



Ecological niche modeling under current and future scenarios for several Amazonian endemic vascular epiphytes

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Abstract

Given the ongoing climate change, information on species distribution is becoming increasingly necessary, particularly for species with restricted distribution ranges, such as endemic ones. We used ecological niche modeling to evaluate the distribution of 28 species of vascular epiphytes endemic to the Amazonia under current and future scenarios. We analyzed the climatic factors influencing current and future environmental suitability using MaxEnt (based on a set of three global circular models: EC-Earth3-Veg, MPI-ESM1-2-HR, and IPSL-CM6A-LR from CMIP6 under the SSP1-2.6 and SSP5-8.5 scenarios for 2090). We predicted that the current distribution of these epiphyte species is concentrated in Northwestern Amazonia, Central Amazonia and the Guiana Shield. In future scenarios, a decrease in environmental suitability is expected, with large gaps predicted for the Southern Amazonia. Species such as *Anthurium vaupesianum* (Araceae), *Aechmea fernandae* (Bromeliaceae), and *Bifrenaria longicornis* (Orchidaceae) showed increased environmental suitability in future scenarios. However, most species showed a trend of loss of suitable areas, resulting in more restricted and less continuous niches, as well as reductions in the southern and southeastern regions of the Amazonia. These results highlight the impacts of climate change on vascular epiphyte communities and reinforce the importance of monitoring these species in the face of ongoing environmental transformations.

Keywords Amazonia forest · Climate change · Epiphyte · Conservation · Endemism · MaxEnt

Introduction

Vascular epiphytes are plants that rely on other plants as hosts without establishing parasitic relationships (Zotz 2016). Approximately 10% of all plant species are vascular epiphytes (Zotz 2016; Zotz et al. 2021a), with significant diversity in the the Amazonia rainforest

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(Quaresma et al. 2022) and in the Neotropical region, representing up to 39% of the vascular flora (Taylor et al. 2021; Marcusso et al. 2022). As an evolutionary consequence and due to habitat conditions, epiphytes show morphological adaptations to water and nutrient limitations such as thicker leaves and stems with a greater water and nutrient storage capacity as well as lower photosynthetic rates compared to terrestrial plants (Hietz et al. 2022; Ceballos 2023). However, water availability is a key factor shaping the macroecological patterns of diversity and distribution of vascular epiphytes in the Neotropical region (Zotz 2016; Marcusso et al. 2022), where temperature variation may increase the risk of local extinction (Acevedo et al. 2020; Carmona-Higuaita et al. 2024).

Geographic distribution data are increasingly needed to understand how changes in landscapes affect species occurrence as well as colonization and extinction processes (Acevedo et al. 2020; Kolanowska 2023). Ecological niche modeling quantifies the relationship between species occurrence and the environment, generating information on how environmental factors control the distribution of species or communities. It is an important tool in the field of ecology with various implications, allowing, for example, the detection of potential areas for species occurrence, which support the evaluation of the impact of the transformation of natural areas into anthropogenic landscapes on species distribution, mapping of potential areas for conservation of bioindicator species, and identification of refugia for species at risk of extinction (Guisan and Zimmermann 2000; Phillips et al. 2004; Saatchi et al. 2008; Kolanowska 2023). Additionally, it allows the assessment of how environmental requirements influence biological aspects of the species (Blanchard and Runkle 2006; Acevedo et al. 2020).

In the Amazonia, 15.8% of the intact humid forest cover was lost between 1990 and 2023 due to deforestation (11.0%, or 61.7 million hectares) or forest degradation (4.9%, or 27.5 million hectares) (Beuchle et al. 2025). Areas such as the Deforestation Arc of the Brazilian Amazonia exhibit intensified forest fragmentation with significant impacts on biodiversity and ecological processes (Favretto and Hirota 2026). This transformation has a negative impact on biodiversity and interferes with precipitation, river water volume, and river flow (Cavalcante et al. 2019; Souza Jr et al. 2022), ultimately affecting the biodiversity of regional phytophysognomies (Leal et al. 2017). A temperature increase of up to 4 °C and a loss of up to 30% of Amazonian tree species richness are expected by 2050 in the event of a 20% reduction in forest cover (Nobre et al. 2016; Gomes et al. 2019). Such species decline is expected to have a cascading effect on other plant groups dependent on trees, including the vascular epiphytes (Sáyago et al. 2013).

Epiphytes can be classified as secondary foundation species (see Thomsen et al. 2018), as they establish micro-habitats that increase the structural complexity of the forest canopy (Zotz and Bader 2009). By modifying environmental conditions and providing resources, these plants contribute to the structuring of the environment, favoring the occurrence and diversity of associated vertebrates, invertebrates, and microorganisms (Spicer and Woods 2022). Thus, the severe alteration or suppression of forests by human activities triggers cascading effects on biodiversity, compromising not only primary foundation species, such as trees, but also secondary foundation species, such as epiphytes, as well as the various organisms that depend on them. As epiphytes do not root in the forest floor, they are closely associated with host characteristics and depend on microenvironmental conditions, which makes them particularly vulnerable to changes in land use and climate, ultimately increasing their risk of extinction, especially in the Neotropical region, where forests are strongly

regulated by water availability (Zotz and Bader 2009; Hsu and Wolf 2013; Poorter et al. 2017; Kolanowska 2023; Carmona-Higuita et al. 2024). Furthermore, the reduction of primary forests and the expansion of secondary forests (a recurring process in the Amazonia due to changes in land use; Projeto Mapbiomas 2025) result in the formation of ecosystems with environmental conditions less favorable to the establishment and maintenance of vascular epiphytes (Krömer et al. 2025).

Ecological niche modeling studies with vascular epiphytes are relatively recent (Hsu et al. 2012, 2014, 2018; Hsu and Wolf 2013; Acevedo et al. 2020; Kolanowska 2023; Males et al. 2023; Parra-Sanchez et al. 2023) because these plants have been disproportionately less studied than other plant groups (e.g., trees – Nepstad et al. 2004; Saatchi et al. 2008; Gomes et al. 2019). Most models use the MaxEnt algorithm (Phillips et al. 2006) because of the ease of working with only presence data, which are especially difficult to obtain for epiphytes due to their occurrence in forest canopies (Hsu et al. 2012). Furthermore, actual absence data are scarce and frequently subject to sampling biases (Guillera-Aroita et al. 2015). Moreover, MaxEnt generates robust models with better predictive performance and greater computational efficiency (Kaky et al. 2020) and better generalization for species with limited occurrence data (Radomski et al. 2022).

