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Climate change will alter Amazonian bumblebees' distribution, but effects are species-specific

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Introduction: Understanding how climate change affects the distribution of Amazonian bumblebee species is essential for their conservation and the pollination services they provide. This study focuses on two poorly known species, *Bombus brevivillus* and *Bombus transversalis*, evaluating how future climate scenarios may alter their suitable habitats in the Brazilian Amazon. Identifying potential refugia and vulnerable areas is crucial for developing targeted conservation strategies.

Methods: Species distribution models were applied using occurrence data from museum records and field collections. Climatic suitability was projected under the baseline period (1970–2000) and two future periods (2021–2040 and 2041–2060) using the high-emission scenario (SSP5-8.5) from the IPCC AR6 report. An ensemble modeling approach combining five different algorithms was used to predict areas of stability, habitat loss, and potential range expansion.

Results: By 2060, *B. brevivillus* is projected to lose 41.6% of its current suitable habitat, with significant reductions in northern and coastal regions. Conversely, *B. transversalis* is expected to retain 89.5% of its current range, showing a westward distribution shift. New climatically suitable areas may emerge for both species, particularly in the western Amazon, potentially serving as future refugia.

Discussion: The findings highlight species-specific responses to climate change, with *B. brevivillus* being more vulnerable than *B. transversalis*. These results emphasize the need for proactive conservation measures to protect critical habitats and mitigate the impacts of climate change. Future research should focus on assessing thermal tolerance and habitat connectivity to refine conservation strategies and ensure the persistence of these essential pollinators in changing environmental conditions.

KEYWORDS

***Bombus*, species distribution modeling, conservation, decision-making, priority zones**

1 Introduction

Bumblebees (*Bombus* spp.) are widely distributed across Europe, America, and Asia, with the most remarkable diversity in temperate regions. Although they are primarily associated with cooler climates, some species are adapted to warmer areas, such as the Mediterranean region, the lowland tropics of Asia, and parts of Central and South America (Williams et al., 2008; Goulson, 2009). However, their species richness is the lowest in neotropical regions, including Brazil, which hosts only eight species: *Bombus bahiensis* Santos Júnior et al., 2015, *Bombus bellicosus* Smith, 1879, *Bombus brasiliensis* Lepeletier, 1836, *Bombus brevivillus* Franklin, 1913, *Bombus morio* (Swederus, 1787), *Bombus pauloensis* Friese, 1913, *Bombus rubriventris* Lepeletier, 1836 and *Bombus transversalis* (Olivier, 1789). None of these species are distributed across the entire Brazilian territory, and their populations are limited to specific habitats (Moure and Melo, 2023; Moure and Sakagami, 1962). While *B. brevivillus* and *B. morio* are entirely black, the other species have yellow pilosity in some areas of the body (Santos Júnior et al., 2015).

Although there are few species, the biology of tropical bumblebees is less well-studied compared to the species of temperate climates. This knowledge gap is partly due to the difficulty in locating their colonies or maintaining them in laboratory settings for extended periods (Garófalo, 2005; Oliveira et al., 2015). Additionally, these tropical bumblebees are much more aggressive than the ones from temperate climates, posing challenges to research efforts (Laroca, 1972, 1976; Garófalo, 2005; Oliveira et al., 2015). Notably, it has been reported that *B. brevivillus*, apart from stinging, may also engage in a defensive behavior spitting an unidentified substance that deters intruders, also hindering people´s affection for these large-body bees (Oliveira et al., 2015).

The nests are built in pre-existing underground cavities or on the ground, with or without a protective layer of litter or vegetation cut by the bumblebees, a variation that occurs between and within species (Laroca, 1972, 1976; Olesen, 1989; Taylor and Cameron, 2003; Oliveira et al., 2015). Bumblebee colonies in tropical regions generally follow an annual reproductive cycle similar to those of temperate species (Laroca, 1976; Oliveira et al., 2015; Paula and Melo, 2015). However, under favorable climatic conditions, it is also possible that the new gynes produced by colonies do not enter diapause, but start new colonies (Garófalo, 1979). Furthermore, the bumblebees can reactive the colonies at the end of each lifecycle, occasionally producing perennial nests (Garófalo, 1979; Oliveira et al., 2022; Garófalo, 2023). This phenomenon may be a survival strategy, enabling colonies to rebound quickly using remaining resources and workers (Oliveira et al., 2022).

The Brazilian species *B. pauloensis* and *B. morio* are better studied and primarily found in Southeast and Northeast Brazil, respectively (Garófalo, 2023). On the contrary, less information is available about *B. brevivillus* and *B. transversalis*, the only bumblebee species inhabiting the Brazilian Amazon (Moure and Sakagami, 1962; Santos Júnior et al., 2015; Françoso et al., 2016). This lack of information is particularly concerning because climate change is predicted to drastically impact the habitat suitability of various bee species in the eastern Amazon region in the coming decades (Giannini et al., 2020a). Furthermore, the predicted reduction of habitat due to climate change, in synergy with losses of land cover and in the size of protected areas, indicates that *B. brevivillus* is one of the most endangered species of bumblebees (Krechemer and Marchioro, 2020).

