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ORIGINAL RESEARCH

The vulnerability of orchids in honduras: assessing loss and resilience under climate change

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Abstract

Climatic niches play a pivotal role in shaping global and regional patterns of species distribution. Tropical rainforests, renowned for their biodiversity and high levels of endemism, are among the most endangered biomes on the planet. In Honduras, which has over 8,000 vascular plant species, 595 of them are orchids. This study represents the first analysis of how future climate projections (RCP2.6 and RCP8.5) could impact the climatic niches of orchids across the country's 112,492 km² area, of which approximately 56% (63,000 km²) is still covered by forest. Using the largest available database of Honduran orchids (retaining 437 species and 3,681 occurrence records) and ordination models, we assessed the potential impact of climate change on orchid niche distributions. The results indicate that Honduras is projected to experience warmer and drier conditions. By the years 2020–2099, this shift in climate is likely to result in a displacement of 88–238 (20–54%) species of orchids depending on the climate scenario. These findings align with recent studies on other taxonomic groups in Honduras, suggesting a troubling shift in climatic niches among some of the country's most significant plant groups. This potential shift poses significant risks to orchid species and highlights the urgent need for conservation efforts that address the effects of climate change on biodiversity. The species list provide here, could be used by conservation practises to inform urgent management strategies.

Keywords Modelling · Niche · Orchidaceae · Temperature · Tropics

Introduction

According to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (Costello et al. 2022) approximately 80% of projections for evaluated terrestrial species, in biodiversity hotspots, suggests that they will be negatively impacted by climate change. Among these, approximately 50% face a very high risk of extinction, particularly in

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cases for endemic species (medium confidence; Manes et al. 2021). The impact of climate change on the species geographical range, has been a key focus across many groups of terrestrial organisms, including vertebrates (Li et al. 2016), invertebrates (Martin-Velez and Abellán 2022) and plants (Corlett and Westcott 2013). For example, data suggests that there is a "high confidence" level that climate change is the driver of altitudinal shifts (Lenoir and Svenning 2015; Steinbauer et al. 2018), where species moving to higher elevations but are limited by decreasing available area, are at higher risk of extinction (Flousek et al. 2015; Kidane et al. 2019; Pie et al. 2022). Similarly, climate velocities (i.e., the pace and trajectory required by a species at a specific location to stay within its climatic habitat; Loarie et al. 2009) are 29% lower inside biodiversity hotspots than outside, and between 1970 and 2019 have ranged between 3 and 4 km per decade (Kocsis et al. 2021).

The climatic niche, defined as the set of environmental conditions that allow a species to survive and reproduce, has become a pivotal concept in modern ecological and evolutionary research. It serves as a crossroads where multiple scientific disciplines converge, including ecophysiology, biogeography, macroecology, and invasion biology (Petitpierre et al. 2012; Wasof et al. 2015; Atwater et al. 2018). Climatic niches are central to the understanding of phylogenetic niche conservatism (Wiens and Donoghue 2004), which sheds light on the geographical distributions of various taxa and contributes to explaining patterns of species diversity, including latitudinal gradients (Kerkhoff et al. 2014). This relevance has gained even more significance as scientists seek to understand how species will adapt to the impacts of anthropogenic climate change (Herrera et al. 2018; Zhao et and Wang 2023).

It has been acknowledged that persistent geographical and taxonomic biases exist in assessments of species' vulnerability to climate change (de los Rios et al. 2018). For example, in the context of Central America, only very few studies have been published (Lagomarsino and Frost 2020), especially from Guatemala, Honduras, El Salvador, Nicaragua, and most of the Caribbean islands. There are several possible reasons for the low regional contributions, including unresolved taxonomic challenges (Ramirez-Barahona et al. 2023), slow integration and curation of species distribution databases (Meineke et al. 2018), low integration of locally digitised specimen collections (Paton et al. 2020) and proportionally fewer specialists working in these countries compared to other Neotropical regions (Ebach et al. 2011; Lagomarsino and Frost 2020). Honduras for example is home to >8,000 vascular plant species (Reyes-Chávez et al. 2021a) but still lacks a published flora. However, an updated checklist and geographically integrated database for ferns (Reyes-Chávez et al. 2021a) and orchids (Vega et al. 2022) became available in 2021 and 2023 respectively. This has opened an opportunity to contribute towards reducing the geographical bias observed in global assessment on the effects of climate change on species distributions.