For vascular epiphytes, some studies model the potential suitability of specific taxa, such as *Polystachya concreta* (Kolanowska et al. 2020), *Dendrophylax lindenii* (Kolanowska 2023), *Guzmania monostachia* (Krupar et al. 2023), *Satyrium nepalense* (Kumar and Rawat 2022), and *Philodendron asplundii* (Luz et al. 2025). In other cases, analyses focus on specific genera, such as *Sobralia* (Kolanowska et al. 2022), *Epipactis* (Evans and Jacquemyn 2022), *Phlegmariurus* (Armenta-Montero et al. 2015), and *Aechmea* (Maciel et al. 2017), or even on particular families, notably Orchidaceae, which account for the majority of available studies (Vollering et al. 2016; Reina-Rodríguez et al. 2017; Estrada-Sánchez et al. 2024; Zhong et al. 2025). In the Amazonian context, Lucas et al. (2025) advanced in this direction by analyzing a multispecific set composed of 20 taxa belonging to different epiphytic families. Despite this progress, the latter study remains limited to current climatic conditions and does not incorporate projections under future climate change scenarios.

In the present study, we used ecological niche modeling under current and future scenarios for 28 species of vascular epiphytes endemic to the Amazonia to analyze how climatic factors influence the potential distribution of these species and predict the species' potential areas under climate change scenarios for the 2090 threshold (2081–2100), considering both an optimistic and a pessimistic outlook. We predicted that the current distribution of epiphytes is concentrated in Northwestern Amazonia, Central Amazonia and the Guiana Shield. In future scenarios, a decrease in environmental suitability is expected, with large gaps predicted for Southern Amazonia. Suitable areas and the influence of environmental predictors are discussed.

Materials and methods

All data processing, analyses, and modeling procedures were performed in the R environment (R Core Team, 2026). The complete code for the procedures is available at Supplementary Material 1.

Compilation of species and occurrence data

The initial database consisted of a list of vascular epiphytes from the Amazonia, compiled from the studies by Lucas et al. (2025) and review data by Luz et al. (2023). From this list, Global Biodiversity Information Facility (GBIF 2026) occurrence data were obtained using the 'rgbif' package (Chamberlain et al. 2026), with the 'occ_search' function to extract records with geographic coordinates. We also included occurrence data from the Jabot (2026), Reflora (2026) and Specieslink (2026) databases. Subsequently, records with coordinates associated with capitals, political centers, research institutions, as well as duplicate records, with identical or null (zero) coordinates, were removed using the 'CoordinateCleaner' package and the 'clean_coordinates' function (Zizka et al. 2019). Data manipulation and organization were performed using the 'dplyr' package (Wickham et al. 2026a). Subsequently, using the 'sf' (Pebesma et al. 2026) and 'terra' (Hijmans et al. 2026) packages, the spatial correspondence of the records with the biogeographical boundaries of the Amazonia was verified. This considered the inclusion of the Amazonia Rainforest ecoregion and the forested areas of the Guiana Shield (Amapá, French Guiana, Guyana, Suriname, southern Venezuela, and eastern Colombia), as well as the exclusion of the seasonally dry forests of the Cerrado (Albert et al. 2021). The boundaries of the Amazonia were defined based on the *Rede Amazônica de Informação Socioambiental Georreferenciada* (RAISG 2026). To reduce a spatial autocorrelation and sampling bias, spatial thinning of the records was applied based on the resolution of bioclimatic variables, corresponding to raster cells of 2.5 arc minutes ($\sim 5 \times 5$ km). Finally, the dataset was refined to include exclusively holoepiphytic species (Zotz et al. 2021b) that, after all filters, had a minimum of 20 valid occurrence records.

Ecological niche modeling

The bioclimatic data used were obtained from the WorldClim platform (Fick and Hijmans 2017), comprising a set of 19 variables related to temperature and precipitation (Bio1 to Bio19), with a spatial resolution of 2.5 arcminutes. The selection of environmental variables was conducted based on the Pearson correlation coefficient ($r < 0.8$) and the Variance Inflation Factor ($VIF < 5$), with the aim of reducing multicollinearity and minimizing biases in the estimates of environmental suitability of the species (as used in other recent studies, e.g., Zhong et al. 2025). These analyses were performed using the color function of the R environment and the 'caret' package (Kuhn et al. 2024) for correlation and the 'usdm' package (Naimi 2023) for VIF analysis.

Based on this set of variables, the distribution of occurrences was projected for the current climate scenario and for future scenarios provided by WorldClim, considering three Global Circulation Models (GCMs) from the Coupled Model Intercomparison Project Phase 6 (O'Neill et al. 2016; Reddy and Saravanan 2023): MIROC6, EC-Earth3-Veg and MPI-ESM1-2-HR selected for their good predictive performance for the Amazonia region (Monteverde et al. 2022; Parry et al. 2022). For each species, a final ensemble model was generated to reduce the uncertainties associated with each individual climate model. The projections considered two Shared Socioeconomic Pathways (SSPs) scenarios: SSP1-2.6, characterized as an optimistic scenario, and SSP5-8.5, considered pessimistic, both refer-

ring to the future period of 2090 (2081–2100). In general, the SSP1-2.6 scenario assumes low greenhouse gas emissions, associated with less intense changes in extreme precipitation regimes, while the SSP5-8.5 scenario assumes high emissions, with more severe changes in these regimes (IPCC 2023; Reddy and Saravanan 2023).