Given these vulnerabilities and their importance as pollinators for Brazilian agriculture (Giannini et al., 2020b), this study aims to evaluate the effects of climate change on the habitat suitability of two Amazonian bumblebee species, *B. brevivillus* and *B. transversalis*, using the most recent climate scenarios from the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC2023). By integrating current biological data and novel information on occurrence sites and plant interactions, this research seeks to provide a comprehensive understanding of the future distribution patterns of these species and identify potential climate refugia to inform conservation strategies.

2 Materials and methods

2.1 Species occurrence database

Empirical data on the occurrence of *B. transversalis and B. brevivillus* was obtained from the following sources: (a) the speciesLink biodiversity database (http://splink.org.br/), (b) the Global Biodiversity Information Facility (GBIF, 2023), and (c) a newly compiled database with data from the entomological collections of the Museu Paraense Emilio Goeldi (MPEG) and the

Bee Collection of the Federal University of Ceara, as well as recent fieldworks (from BFM). Records with inaccurate coordinates (e.g., missing numbers or signs), questionable locations (e.g., points over water bodies), and duplicate entries with identical coordinates for the species were excluded during the initial screening. The final dataset ("c") was not applied in the modeling process, as it was obtained afterwards; it was used exclusively in subsequent analyses. The database on species occurrences and their respective pseudo-absences can be accessed in the Supplementary Material 1.

2.2 Climate and change scenarios

The latest IPCC report (IPCC-AR6, 2023) consolidated sixty phases of the Coupled Model Intercomparison Project (CMIP6) as the reference for Global Circulation Models (GCMs) for the following decades, improving the accuracy of climate effect projections with significant updates in emission trends and spatial distributions (Hausfather, 2019; McBride et al., 2021). Updated climatic variables directly influence analysis results on terrestrial species. This aspect highlights the need to renew or develop new climate suitability models for species to support precise decision-making on conservation, management and ecological restoration (McBride et al., 2021; Schramek, 2021).

Three sets of digital layers were acquired from WorldClim (Fick and Hijmans, 2017) at 2.5 arc minutes of resolution, each set representing 19 bioclimatic variables in different periods and altitudes. These bioclimatic variables capture geographic patterns of averages, seasonality, and extremes in precipitation and temperature, along with their combinations. The first set (baseline scenario) represents historical climate data for 1970-2000 based on interpolated empirical conditions (Hijmans et al., 2005). The remaining two sets are projections for future climate scenarios under climate change effects: 2021-2040 and 2041-2060. For both periods, the latest CMIP6-GCMs are produced by the Japanese Agency for Marine-Earth Science and Technology (MIROC6-GCM), based on the SSP585 scenario. All variables were cropped to the extent of South America, as both species are endemic to this neotropical region.

Among the Shared Socioeconomic Pathways (SSPs), the SSP5-8.5 represents the most intensive global greenhouse gas emission trajectories projected by AR6 (IPCC-AR6, 2023). While no scenario can be guaranteed as the definitive future climate outcome, SSP5-8.5 is considered the most appropriate for this study because considering the worst possible scenario will ensure that conservation actions will be most effective under any potential future conditions, including the most pessimistic climate outcome. The model's predictive accuracy was enhanced by assessing the initial set of 19 bioclimatic variables from the baseline period (1970–2000) to identify and exclude those with high inter-correlation, as multicollinearity can negatively impact the predictive performance of regression-based models. A Variance Inflation Factor (VIF) analysis was performed using the `vifcor` function from the R package `usdm` (Naimi et al., 2014) to avoid deleterious multicollinearity effects on regression algorithms. The refined set of variables was subsequently used in the modeling process, with future climate variables selected accordingly to match the baseline set. The variables chosen for species after VIF can be accessed in the SM-B.

2.3 Climate habitat suitability approach

A habitat suitability approach was employed (Hirzel and Le Lay, 2008) using the Biomod2 package version 3.5.1 (Thuiller et al., 2021) in R (R Core Team, 2021) to map the climatic suitability of the species under the baseline conditions (1970-2000). Five algorithms were selected based on their high performance in similar studies (Aguirre-Gutiérrez et al., 2013; Acosta et al., 2016): GLM – Generalized Linear Model (glm package; Hastie and Pregibon, 1992), GBM – Generalized Boosting Model (gbm package; Greenwell et al., 2020), GAM – Generalized Additive Model (mgcv package; Hastie and Tibshirani, 1990), RF – Random Forest (randomForest package; Breiman, 2001), and MAXENT – Maximum Entropy (maxent package; Phillips et al., 2021). Algorithm parameterization followed recommendations from the literature (Guisan and Thuiller, 2005; Phillips et al., 2006; Thuiller et al., 2009; Thuiller et al., 2021).

This modeling approach requires presence and absence data; however, confirmed absence data for the target species were unavailable. To address this, five pseudo-absence datasets, each containing ten times the number of presence points (as suggested by Chefaoui and Lobo (2008) for improved predictive performance), were generated randomly outside predefined exclusion zones (20 km buffer radius) around presence points. These buffers represent twice the estimated maximum dispersal distance of individuals from their colonies (Borges et al., 2020), ensuring that pseudo-absences were not placed within these areas.

