-rearing temperature, causing developmental problems in offspring and reproductive failure. Controlling climate change is thus a basic requirement for ensuring the species' survival worldwide.

The model also pointed to major spatial restructuring of future *B. affinis* habitat distribution, with the southern margin retreating and the northern margin expanding. The species is expected to move toward higher latitudes, especially southern Canada, following suitable climatic conditions. Warming has been shown to lower the suitability of previously occupied habitats. To keep pace with suitable climates, North American bumble bee populations are likely to shift toward cooler, higher-latitude regions [10]. Still, this climate-driven movement involves considerable uncertainty and ecological risk. Because bumble bee colonies live only one year and have limited dispersal ability [12], successful colonization of newly suitable habitats is not guaranteed. Even if a colony reaches a new suitable habitat, the availability of enough food to meet basic survival needs will largely determine whether the species can survive there. Even when several healthy populations adjust to the new habitat, the rate and success of gene flow can affect offspring number and quality, directly influencing *B. affinis* survival probability and, in the end, whether the species can persist in that new location. In addition, non-climatic features of new habitats, such as soil and habitat structure, will strongly affect whether populations can persist. If the match is poor, individuals lost during migration could speed up species extinction. More broadly, species whose dispersal rates cannot keep up with the speed of climate change may fail to colonize shifting suitable habitats [45].

These findings indicate that future conservation should move from static habitat protection to dynamic, climate-adaptive management. This calls for forward-looking planning that pinpoints potential climate refugia and evaluates their suitability for occupation ahead of time. It also calls for rigorous assessment of the risks and benefits of strategies such as natural dispersal and assisted migration, together with remedies for possible migration failures. Because range shifts cross borders, an effective conservation approach must rest on a strong international network built from shared monitoring and coordinated conservation action across boundaries.

4.3. Implications for conservation practice

This study offers useful guidance for conserving *B. affinis*. The species' persistence is limited by climate constraints and by its complex reliance on human-modified landscapes, and future suitable habitats will face both shrinkage and redistribution. Conservation efforts should therefore combine spatially targeted interventions, climate-adaptive planning, and supporting policy frameworks to tackle present threats and get ready for long-term changes.

First, the main conservation strategy should aim at strengthening existing distribution hotspots and improving how they function. The model's heterogeneous distribution pattern means conservation resources should be directed toward the small, high-suitability areas that hold core populations. In the heavily urbanized core areas of the northeastern United States, protection should concentrate on optimizing and maintaining existing habitat function through careful landscape management, such as systematically adding native nectar-rich plants to urban green spaces and improving urban greenspace layout to support pollinator populations [41]. In the Great Lakes agricultural-natural mosaic, strategies should reduce human pressures and keep habitats connected.

This means promoting pollinator-friendly farming, including cutting harmful insecticide effects on bumble bees [42], safeguarding remaining natural habitats, and restoring corridors along ecological gradients. In natural reserves such as the Appalachians, the central goal is to stop habitat loss and maintain ecological integrity. This requires strict prevention of habitat loss and fragmentation through laws and land management, along with monitoring to sustain ecological integrity.

Second, a forward-looking conservation framework needs adaptive management for climate-driven distribution shifts. Because suitable habitats are predicted to move northward, protection planning should take a dynamic view. We should assess early on whether populations could become established in northern climate refugia, making sure these regions have the nectar sources and non-climatic conditions needed for successful settlement. At the same time, we must deal with the mismatch between the species' limited dispersal ability and rapid climate change. Adaptive measures should give priority to maintaining and restoring high-quality habitats and to improving landscape connectivity in areas identified as important for future range shifts [46]. When scientific assessment suggests natural dispersal may not suffice, carefully designed and monitored assisted migration plans could act as a risk-management tool to improve species persistence [47].