The potential distribution areas of the species in current and future scenarios were estimated by using the MaxEnt algorithm (Phillips et al. 2006), implemented in the 'ENMeval' package (Kass et al. 2025). Model calibration was performed by generating 10,000 pseudo-absence points using the 'spatSample' function. The models were evaluated using different combinations of regularization multipliers (RM), ranging from 0.5 to 5.0, with increments of 0.5, associated with different feature classes (FC): Linear (L), Quadratic (Q) and Hinge (H). For internal validation, data partitioning was performed using a random "block". The selection of the optimal model was based on the lowest value of the Akaike Information Criterion corrected for small samples ($\Delta AICc$), combined with the Boyce Index, ensuring better fit and predictive capacity (Liu et al. 2025). This procedure was performed using the 'eval.results()' function from the ENMeval package. The relative importance of the predictor variables was also extracted from this function, and subsequently processed using the 'grep()' function to filter the contribution metrics. The graphical visualization of the results was created using the 'ggplot2' package (Wickham et al. 2026b). The projections of the selected model were then generated and extrapolated to future scenarios using the predict 'function'. The results produced by the MaxEnt algorithm were subsequently reclassified into binary presence/absence maps, in which probability values ranged from 0 (absence) to 1 (highest probability of occurrence). To define the suitability thresholds, the Maximization True Skill Statistic (MaxTSS) (Liu et al. 2016) criteria were used, applied individually to each species using the thresholds function of the 'dismo' package (Hijmans et al. 2024).

Finally, the suitability maps were processed using QGIS software version 3.22.5. We used the sub-regions of the Amazonia according to ter Steege et al. (2013): Central Amazonia; Eastern Amazonia; Guiana Shield; Southern Amazonia; Northwestern Amazonia; and Southwestern Amazonia.

Results

Selected species and model prediction

The initial list comprised 1,206 vascular epiphyte species occurring exclusively in the Amazonia. Of these, 28 holoepiphytic species were selected based on the availability of at least 20 valid occurrence records. In total, 1,165 occurrence records were included for these 28 Amazonian endemic species belonging to ten families of the following epiphytic taxonomic groups: Araceae (2 species), Bromeliaceae (12 spp.), Ericaceae (1 sp.), Gesneriaceae (3 spp.), Hymenophyllaceae (1 sp.), Lentibulariaceae (3 spp.), Melastomataceae (2 spp.), Orchidaceae (2 spp.), Piperaceae (1 sp.), and Polypodiaceae (1 sp.) (Table 1; Supplementary Material 2). The application of correlation tests (Pearson's coefficient) and multicollinearity (VIF) allowed the selection of four to eight environmental variables per model, depending on the species considered (Full performance data for each species of the models is available in Supplementary Material 3). Species distribution models (SDMs) presented ΔAIC and

Table 1 Species list, number of records (n), and bioclimatic variables used in ecological niche models of endemic vascular epiphytes from the Amazonia. The main variables (> 10% relative contribution) for each group are presented in bold

Family	Scientific name	n	Variables
Araceae	<i>Anthurium expansum</i> Gleason	35	bio03, bio07 , bio08 , bio16, bio17 , bio18, bio19
Araceae	<i>Anthurium vaupesianum</i> Croat	22	bio06, bio09, bio13, bio17
Bromeliaceae	<i>Aechmea colombiana</i> (L.B.Sm.) L.B.Sm. & M.A.Spencer	20	bio02, bio09, bio15 , bio18, bio19
Bromeliaceae	<i>Aechmea contracta</i> (Mart. ex Schult. & Schult.f.) Baker	86	bio03, bio04, bio05, bio07, bio15 , bio16, bio19
Bromeliaceae	<i>Aechmea eglariana</i> L.B.Sm.	20	bio01, bio02 , bio04, bio15 , bio16
Bromeliaceae	<i>Aechmea fernandae</i> (É.Morren) Baker	32	bio02, bio03 , bio04, bio10, bio15 , bio16, bio18 , bio19
Bromeliaceae	<i>Aechmea nivea</i> L.B.Sm.	22	bio02 , bio09, bio13, bio18
Bromeliaceae	<i>Aechmea poitaei</i> (Baker) L.B.Sm. & M.A.Spencer	46	bio02, bio03, bio04, bio10, bio15 , bio18, bio19
Bromeliaceae	<i>Aechmea politii</i> L.B.Sm.	23	bio02, bio06, bio16 , bio17
Bromeliaceae	<i>Aechmea zebrina</i> L.B.Sm.	26	bio02, bio03, bio15 , bio18
Bromeliaceae	<i>Disteganthus basilateralis</i> Lem.	24	bio04, bio07 , bio10, bio14 , bio15 , bio18
Bromeliaceae	<i>Guzmania vittata</i> (Mart. ex Schult. & Schult.f.) Mez	38	bio03 , bio04 , bio05, bio10 , bio18
Bromeliaceae	<i>Hylaeicum eleutheropetalum</i> (Ule) Leme & Forzza	36	bio02, bio04, bio08, bio15 , bio18, bio19
Bromeliaceae	<i>Hylaeicum myrmecophilum</i> (Ule) Leme & Forzza	21	bio02, bio03 , bio04, bio07 , bio16, bio18
Ericaceae	<i>Thibaudia formosa</i> (Klotzsch) Hoerold	42	bio01 , bio03 , bio07, bio13 , bio18, bio19
Gesneriaceae	<i>Codonanthesis dissimulata</i> (H.E.Moore) Wiehler	54	bio02, bio04, bio11, bio13, bio15 , bio18, bio19
Gesneriaceae	<i>Codonanthesis ulei</i> Mansf.	58	bio02, bio04, bio10, bio15 , bio16, bio18, bio19
Gesneriaceae	<i>Paradrymonia campostyla</i> (Leeuwenb.) Wiehler	35	bio01 , bio03 , bio04 , bio13 , bio15
Hymenophyllaceae	<i>Trichomanes trollii</i> Bergdolt	171	bio03, bio04, bio07 , bio08 , bio15, bio16 , bio18, bio19
Lentibulariaceae	<i>Utricularia campbelliana</i> Oliv.	32	bio07 , bio11 , bio13 , bio15, bio18, bio19
Lentibulariaceae	<i>Utricularia humboldtii</i> R.H.Schomb.	67	bio01 , bio04, bio07 , bio13 , bio18, bio19
Lentibulariaceae	<i>Utricularia quelchii</i> N.E.Br.	27	bio02, bio03 , bio04, bio10 , bio13 , bio15, bio18, bio19
Melastomataceae	<i>Macrocentrum droseroides</i> Triana	28	bio01 , bio07 , bio15, bio16, bio19
Melastomataceae	<i>Macrocentrum minus</i> Gleason	22	bio02 , bio04, bio06 , bio14, bio16 , bio18, bio19
Orchidaceae	<i>Bifrenaria longicornis</i> Lindl.	36	bio01 , bio02, bio03, bio04 , bio14 , bio16, bio18, bio19
Orchidaceae	<i>Zygosepalum labiosum</i> (Rich.) C.Schweinf.	60	bio02 , bio03 , bio04, bio08, bio15, bio16 , bio18 , bio19
Piperaceae	<i>Peperomia mishuyacana</i> Trel.	20	bio03 , bio08 , bio18 , bio19
Polypodiaceae	<i>Elaphoglossum styriacum</i> Mickel	62	bio03 , bio04, bio05, bio07 , bio13, bio18 , bio19