Since ferns have been shown to be particularly sensitive to climate fluctuations (Pie et al. 2022), it is crucial to understand whether these findings can be generalised to other taxa. With the emergence of new geographical data on various plant groups, such as orchids (Vega et al. 2022), we now can investigate whether the climate-driven shifts observed from models in ferns might also occur in other species-rich groups. Given that orchids are the second most diverse group of vascular plants in Honduras, following ferns, they present an ideal continuation for studying the broader impact of climate change. This exploration could offer valuable insights into how climate change affects a broader spectrum of biodiversity and guide future conservation efforts.

Orchidaceae represent a diverse and ecologically significant group of flowering plants, with a high proportion of epiphytes (Zots 2013). Current estimates suggest that there are over 34,000 orchid species globally, making them one of the largest plant families in the world (Cribb et al. 2003; POWO 2025). For example, the Honduran checklist of orchids includes 145 genera, represented by a total of 595 species, two subspecies and seven natural hybrids, with ten orchid species being endemic to the country (Vega et al. 2022). Of these, 74% (444) of the taxa are epiphytes, 20% (120) terrestrial, 1.5% (9) hemiepiphytes, 1% (9) lithophytes, and 3% (19) terrestrial-epiphytes. In addition, 26 are under one of the IUCN categories (1 = Critically Endangered; 5 = Endangered; 17 = Least Concern; 1 = Near Threatened; 2 = Vulnerable; IUCN 2024). Due to the high proportion of orchids being epiphytic, it is likely that orchids are more vulnerable to changes in climate as a taxonomic group compared to other plant species, due to their close reliance on the arboreal habitat. It has been shown that epiphytes are more likely to show a stronger response to shifting climate niches compared to their non-epiphytic relatives (Pie et al. 2022; Murakami et al. 2023). Nonetheless, the impact of climate change on orchid species niches has not been extensively studied, and there have been few investigations focusing on geographic regions like Honduras (Vega et al. 2022).

Therefore, this study makes use of the first comprehensive dataset of orchid occurrence records from Honduras to investigate the relationship between their climatic niches and the available niche space. Our objectives are: (1) to assess how much of the Honduran climatic space is occupied by different orchid species; (2) to evaluate which regions are most likely to face significant shifts in the climate space under various climate change scenarios; and (3) how many orchid species that are currently known from Honduras and have sufficient distribution records are likely to be displaced in the future under different climate scenarios. By addressing these objectives, we will enhance our understanding of the susceptibility of orchids in Honduras to the ongoing effects of climate change. Additionally, we will discuss variations in their responses compared to ferns for which we presently possess high-quality data. This work will shed light on the unique challenges faced by orchids and contribute to a more nuanced understanding of the broader implications of climate change on plant diversity in the region.

Methodology

Occurrence data

We used Vega et al. (2022) orchid occurrence dataset. This is the most up-to-date and comprehensive checklist of Honduran orchids. The original data was compiled from published sources (comprising peer-reviewed articles and books), unpublished data, and herbarium records, spanning from 1920s to 2022 (Fig. 1). We updated the taxonomy of the dataset using Hassler's World Orchids database (Hassler 2025). Following the updated taxonomy, the dataset comprised 573 species and 4,457 occurrence records. However, we retained only 437 species from 3,681 records, excluding those not considered valid for Honduras by Vega et al. (2022).