Each modeling run involved randomly splitting the presence dataset into 80% for training and 20% for evaluation using True Skill Statistics (TSS; Allouche et al., 2006). This random division and replacement of presence and pseudo-absence datasets were repeated for each run. 125 models were generated for each *Bombus* species under the baseline scenario, resulting from the combination of five algorithms, five pseudo-absence datasets, and five random partitions of the presence data (5 algorithms × 5 pseudo-absences × 5 runs = 125 models).

Only the models with the highest predictive performance (TSS > 0.8) were retained for further analysis. These top-performing models were used to construct a Baseline Ensemble Forecast Model (BEFM) using the Committee Averaging method, which converts probabilistic predictions into binary outcomes by maximizing specificity and sensitivity thresholds and then averaging them (Wisz et al., 2008; Hao et al., 2019; Thuiller et al., 2021). The selected models to build the BEFM were also projected onto future climate scenarios using the Biomod2 projection function and ensembled. Each ensemble forecast model (baseline, 2040, and 2060) was subsequently reclassified in binary values for further comparison: areas with suitability values ≥ 75% in continuous models were reclassified as binary=1 (suitable), and regions with < 75% were reclassified as binary=0 (unsuitable).

We then generated delta models by comparing the baseline with each future scenario, achieved by concatenating binary values side-by-side. This approach allowed us to classify four categories: (A) consistently suitable (potential climate sanctuary and/or refuge) - areas currently suitable (baseline zones with value = 1) that remain suitable (value = 1) in future scenarios (delta value = 11); (B) loss of suitability - areas currently suitable (baseline value = 1) that become unsuitable (value = 0) in future scenarios (delta value = 10); (C) gain of suitability (potential climate refuge) - areas currently unsuitable (baseline value = 0) that become suitable (value=1) in future scenarios (delta value = 01); and (D) consistently unsuitable - areas consistently unsuitable (baseline value = 0) that remain unsuitable (value=0) in future scenarios (combined value = 00). It is important to note that the calculation of areas lost in terms of climatic suitability is not offset by areas gained, as there is no guarantee that the species will be able to occupy these new areas in future. This is due to non-climatic factors not accounted for in the model, such as dispersal capacity relative to the pace of climate change, the availability of food resources and shelter, competition from other species, diseases, and the lack of ecological/landscape connectivity between currently suitable patches and new projected suitable zones in the future. For details on modeling outputs, parameters and input data, see Supplementary Material 1.

3 Results

3.1 Effect of climate change on *B. transversalis*

The suitable climate range of *B. transversalis* is expected to significantly change the geospatial distribution of suitability levels over the coming decades (2040, 2060) within its near-current range (Figure 1A). A visual comparison between the continuous models from the baseline to future scenarios (Figures 1A–C) indicates that, while there is a reduction in suitability in marginal areas to the