Boyce Index values ranging from 0 (most species) to 1.88 (*Hylaeaicum eleutheropetalum*), and from 0.43 (*Aechmea poiteaei*) to 0.75 (*Macrocentrum droseroides*), respectively.

Among the environmental variables incorporated into ecological niche models for different species, bio19 (precipitation in the coldest quarter), bio15 (seasonality of precipitation), bio18 (precipitation in the warmest quarter), bio3 (isothermality), and bio7 (annual temperature range) stood out as those with the greatest contribution to predicting environmental suitability (Supplementary Material 4).

Ecological niche models of vascular epiphytes endemic to the Amazonia

The environmental suitability models for vascular epiphyte species endemic to the Amazonia showed, overall, a tendency of high suitability in Northwestern Amazonia for most of the species evaluated, especially in Ecuador. In contrast, regions of Eastern Amazonia, Southern Amazonia, and Southwestern Amazonia presented the lowest proportions of suitable areas, both in current and future scenarios. For the current climate scenario, most of the analyzed species showed environmental suitability consistent with known occurrence records. In spatial terms, some species stood out for presenting higher levels of environmental suitability in different sub-regions of the Amazonia, such as *Aechmea fernandae* (Fig. 1), *Aechmea politii* (Fig. 2), and *Bifrenaria longicornis* (Fig. 4). Species such as *Anthurium vaupesianum*, *Aechmea colombiana*, *Aechmea contracta* (Fig. 1), *Guzmania vittata*, *Hylaeaicum eleutheropetalum*, *Hylaeaicum myrmecophilum* (Fig. 2), *Codonanthopsis dissimulata*, *Codonanthopsis ulei* (Fig. 3), and *Peperomia mishuyacana* (Fig. 4) showed suitability patterns for the Northwestern and Central portions of the Amazonia.

In the optimistic future scenario (SSP1-2.6), species such as *Anthurium vaupesianum*, *Aechmea fernandae*, *Aechmea nivea*, *Codonanthopsis ulei*, and *Bifrenaria longicornis* showed an increase in environmentally suitable areas greater than the losses recorded (Table 2; Supplementary Material 4). However, in the pessimistic scenario (SSP5-8.5), a reduction in suitability area for this group is observed, with only *Anthurium vaupesianum*, *Aechmea fernandae*, and *Bifrenaria longicornis* maintaining the pattern of greater gain in suitability relative to loss. For example, *Aechmea fernandae* maintains and expands areas of high suitability in certain sub-regions, especially in Central Amazonia and the Guiana Shield, even under pessimistic projections.

In general, most species showed a tendency towards reduced environmental suitability in both future scenarios, with more moderate losses in the optimistic scenario and more pronounced losses in the pessimistic scenario, reflecting in more restricted and less continuous suitable areas, in addition to evident losses in the Southern and Southeastern sub-regions of the Amazonia. In this context, species such as *Anthurium expansum*, *Codonanthopsis dissimulata*, *Macrocentrum droseroides*, *Thibaudia formosa*, *Trichomanes trollii*, and *Utricularia campbelliana* showed reductions greater than 50% in both scenarios, associated with very low increments, indicating a strong contraction of environmentally suitable areas throughout the climate projections.

It should also be noted that *Guzmania vittata* and *Zygosepalum labiosum* exhibited intermediate behavior, characterized by a more balanced ratio between reduction and increase in suitable areas in the optimistic scenario, followed by a clear predominance of losses in the pessimistic scenario. Complementarily, species such as *Disteganthus basilateralis*, *Paradrymonia campostyla*, *Utricularia campbelliana*, *Utricularia humboldtii*, *Utricularia*