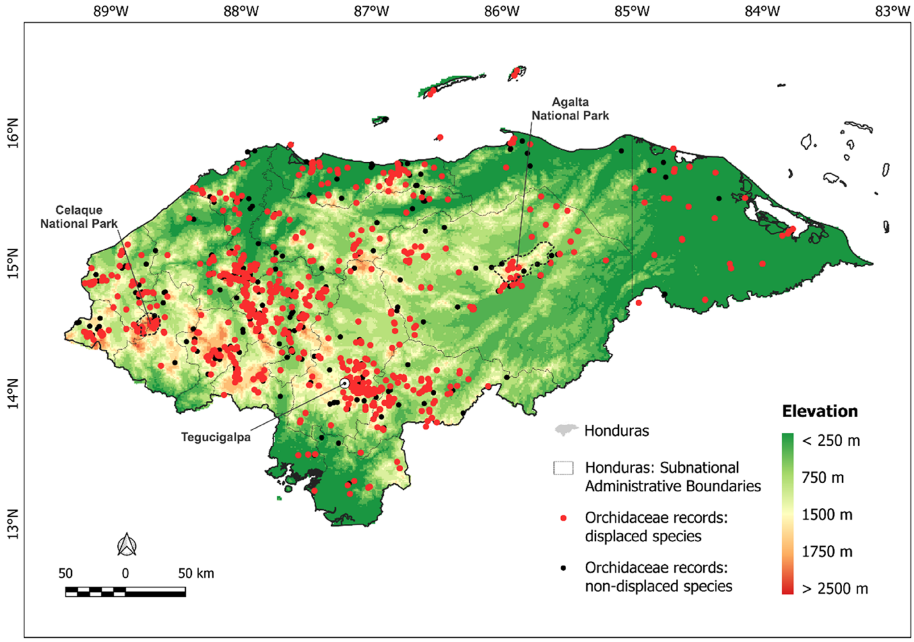

Fig. 1 Elevation map of Honduras. Changes in colour represent differences in elevation, black lines outline major administrative boundaries and dots represent displaced (red) and non-displaced (black) orchid records based on the modelling output (see text for detail)

Growth form classification

To assess whether there was a difference in niche shifts between orchid life forms, we cross referenced our database against Plant of the World Online (POWO 2025) and Tropicos record labels (Tropicos 2025). Each species was then assigned a specific life form according to their typical growth habit (terrestrial, epiphyte, lithophyte).

Climatic variables

Climate variables were obtained from Racines et al. (2018) and comprised gridded climate surfaces data for Honduras. The climate surfaces were generated by processing weather station observations from a range of official sources, including local, national, and regional institutions, over the period between 1981 and 2010. The climate surfaces were calculated at a spatial resolution of 30 s (~ 1 km^2) and represented a 30-year average. The dataset in this study consisted of 85 variables, including monthly precipitation (prec), monthly minimum temperature (tmin), maximum temperature (tmax), mean temperature (tmean), and diurnal temperature range (dtr) as well as seasonal and annual rasters that were derived from the monthly data. To address collinearity within the dataset, we exclusively incorporated annual and seasonal means of the variables.

Projection of occurrence data

Following this, a Principal Component Analysis (PCA) was performed on the covariance matrix of the 25 remaining bioclimatic variables, which had been appropriately scaled and centred (i.e., divided and subtracted by their respective means and variances) prior to the analysis. The determination of the number of Principal Components (PCs) to be retained for subsequent analyses in this study was based on a broken-stick criterion, as implemented in ‘vegan’ 2.5-7 (Oksanen et al. 2020a, b). Following Pie et al. (2022) we extracted bioclimatic data from orchid occurrence records using the extract function in ‘raster’ 3.4–13 (Hijmans 2021) and projected them onto the principal components calculated previously. To further explore the extent of species occupation in the available climate space we used Levene’s test to compare the variance in scores across different ordination quadrants, as implemented in ‘car’ 3.0–11 (Fox and Weisberg 2018).