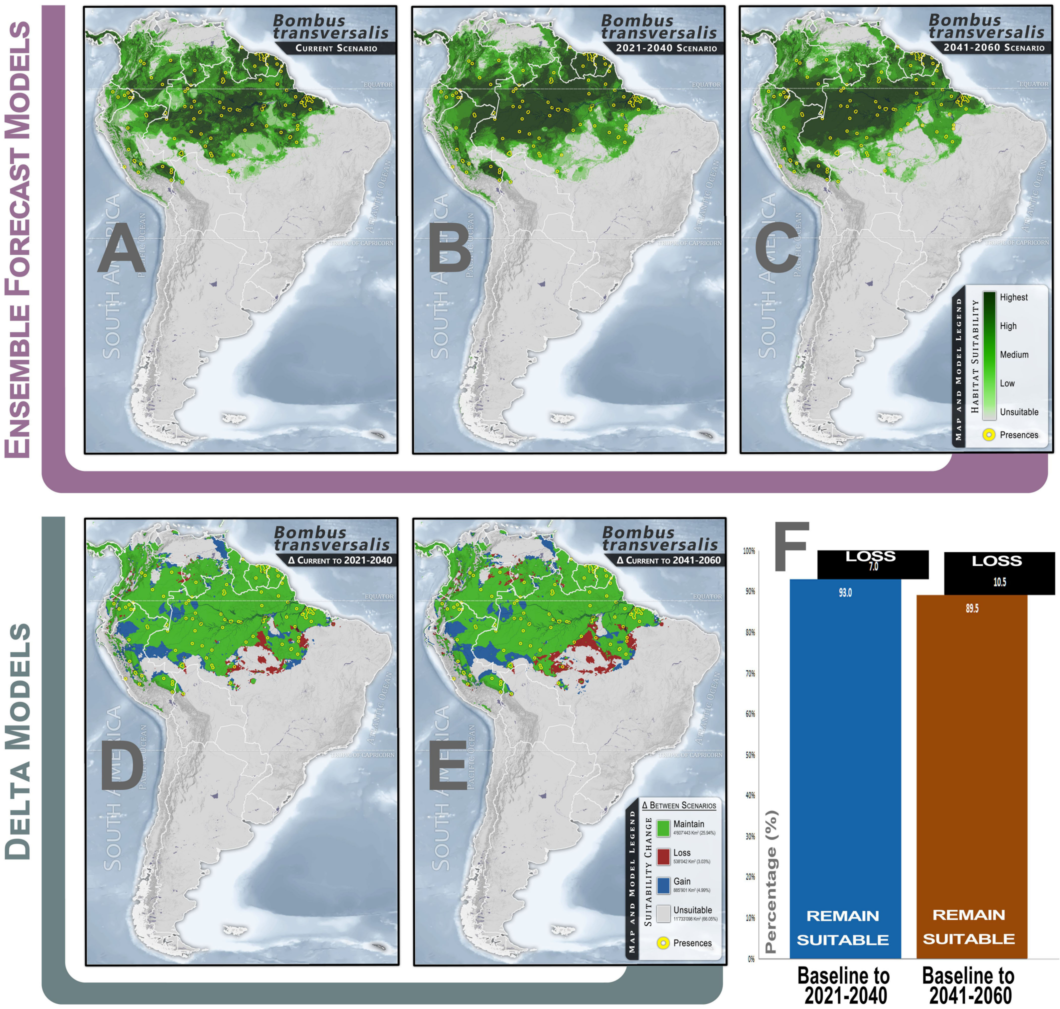

FIGURE 1
Climate habitat suitability and climate change effects for *Bombus transversalis*. **(A)** Continuous climate suitability for the species in the baseline scenario, considering near-current climate conditions (1970-2000); **(B)** Continuous climate suitability projection based on MIROC6-SSP-858 GCMs for 2021-2040; **(C)** Continuous climate suitability projection based on MIROC6-SSP-858 GCMs for 2041-2060; **(D)** Delta model comparing changes from baseline to the 2021-2040 scenario; **(E)** Delta model comparing changes from baseline to the 2041-2060 scenario; **(F)** Bar plot showing the proportion (%) of changes (loss and maintenance) in the climatically suitable range for the species.

southeast of the Amazon Biome, there is a concurrent shift in suitability towards the northwest and west. This shift is accompanied by increased homogeneity in the coverage of areas with higher suitability.

The models predict a 7% reduction in climatically suitable habitat extension for *B. transversalis* from the baseline period (1970–2000) to the 2021–2040 scenario and a 10.5% from baseline to the 2041–2060 scenario. In all future scenarios, consistent habitat suitability losses are detected for this species, predominantly in the southeastern region of the Amazon biome (Figures 1D–F; Supplementary Table S1). These losses are relatively minor in area compared to the regions that maintain suitability. An immense suitable zone of species' climate suitability will persist, stretching from the Atlantic coast to the Andean Mountain ranges. New suitable areas, mainly concentrated in the western Amazon and near the Andean region, are projected to emerge. This matches the prediction that the species' range will shift westward.

3.2 Effect of climate change on *B. brevivillus*

Habitats with the highest levels of climate suitability for *B. brevivillus* (dark green zones) were detected primarily in spots concentrated in northern and northeastern Brazil, with a relatively wide but scattered distribution across several other parts of the continent (Figure 2A). The species is mainly found in coastal zones (Mata Atlantica Biome), large river basins (riparian forests and surroundings), and areas of relatively higher altitudes, notably plateaus and highlands (Araripe plateau, Ibiapaba plateau, Mirador