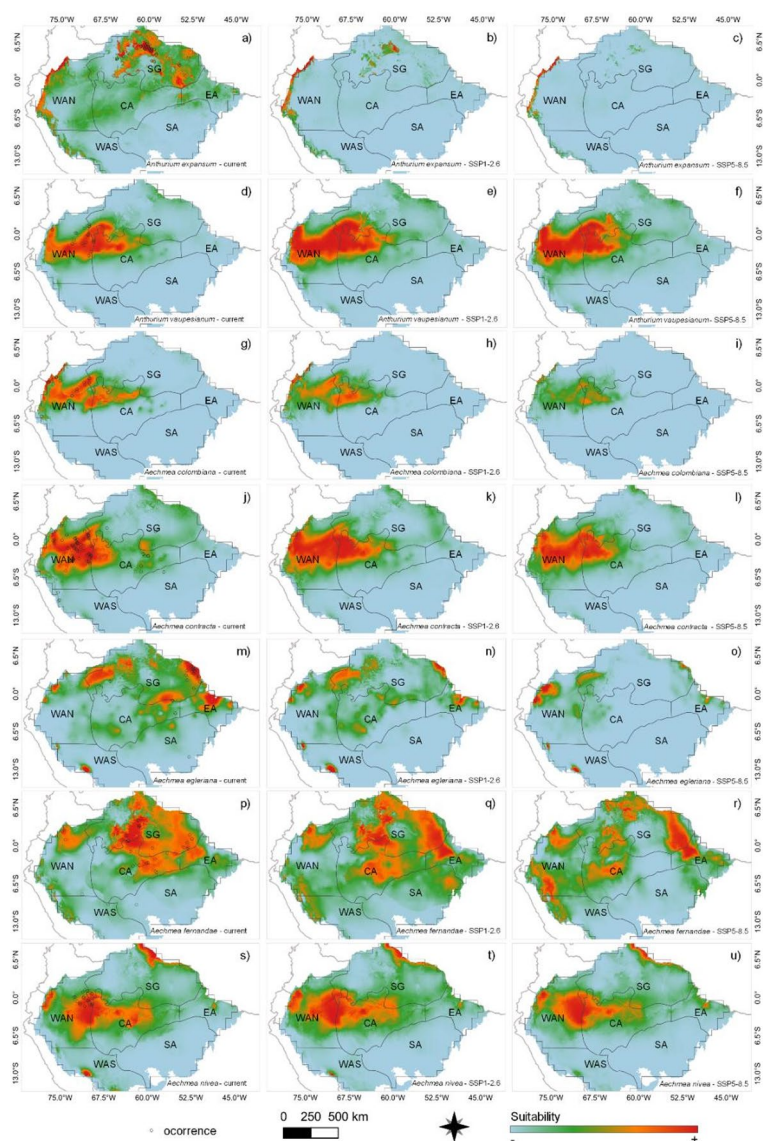


Fig. 1 Ecological niche models for vascular epiphyte species in the Amazonia, considering the current climate scenario (images on the left) and future projections under an optimistic (SSP1-2.6) (images in the center) and pessimistic (SSP5-8.5) scenario (images on the right). Projected distributions are presented for: *Anthurium expansum* (a–c); *Anthurium vaupesianum* (d–f); *Aechmea colombiana* (g–i); *Aechmea contracta* (j–l); *Aechmea eglariana* (m–o); *Aechmea fernandae* (p–r); and *Aechmea nivea* (s–u). The areas of suitability range from zero (light blue shades) to one (shades of red). Sub-regions of the Amazonia according to ter Steege et al. (2013): CA=Central Amazonia; EA=Eastern Amazonia; GS=Guiana Shield; SA=Southern Amazonia; WAN=Northwestern Amazonia; and WAS=Southwestern Amazonia

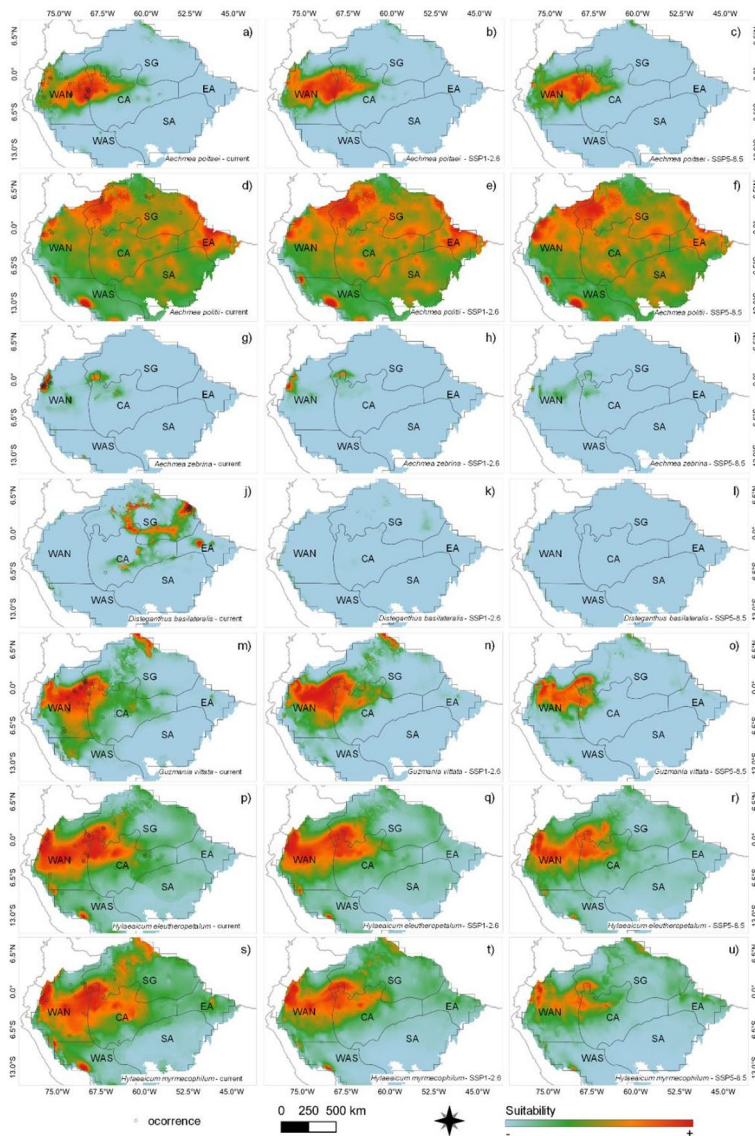


Fig. 2 Ecological niche models for vascular epiphyte species in the Amazonia, considering the current climate scenario (images on the left) and future projections under an optimistic (SSP1-2.6) (images in the center) and pessimistic (SSP5-8.5) scenario (images on the right). Projected distributions are presented for: *Aechmea poiteai* (a-c); *Aechmea politii* (d-f); *Aechmea zebrina* (g-i); *Disteganthus basilateralis* (j-l); *Guzmania vittata* (m-o); *Hylaeicum eleutheropetalum* (p-r); and *Hylaeicum myrmecophilum* (s-u). The areas of suitability range from zero (light blue shades) to one (shades of red). Sub-regions of the Amazonia according to ter Steege et al. (2013): CA=Central Amazonia; EA=Eastern Amazonia; GS=Guiana Shield; SA=Southern Amazonia; WAN=Northwestern Amazonia; and WAS=Southwestern Amazonia