Third, supportive policy tools and cross-jurisdictional governance are essential. Carrying out these strategies successfully depends on strong policy support and collaboration among multiple stakeholders. The spatial conservation priorities and habitat needs identified here should be brought into wider policy frameworks, such as U.S. federal and state endangered species recovery plans, agricultural conservation programs, and nature-based climate solution frameworks. Because the species' potential future range may cross national borders, a solid bilateral cooperation mechanism between the United States and Canada is needed to coordinate joint monitoring, data sharing, protected-area network planning, and cross-border assisted migration. Finally, because the species' range overlaps with human settlements, empowering local communities, building citizen science networks, and raising public awareness are key foundations for creating a sustainable and socially inclusive conservation system.

4.4. Model uncertainties and limitations

Though we tried our best to make data-picking steps and model structures strict, people need to think fully about the following method-related weaknesses when they understand these results. First, how trustworthy the model is largely rests on the quality of input materials. We have sorted out occurrence records with great care by using the steps mentioned above, but some spatial sampling bias may still exist. For example, observation records are likely to gather in spots easy for people to get to, such as roads, cities and nature reserves. This situation may make the model mix easy-to-sample locations with good living conditions. Then it may judge places with heavy human influence as more suitable for the species than they really are [48]. Second, future-oriented predictions face one big problem: niche extrapolation. When the forecast time gets longer, future environmental states may go outside the scope of data used to train the model. This will make prediction results less certain [49]. Our model worked well to tell suitable habitats apart from unsuitable ones, yet it cannot make sure the model catches every ecological rule that shapes where species live. Besides, the MaxEnt model holds one basic idea: species keep a balanced state with their surroundings and occupy all climate-fit living spaces [50]. For endangered animals like **B. affinis**, their groups have dropped in number sharply. Their present living ranges can be much smaller than what climate can support. Past population drops, limits on species spread, and the loss of living places can all lead to this gap. So the model may keep giving lower estimates for real suitable habitat size in general. It will produce conservation priority zones that tend to be too safe

and cautious. Knowing about these weaknesses will not make the model less useful. On the contrary, it tells us we must read model outputs very carefully. The forecasts from this paper are only scientific guesses built on our collected data and set rules. They are not fixed, definite pictures of what will happen in days ahead. When researchers turn these spatial guesses into real protection choices, they need to combine field-based ecological checks, clear knowledge of the species' life cycle, and local land-use facts. In this way, they can get more complete assessments and polish related plans. Later research can cut down uncertainty and make predictions more steady. Researchers may add population change models, improve ways to collect occurrence samples, and bring in more data about the species' physical tolerance to surroundings.

5. Conclusion

By combining multi-source environmental data with the MaxEnt model, this study mapped suitable habitats for the endangered North American bumble bee *Bombus affinis* and examined how they might respond to future climate change. The results showed that historical suitable habitats were highly concentrated and spatially heterogeneous, mainly located around the Great Lakes region, the North Atlantic coastal areas of the northeastern United States-especially Connecticut, Massachusetts, and Rhode Island-and the northern Appalachian Mountains. These areas have relatively cool summers, stable rainfall patterns, and landscape structures modified by human activity that provide suitable habitat conditions. The current distribution of *B. affinis* is shaped not by a single environmental factor but by the combined filtering effects of climate constraints and anthropogenic landscape change, with BIO10 emerging as the most important limiting factor. Future projections indicated that, under high-emission scenarios, both the extent and quality of suitable habitats would fall together. The distribution centroid would move northward from the central and eastern United States toward higher latitudes, with suitable habitats becoming increasingly concentrated in southern Canada. Yet this northward shift does not guarantee species persistence, because dispersal ability, resource availability, and habitat connectivity all limit the species. Overall, cutting greenhouse gas emissions remains the basic requirement for the long-term conservation of *B. affinis*, while conservation strategies should move toward spatially explicit, adaptive management frameworks. These strategies should include targeted habitat maintenance and connectivity enhancement in existing core areas, early identification of potential climate refugia and cross-border conservation needs, and incorporation of these actions into broader agricultural and climate policy frameworks to advance biodiversity conservation and sustainable development together.

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