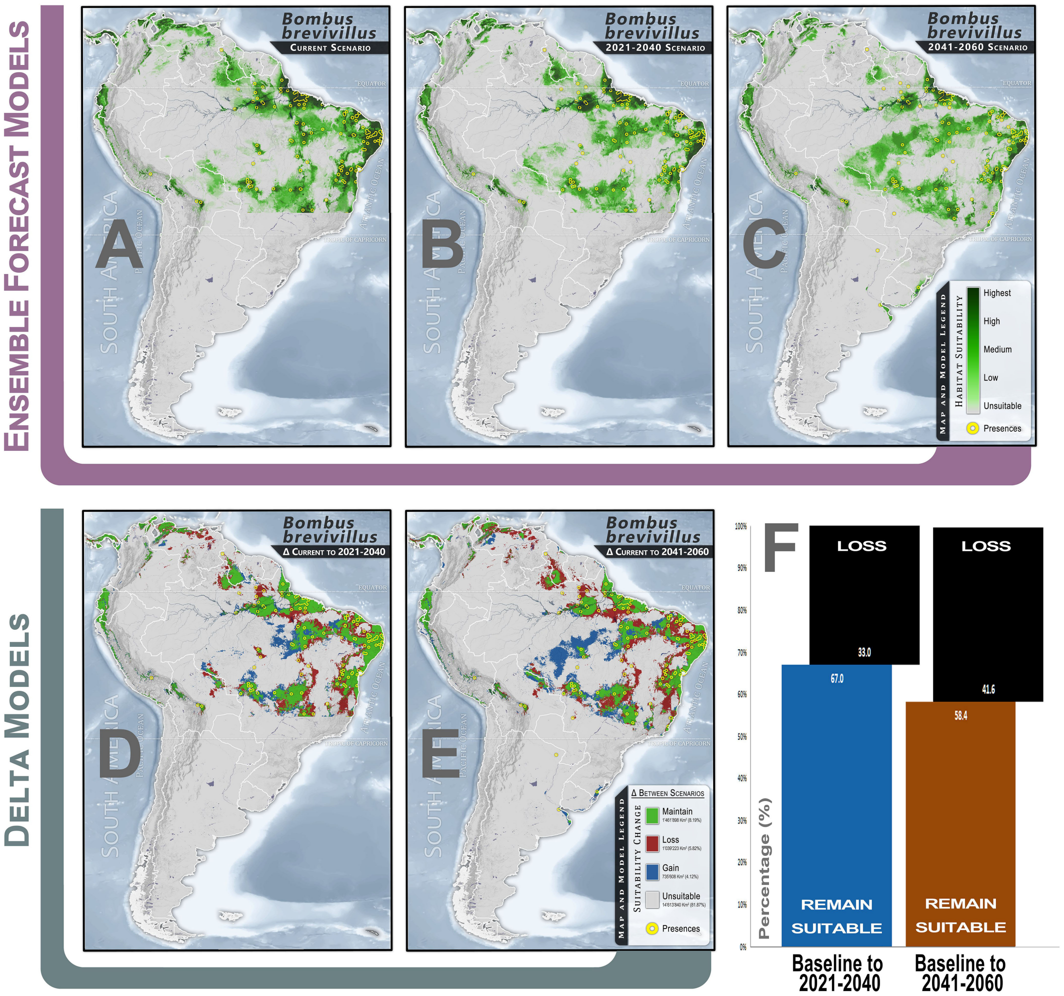

FIGURE 2
Climate habitat suitability and climate change effects for *Bombus brevivillus*. **(A)** Continuous climate suitability for the species in the baseline scenario, considering near-current climate conditions (1970-2000); **(B)** Continuous climate suitability projection based on MIROC6-SSP-858 GCMs for 2021-2040; **(C)** Continuous climate suitability projection based on MIROC6-SSP-858 GCMs for 2041-2060; **(D)** Delta model comparing changes from baseline to the 2021-2040 scenario; **(E)** Delta model comparing changes from baseline to the 2041-2060 scenario; **(F)** Bar plot showing the proportion (%) of changes (loss and maintenance) in the climatically suitable range for the species.

plateau, Meruoca mountains, Baturité mountains and Carajás mountain range).

For the coming decades, significant shifts will occur in the distribution of currently suitable areas (Figures 2A–C), with a decrease in suitability levels in northern and coastal zones (evidenced by the decrease in green intensity across scenarios) and an expansion of suitability coverage towards the eastern regions. The models detected a 33% reduction in the extent of climatically suitable habitats from the baseline to the 2021-2040 scenario and a 41.6% reduction for the 2041-2060 (Figures 2D–F; Supplementary Table S1). Losses will be more pronounced in the marginal zones of the baseline suitable areas, indicating a contraction of the overall suitable extent (Red zones in Figures 2D, E). However, gain zones were also detected in the most central areas of the climatically suitable distribution area for the species, although it cannot be guaranteed that the species will be able to occupy these zones in the future. (Blue zones in Figures 2D, E).

3.3 Bumblebee temporal distribution and interaction with flowers

Overall, we found 206 *B. transversalis* and 388 specimens of *Bombus brevivilus* in the entomological collections (MPEG and CAUFC). Bees from both species have been collected in all 12 months of the year from 1877 to 2024. Although both species appear to be active throughout the year, more than 65% of the *B. brevivilus* specimens were collected in the first five months of the year (January to May), 30% of individuals were collected between June and October and about 4% were collected between November and December (Figure 3). In a dissimilar trend, 29% of the *B. transversalis* specimens were collected between January and May, more than 62% were collected between June and October, and 5% of the bees were collected between November and December (Figure 3A).

Although most of the specimens found in the collections were probably collected when interacting with flowers, these are not described in the specimens´ labels. Only specimens collected