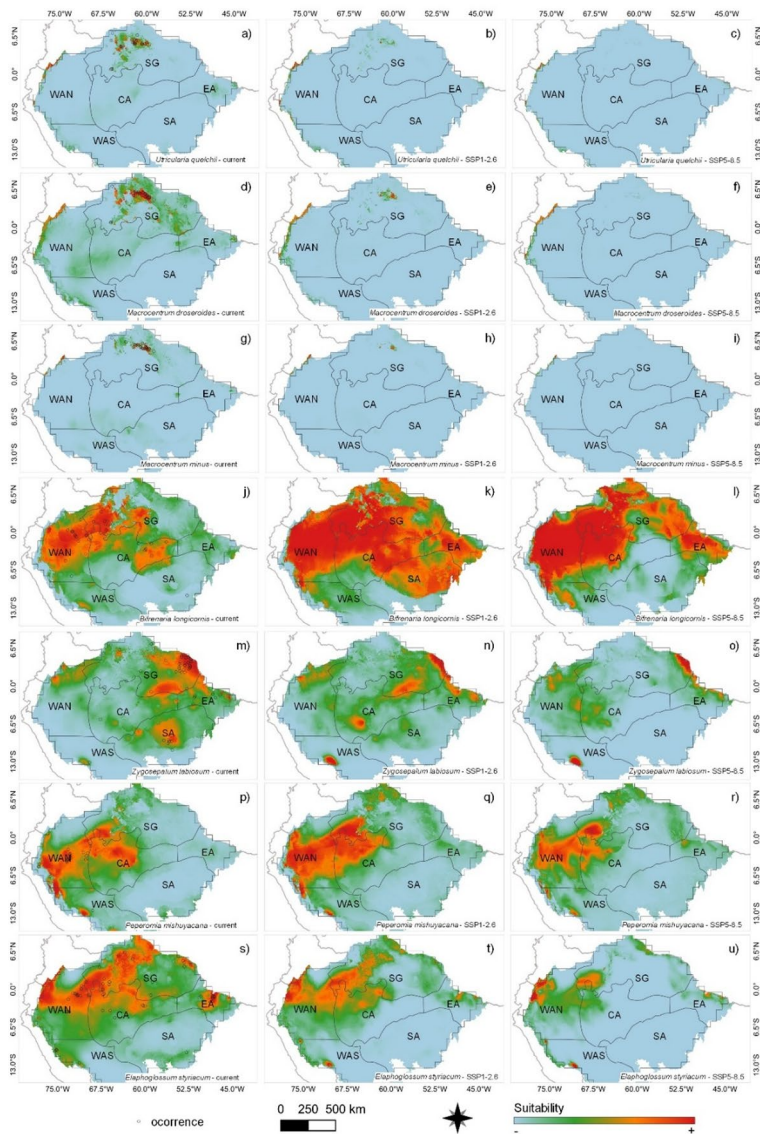


Fig. 4 Ecological niche models for vascular epiphyte species in the Amazonia, considering the current climate scenario (images on the left) and future projections under an optimistic (SSP1-2.6) (images in the center) and pessimistic (SSP5-8.5) scenario (images on the right). Projected distributions are presented for: *Utricularia quelchii* (a–c); *Macrocentrum droseroides* (d–f); *Macrocentrum minus* (g–i); *Bifrenaria longicornis* (j–l); *Zygosepalum labiosum* (m–o); *Peperomia mishuyacana* (p–r); and *Elaphoglossum styriacum* (s–u). The areas of suitability range from zero (light blue shades) to one (shades of red). Sub-regions of the Amazonia according to ter Steege et al. (2013): CA=Central Amazonia; EA=Eastern Amazonia; GS=Guiana Shield; SA=Southern Amazonia; WAN=Northwestern Amazonia; and WAS=Southwestern Amazonia

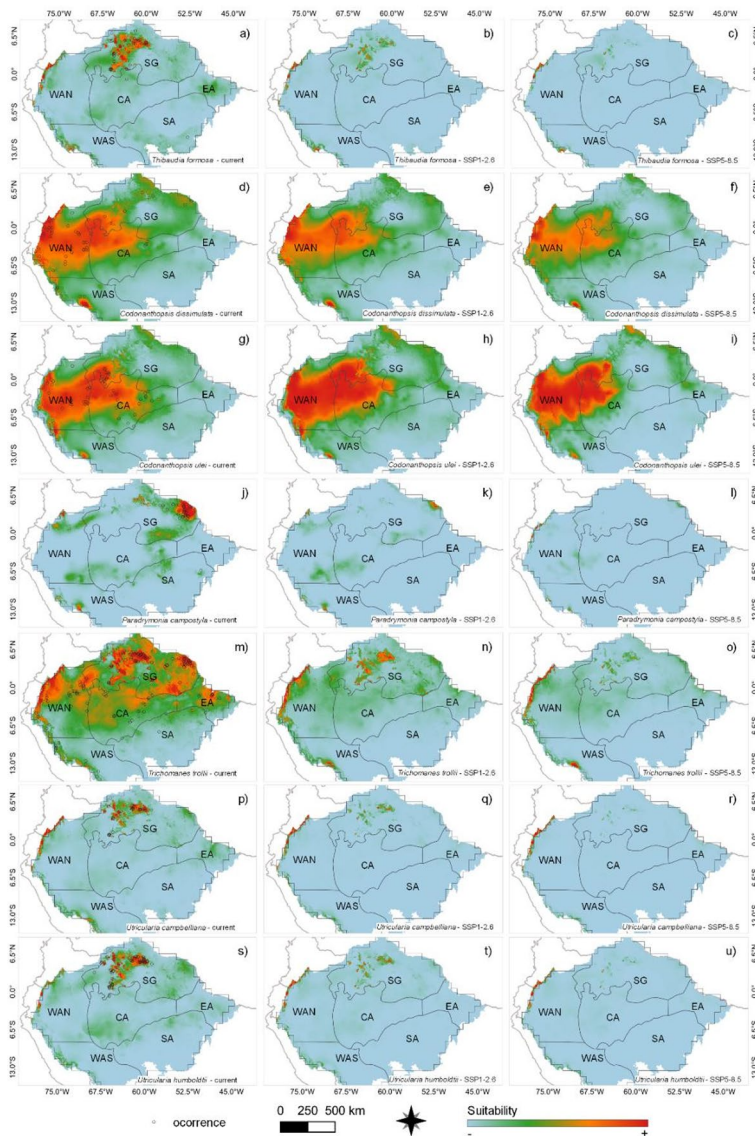


Fig. 3 Ecological niche models for vascular epiphyte species in the Amazonia, considering the current climate scenario (images on the left) and future projections under an optimistic (SSP1-2.6) (images in the center) and pessimistic (SSP5-8.5) scenario (images on the right). Projected distributions are presented for: *Thibaudia formosa* (a-c); *Codonanthopsis dissimulata* (d-f); *Codonanthopsis ulei* (g-i); *Paradrymonia campostyla* (j-l); *Trichomanes trollii* (m-o); *Utricularia campbelliana* (p-r); and *Utricularia humboldtii* (s-u). The areas of suitability range from zero (light blue shades) to one (shades of red). Sub-regions of the Amazonia according to ter Steege et al. (2013): CA=Central Amazonia; EA=Eastern Amazonia; GS=Guiana Shield; SA=Southern Amazonia; WAN=Northwestern Amazonia; and WAS=Southwestern Amazonia