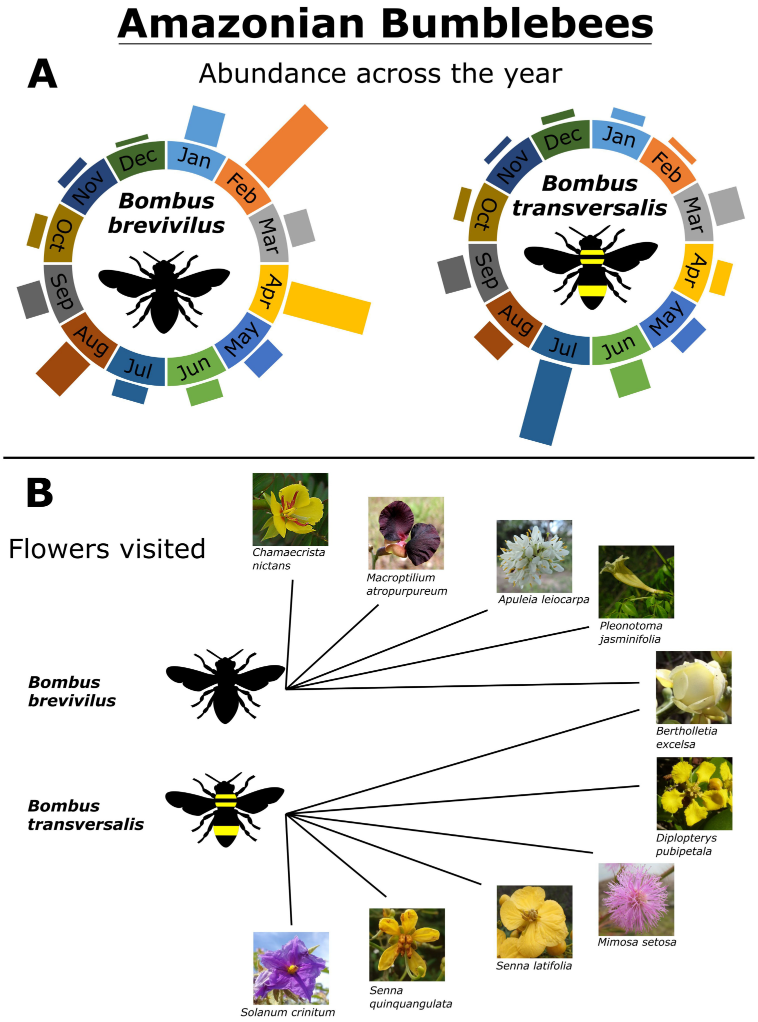

FIGURE 3
Amazonian bumblebees (*Bombus brevivillus* and *B. transversalis*). **(A)** Relative abundance of Amazonian bumblebees according to the historical data from entomological collections (MPEG and CAUFC). The total abundance of *B. brevivillus* is 383 specimens, *B. transversalis* 206 specimens. **(B)** Amazonian bumblebee interactions with local flowers. Data was obtained from specimen labels and the analysis of the pollen grains adhered to the specimen body (Romeiro et al., 2023).

between 2018 and 2024 provide an identification of the plants visited. The two species interacted with ten plant species (Figure 3B), all plants with flowers with matching sizes and exposed rewards.

4 Discussion

The models predicted that both *B. brevivillus* and *B. transversalis* will experience shifts in their geographic distribution due to climate change in future decades, with variations in the extent of suitable habitats over time. By 2060, *B. brevivillus* is expected to lose more than 40% of its suitable climate zone extent, while *B. transversalis* will maintain its large climatically suitable zone, with limited losses (10.5%) and a westward shift. Previous predictions have suggested that *B. brevivillus* may lose between 57.2% to 67.2% of climatically suitable habitat by 2050, and between 66% and 78.4% by 2070, depending on the scenario (Krechemer and Marchioro, 2020). Our results indicate lower losses, likely due to the use of updated future climate scenarios (IPCC-AR6, 2023). In contrast, *B. transversalis* is projected to maintain a significant portion of its current habitat and shift its range westward, suggesting potential stability in its core distribution (Krechemer and Marchioro, 2020). The limited losses predicted for *B. transversalis* are consistent with previous studies that estimated a 9.1% to 19% decrease in climatically suitable areas by 2050 and 20% to 24.7% by 2070 (Krechemer and Marchioro, 2020). This relative stability is likely due to the predicted climate stability for the central and western portions of the Brazilian Amazon (Bottino et al., 2024), which also supports the observed westward shift.

Regarding changes in geographic distribution, *B. brevivillus* will undergo significant range shifts: while expanding into eastern regions, northern and coastal zones will experience a drastic reduction in suitability levels. Krechemer and Marchioro (2020) also predicted this eastward shift of distribution. Meanwhile, *B. transversalis* is projected to expand westward into newly suitable areas, potentially using these regions as future climate refugia. However, whether *B. transversallis* can effectively colonize these areas depends on other limiting ecological and environmental factors not accounted for in this study. The reduction in suitability along the southeastern margins of its range within the Amazon Biome, as observed here, aligns with the predictions of Krechemer and Marchioro (2020), who predicted that *B. transversalis* would lose regions that are climatically suitable in the southern range of its distribution.

Climate change impacts on four other South American bumblebee species have been predicted by Krechemer and Marchioro (2020): *Bombus bellicosus*, *Bombus brasiliensis*, *Bombus morio* and *Bombus pauloensis*. The expected effect varied with the species, but *B. bellicosus*, *B. brevivillus* and *B. brasiliensis* were considered the most vulnerable due to significant habitat losses, limited protected areas, and habitat fragmentation (Krechemer and Marchioro, 2020). Similarly, Martins et al. (2015) have also pointed out the vulnerability of *B. bellicosus* because of climate change, among other factors. Losses in climatically suitable areas have also been predicted for *B. morio* (Elias et al., 2017; Françoso et al., 2019) and *B. pauloensis* (Françoso et al., 2019). In the Neotropics, changes in distribution range were also predicted for *Bombus funebris* in the western region of South America (Nascimento et al., 2022). Populations of this species are expected to become restricted to high-altitude areas in the Andean region by 2070 (Nascimento et al., 2022).