Table 2 Estimates of decrease and increase in environmental suitability for vascular epiphytic species endemic to the Amazonia, considering future projections under optimistic (SSP1-2.6) and pessimistic (SSP5-8.5) scenarios

Species	Scenario SSP1-2.6		Scenario SSP5-8.5	
	Decrease	Increase	Decrease	Increase
	%			
<i>Aechmea colombiana</i>	44.5	12.6	48.6	8.49
<i>Aechmea contracta</i>	41.6	15.5	46.9	10.2
<i>Aechmea egleriana</i>	40.9	16.1	48.5	8.52
<i>Aechmea fernandae</i>	20	37.1	28.4	28.7
<i>Aechmea nivea</i>	26.3	30.8	37.6	19.5
<i>Aechmea poitaei</i>	51.5	5.62	55.3	1.87
<i>Aechmea politii</i>	45.4	11.8	53.1	4.04
<i>Aechmea zebrina</i>	51.2	5.7	55.5	1.35
<i>Anthurium expansum</i>	56.4	0.771	56.7	0.391
<i>Anthurium vaupesianum</i>	1.08	56.1	5.53	51.6
<i>Bifrenaria longicornis</i>	3.99	53.1	15.4	41.8
<i>Codonanthopsis dissimulata</i>	56.3	0.8	56.9	0.207
<i>Codonanthopsis ulei</i>	20.1	37	38.7	18.4
<i>Disteganthus basilateralis</i>	44.5	10.4	47.3	8.17
<i>Elaphoglossum styriacum</i>	54.7	2.39	56.1	0.992
<i>Guzmania vittata</i>	36.6	20.4	52.6	4.47
<i>Hylaeaicum eleutheropetalum</i>	48.4	8.75	53	4.13
<i>Hylaeaicum myrmecophilum</i>	50.4	6.73	55.5	1.67
<i>Macrocentrum droseroides</i>	56.4	0.747	56.7	0.471
<i>Macrocentrum minus</i>	51.7	5.31	53.1	3.98
<i>Paradrymonia campostyla</i>	44.6	11.5	47	9.19
<i>Peperomia mishuyacana</i>	18.9	38.2	30.9	26.2
<i>Thibaudia formosa</i>	56	1.16	56.2	0.93
<i>Trichomanes trollii</i>	55.7	1.47	55.8	1.31
<i>Utricularia campbelliana</i>	56.5	0.63	56.7	0.472
<i>Utricularia humboldtii</i>	50.5	6.62	53.3	3.85
<i>Utricularia quelchii</i>	53.6	3.53	55.1	2.06
<i>Zygosepalum labiosum</i>	33.2	23.9	41.4	15.7

quelchii, *Macrocentrum droseroides*, and *Macrocentrum minus* showed high environmental suitability in the Guiana Shield region in the current scenario. However, these species showed a tendency towards reduced suitability in the optimistic scenario, which intensifies under the pessimistic scenario, evidencing a progressive contraction of environmentally favorable areas in this region.

Discussion

The $\Delta AICc$ and Boyce Index values showed good predictions for the different vascular epiphyte species endemic to the Amazonia, with precipitation in the coldest quarter and precipitation seasonality being the most important predictors for most species. The seasonality of rainfall was also one of the main environmental predictors for giant trees in the Amazonia

(Lima et al. 2026). Environmental niches marked by high rainfall levels throughout the year, a reduced number of dry months, combined with reduced climatic seasonality, as occurs in Western Amazonia, create an environment conducive to the establishment and maintenance of a high richness of epiphytic species (Kreft et al. 2004). In contrast, precipitation presents a highly seasonal regime in the South and Southwest portions of the Amazonia, with longer dry seasons (over 4 months) and monthly precipitation less than 100 mm, where the climate pattern resembles that of a savanna (Nobre et al. 2016; Bottino et al. 2024). It was precisely in these portions where we found fewer areas suitable for epiphytes in current and future scenarios. In parts of this region, which comprise the Deforestation Arc of the Brazilian Amazonia, extensive gaps in floristic sampling persist. Furthermore, this is a landscape strip intensely modified by different land uses, where impacts from climate change are predicted, such as CO₂ emissions and, consequently, increased temperatures (Santos et al. 2024).