In contrast, climate change does not appear to play a significant role in the decline of the southernmost bumblebee, *Bombus dahlbomii* and will probably have a small impact on its geographic range, which may decrease by 13% to 14% between 2080 and 2100 due to this stressor alone (Morales et al., 2022). These contrasting responses highlight that species-specific traits, such as thermal tolerance, nesting behavior, ecological interactions, and flexibility, influence how different bumblebee species respond to changing climates.

As discussed above, species-specific responses to climate change have been reported for other bumblebee species (Jackson et al., 2022; Singh et al., 2023), often linked to differences in their ecology and physiology. There is both inter- and intraspecific variation in heat resistance among bumblebees (Martinet et al., 2021). Intraspecific variation can occur between populations in different geographic areas (Oyen et al., 2016; Martinet et al., 2021), but is also species-specific and associated with geographically widespread species (Martinet et al., 2021). Furthermore, Martinet et al. (2021) pointed out that bumblebees are generally more tolerant to cold than to heat, and the capacity to tolerate extreme temperatures may limit their distributions, which affect, at least partially, species population trends for expansion or contraction. However, existing studies do not include tropical bumblebee species. *B. brevivillus* and *B. transversalis* may be more tolerant to heat than bumblebees from temperate and polar regions, and there may be interspecific variation in heat tolerance that could explain the difference in the predicted range shifts and suitable habitat losses and gains. Studying the thermal tolerance of those bumblebees would contribute to understanding and making more precise predictions of the effects of climate change on them.

Nest temperature and architecture may also play a role in the species-specific responses of bumblebees to climate change. Recently, Kevan et al. (2024) emphasized that the nest temperature, especially in and around it, are critical factors in comprehending the consequences of heat stress on bumblebees, but nest architecture and the thermal characteristics of nest substrates have yet to be studied. Their review indicated that, in general, the optimum temperature for brood rearing ranges from 28 to 32°C for species that live from the cold High Arctic to tropical environments, and it is conserved among bumblebee species. However, the authors have found data on only around 25 bumblebee species in 20 studies (Kevan et al., 2024), and among them, the only bumblebee from South America was *Bombus atratus* (now *B. pauloensis*, Moure and Melo, 2023) (Vega et al., 2011).

Although *B. transversalis* was not included in the review, Taylor and Cameron (2003) measured the internal temperature of four nests and found a mean of 30.1°C, which is around 4.5°C warmer than the ambient temperature. The nest humidity and temperature were maintained regardless of ambient conditions, which was attributed to the insulating nest cover (built with leaves and pieces of wood) and the fanning behavior of workers under direct sunlight on the nest (Taylor and Cameron, 2003). Still, no experimental study on the role of these two factors has been conducted. Furthermore, fanning may not be effective under extreme temperatures. Although there may be differences between tropical and temperate species, the temperate bumblebee *B. impatiens* fails to maintain nest temperature even by increasing fanning at 35°C and workers abandon the colony at this temperature. This suggests that heatwaves exceeding 30°C negatively impact on colony health (Bretzlaff et al., 2024).

The nests of *B. transversalis* are built on the ground surface, on a pile of leaves and sticks, and the bumblebees use vegetation (cut woven leaven) to cover it (Taylor and Cameron, 2003). *B. brevivillus* also constructs its nests on the ground surface but nests underground, covering the nests with vegetation (Oliveira et al., 2015). A thin layer of wax is constructed over the brood area (Oliveira et al., 2015), which is not frequent for *B. transversalis*, that may occasionally construct a thin layer of wax that covers part of the brood area (Taylor and Cameron, 2003). The vegetation cover (as also suggested by Taylor and Cameron, 2003) and the layers of wax and old brood cells may act in passive thermoregulation. Thus, investigating these mechanisms is crucial to predict how these species will respond to heat stress and climate change.

Furthermore, there is an urgent need to study the thermal tolerance of bumblebee species, to understand and predict the effects of climate change more precisely, in particular of South American bumblebees. The few species of bumblebees (*B. terrestris* and *B. impatiens*) tested for thermal tolerance were not capable of acclimation after prolonged heat and heat waves, decreasing their ability to cope with heat stress (Oyen and Dillon, 2018; Quinlan et al., 2023; Sepúlveda and Goulson, 2023). In addition, nutritional stress (e.g. starvation) lowers the survival of *B. impatiens* after heat stress compared to bumblebees with access to food, indicating that nutrition directly affects heat tolerance (Quinlan et al., 2023; but see Oyen and Dillon, 2018). In summary, heat stress can negatively affect survival, foraging behavior, reproduction, colony development, and fertility (White and Dillon, 2023). For example, thermal stress affects the viability and integrity of the DNA of the sperm of the cold-adapted species like *Bombus magnus* and *Bombus jonellus* (both declining), but not of the warm-adapted and widespread *B. terrestris* (Martinet et al., 2021).

Species-specific responses to extreme temperatures and thermal tolerances must be further investigated, as they drive changes in bumblebee community composition. These changes occur as some species' populations increase while others decline, leading to shifts in population ranges (e.g. Kerr et al., 2015; Martinet et al., 2015; Arnóczkyné Jakab et al., 2023). For instance, some species' geographic distribution may change as a result of warmer winters (Biella et al., 2021). Unfortunately, monitoring of bumblebee communities in the Neotropical region, especially in the Amazon region, is virtually nonexistent. This lack of data makes it impossible to track population changes, highlighting the urgent need for year-round monitoring.