Endemic epiphyte species occur in geographically limited areas and have narrower ecological tolerance, thus they are theoretically more vulnerable to habitat changes and face a higher risk of extinction (Köster et al. 2013; Einzmann and Zotz 2016; Carmona-Higuaita et al. 2025). Nearly 60% of the species from the Araceae, Bromeliaceae, Orchidaceae, Piperaceae, and Polypodiaceae occurring in the Neotropical region are at some degree of vulnerability and risk of extinction (Carmona-Higuaita et al. 2024). We noted that the areas of maximum suitability for vascular epiphytes are located in key areas for epiphyte conservation, such as the Andes' center of endemism (Ecuador, Colombia, and Peru) (Carmona-Higuaita et al. 2024), corroborating the results found by Lucas et al. (2025). In Ecuador, epiphytes constitute 25% of all vascular plant species, and 35% are endemic to the country (Valencia et al. 2001; Küper et al. 2004). The humid montane forests of the Andes have characteristics that promote abundant epiphytic vegetation, specifically at mid-elevations (species richness peak at 1,000–1,500 m; Krömer et al. 2005), such as frequent mist cover, high precipitation (2,500 to 4,000 mm), and topographical complexity (Köster et al. 2013; Carmona-Higuaita et al. 2024). However, Benavides et al. (2023), when investigating the survival of epiphytes translocated from secondary Andean forests in Colombia, found that increased rainfall seasonality was associated with increased mortality rates. In our study, climate change results in drastic losses of environmentally suitable areas, intensifying the risk of species extinction. Almost half of them showed a sharp reduction in maximum environmental suitability in the Amazonia under future scenarios, with more pronounced impacts in the pessimistic scenario. Species such as *Anthurium expansum*, *Aechmea egleriana*, *Aechmea zebrina*, *Disteganthus basilateralis*, *Macrocentrum droseroides*, *Macrocentrum minus*, *Paradrymonia campostyla*, *Thibadia formosa*, *Trichomanes trollii*, *Utricularia campbelliana*, *Utricularia humboldtii*, and *Utricularia quelchii* exhibited losses of suitable areas, which was reflected in low probabilities of occurrence in future scenarios. Additionally, *Aechmea fernandae* and *Zygosepalum labiosum* showed high fragmentation of areas of maximum environmental suitability. Protected areas and monitoring efforts in these regions are essential for epiphyte conservation and for mitigating future impacts on their populations.

Other centers of endemism for vascular epiphytes, such as Central Amazonia (Brazil) and the Guiana Shield, also stand out as favorable locations for the occurrence of endemic epiphytes, especially in the current scenario. Central Amazonia has a climate characterized by high humidity and precipitation (on average 2,100 mm per year), well-defined seasons (rainy season from November to May and dry season from July to September), and a diversity of phytophysiognomies and ecosystems important for epiphytes (Demarchi et al. 2018;

Klein et al. 2024). In French Guiana, Tropical Lowland Cloud Forests are characterized by the presence of mist layers in the forest canopy, which serve as a climatic refuge against unfavorable weather conditions (Obregon et al. 2014). However, the continued advance of deforestation in these areas has the potential to trigger significant hydroclimatic impacts, capable of severely affecting the biodiversity and ecosystem services of the region (Bovolo et al. 2018). Considering the drastic niche losses projected for some epiphytes in this region, the potential impacts on endemic epiphyte communities reinforce the need for more effective and targeted conservation strategies. For these regions, there is a need for a political ecology approach that integrates an understanding of the affective and biophysical dynamics associated with environmental changes along spatiotemporal gradients, as proposed by Collins et al. (2024).

The increased habitat suitability for epiphytes in future scenarios, as shown for *Anthurium vaupesianum*, *Aechmea fernandae*, and *Bifrenaria longicornis*, suggests a plasticity in ecological requirements, with evidence of some tolerance to future climate changes. For example, many epiphytes produce large quantities of seeds or diaspores that are easily dispersed by wind (Benzing 1990), and several orchids possess thickened stems, leaves, and pseudobulbs that function as specialized organs for water and nutrient storage (Benavides et al. 2023). However, this is not conclusive or comprehensive for all epiphytes, since the impacts of climate change on species adaptability have been investigated for a still limited number of taxa. This limitation is partly due to the need for carefully planned and conducted long-term experiments, often associated with the transplantation of individuals to controlled environments (*ex situ*), which imposes methodological limitations and makes it difficult to formulate broader and more generalizable conclusions. Evidence indicates that seed germination performance of some epiphytic bromeliads is favored by 3 °C increases in temperature (Müller et al. 2017). However, tropical lowland species may be more affected by the increased thermal seasonality caused by climate change, which could impose physiological challenges such as the need for migration (Tagliari et al. 2021) or the concentration of suitable niches in Central and Northwestern Amazonia. Predictions indicate that these areas will also be important for Amazonian tree diversity in the future (ter Steege et al. 2013; Gomes et al. 2019).

We suggest that governments committed to complying with environmental agreements such as the Kunming-Montreal Global Biodiversity Framework (GBF 2024), whose goals include the increase of conservation areas and reduction of species extinction risk, allocate resources for research and conservation efforts to these areas. It is important to highlight that other pressures, such as the predatory and destructive collection of epiphytes for various purposes (e.g., cultural uses or cultivation as ornamentals in private collections), result in significant population reductions, because many epiphytes are considered multi-use non-timber forest products with medicinal, ornamental, food, and fiber production applications for handicrafts (Flores-Palacios and Valencia-Díaz 2007; Acebey et al. 2010; Elliott and Ticktin 2013). Although these resources can represent a supplement to the income of traditional populations in the Amazonia (Acebey et al. 2010), their use reinforces the need for priority conservation and management strategies, including the incorporation of epiphytes into sustainable forest management plans (Elliott and Ticktin 2013). Such strategies should prioritize non-destructive collection practices, such as collecting specimens naturally detached from the canopy, as is the case with some bromeliads (Chaparro and Ticktin 2011; Elliott and Ticktin 2013).

This study provided a comprehensive overview of the niche distribution patterns of vascular epiphyte species endemic to the Amazonia. Although ecological niche models generally focus on estimating environmental suitability, in the case of epiphytes, information on dispersal limitations, population persistence, availability of host trees, anthropogenic influences, and forest structural integrity is still scarce. These gaps hinder the construction of species distribution models (Xu et al. 2025) and represent significant obstacles to obtaining more comprehensive conclusions. Our results indicate that most species are sensitive to climate change, showing low environmental suitability in areas of Southwestern and Southern Amazonia, regions characterized by higher temperatures and lower rainfall. Furthermore, advances in epiphyte modeling are still limited by several conceptual and methodological obstacles. Among these, the lack of standardization in the selection of environmental and physical variables, especially in future scenarios, that are truly representative of the ecological niche of these species stands out, hindering comparability between studies and the generalization of results. Furthermore, there is a lack of well-established modeling protocols that integrate different ecological and taxonomic contexts, as well as a need to expand initiatives based on long-term permanent plots, in situ monitoring, and the use of remote sensing applied to epiphyte inventories. In this context, our results can serve as a relevant reference for future investigations on the distribution of vascular epiphytes in the Amazonia, while reinforcing the importance of continuous monitoring of these species.

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

Declarations

Competing interests The authors declare no competing interests.

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