This monitoring is urgent and should be carried out throughout the year because both *B. brevivillus* and *B. transversalis* have been observed throughout the year, although their activity peaks at specific times (*B. brevivilus*: January to May; *B. transversalis*: June to October). The colony cycle of *B. transversalis* aligns closely with the wet-dry seasons in the Amazon: colonies establish during the wet season and mature in the dry season. Traditional communities have noted that most nests in pristine areas appear perennial, as new queens reuse old nest structures rather than building new ones (Taylor and Cameron, 2003). However, this trait could make this species vulnerable under global changes scenarios. Nest construction involves significant investment, and the inability to establish new nests in response to climate and land use change may threaten their populations. Similarly, *B. brevivillus*, exhibits a colony cycle where, during periods of high worker population, colonies prioritize producing males and gynes, which will disperse in search of mates just before and during the characteristic colony collapse observed in *Bombus* colonies (Oliveira et al., 2015). Reactivation of *B. brevivillus* nests have been observed (Oliveira et al., 2022), possibly as a survival strategy to avoid predation. Reactivated nests retain some workers and resources, allowing for rapid colony growth and the early establishment of a defensive worker force.

Landscape also influences the distribution of bumblebee species and the composition of their communities; thus, land use should also be considered in the planning of bumblebee conservation strategies along with climate, and, when possible, their effects should be evaluated together (Christman et al., 2022). Colonies of *B. terrestris*, for example, produce more individuals as temperature increases, however, only when there is high availability of resources (Zaragoza-Trello et al., 2021). When the resource availability is low, the number of queens and males produced by colonies decreases, but not of workers, showing that the effect of climate interacts with resource availability and varies with caste (Zaragoza-Trello et al., 2021). Therefore, although producing more workers may be a strategy to survive under low resource availability, ensuring enough floral resources for colonies is essential for minimizing the effects of climate change (Zaragoza-Trello et al., 2021). For *B. brevivillus* and *B. transversalis*, further research is needed to identify the plants they rely on for foraging, as few records exist on their floral preferences.

Moreover, climate change may influence bumblebees by changing habitats, which should also be considered in the predictions. In Belgium, for example, the probability of species decline was linked to the kind of habitat preferred by the species, and species that choose to live in open habitats presented a higher chance to decline than species preferring forests (Rollin et al., 2020). This difference may explain why *B. brevivillus* appears more vulnerable than *B. transversalis.* While *B. brevivillus* occupies both forests and open habitats (Oliveira et al., 2015), *B. transversalis* constructs its nests on *terra firme* in the Amazon Forest (Olesen, 1989; Taylor and Cameron, 2003).

Unfortunately, besides the threats from climate change and deforestation reducing its suitable areas, *B. brevivillus* also faces the direct action of humans that usually destroy its colonies as soon as they are found in precaution against the highly defensive behavior shown by this species. This is markedly recurrent when nests are built close to urban areas and agricultural settings, especially banana and coffee plantations (Oliveira et al., 2015). Considering this scenario and the results reported in this study, one question is if there will be losses of the pollination services provided by *B. brevivillus*.

Conversely, *B. transversalis* may become an essential pollinator in the coming decades. Bumblebee species are important pollinators of commodities such as the Brazil nut (Cavalcante et al., 2018); with a large body size and long flight distance (Borges et al., 2020), efforts for the conservation of pollination services should consider the maintenance of protected areas for supporting bumblebee populations (Freitas et al., 2014). This is particularly important in that, at least in the Eastern Amazon (Carajás Forest), it is predicted that the populations of 95% of bee species will suffer a decrease in occurrence area (Giannini et al., 2020a). Climate change will potentially have negative consequences for crop pollination in Brazil (Elias et al., 2017; Giannini et al., 2020a; Sales et al., 2021), thus predicting the effects of climate change on bees, which are the leading group of crop pollinators in the country (Oliveira et al., 2024), is essential to conservation management policies. In conclusion, both *B. brevivillus* and *B. transversalis* are predicted to experience range shifts and habitats losses by 2060. These changes may reduce their geographic overlap and are likely tied to species-specific traits that require further investigation. Therefore, scientifically accurate predictions are essential for developing conservation and management plans to ensure the survival of these species and the pollination services they provide.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Ethics statement

The manuscript presents research on animals that do not require ethical approval for their study.

Author contributions

PN-S: Visualization, Writing – original draft, Writing – review & editing. AA: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. RB: Formal analysis, Visualization, Writing – original draft, Writing – review & editing. BF: Data curation, Funding acquisition, Resources, Writing – original draft, Writing – review & editing. RO: Conceptualization, Formal analysis, Investigation, Methodology, Writing – review & editing. TG: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Writing – review & editing. VI-F: Conceptualization, Data curation, Funding acquisition, Methodology, Project administration, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher’s note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frbee.2025.1510004/full#supplementary-material

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