Climate scenarios and projections

We investigated the potential consequences of climate change on the structure of the available climatic space, utilising insights from projections outlined by Racines et al. (2018b). We specifically considered the RCP2.6 and RCP8.5 scenarios proposed by the IPCC, which represent contrasting outlooks on future climate forcing. RCP2.6 presents an optimistic trajectory where atmospheric CO_2 concentration stabilises by 2020 and decreases by 2100, thereby limiting global temperature rise below 2 °C by century’s end. In contrast, RCP8.5 presents a pessimistic scenario characterised by continuous emissions escalation throughout the twenty-first century.

To assess the potential shifts in climatic space resulting from these projected changes, we extracted the values of the same climatic variables utilised previously for each grid cell and projected them based on the PCA constructed from current climate data. Subsequently, we evaluated the extent of the corresponding climatic envelopes using concave hulls, implemented through the ‘concaveman’ 1.1.0 package (Gombin et al. 2020). This analytical approach provides a practical means to identify regions within the climatic realm most vulnerable to disruptions induced by climate change.

Climatic suitability envelopes

Finally, we extracted the actual values of the three most important climatic variables as identified by each PCA axis (e.g., tmin_djf, tmin_jja, and tmin_ann for PC1, and tmax_mam, tmax_djf, and dtr_son for PC2 from the Orchidaceae occurrence points under current climatic conditions. We then calculated the mean and standard deviation values for each of these six variables to define climatic suitability envelopes using the intervals (e.g., $\bar{x}$–s; $\bar{x}$+s) (Table 3). Based on these intervals, we generated binary climatic suitability raster’s to delineate the current spatial extent of suitable climate for Honduran orchids. Applying the same envelope thresholds to future climate layers (e.g. RCP8.5 2049, RCP8.5 2069, and RCP8.5 2099) we identified climatically suitable areas across different moments in time. Last, we intersected the resulting future raster’s to map the projected area of persistent climatic suitability (Fig. 4). All computations and analyses were conducted within the R 4.2.2 environment (Team 2021).

Results

The first two PCA axes explained 92% of the variance in climatic conditions across Honduras. Axis one explained 63%, with higher minimum temperature being the variable with the highest contribution. Axis two explained 29% of the variance, with lower temperature seasonality being more important (Table 1).

Species records were distributed across most of the available climate space (Fig. 2). However, there were large geographical areas in the East and South of the country where orchid records were less prevalent, primarily at lower elevation (Fig. 1). These areas are also categorised broadly by regions that are warmer and show lower seasonal variation (Fig. 3). Lower seasonality and lower minimum temperature were also associated with areas of higher elevation, in particular the Sierra Madre Mountain range, Celaque National Park, Sierra de Agalta, and areas around Tegucigalpa (Figs. 3 and 4). A particularly high number of records were observed where PC2 scores were between 0 and 5, placing close to the limit of the current available climate space (Fig. 2).

As previously modelled by Pie et al. (2022), the projected climate space for Honduras is likely to shift in the future to hotter and drier conditions, with the most significant changes observed under RCP8.5 (Fig. 4 in Pie et al. 2022). Similarly, in our study, the most significant shift in climate space was observed under RCP8.5 for the year 2099, where the overlap

Table 1 Principal component analysis showing PC1 and PC2 of bioclimatic variables found in Honduras

Climatic descriptor	Variable code	PC1	PC2
Diurnal Temp Range Annual	dtr_ann	0.16	0.28
Diurnal Temp Range - Dec/Jan/Feb	dtr_djf	0.15	0.28
Diurnal Temp Range - Mar/Apr/May	dtr_mam	0.17	0.26
Diurnal Temp Range - Jun/Jul/Aug	dtr_jja	0.17	0.27
Diurnal Temp Range - Sep/Oct/Nov	dtr_son	0.14	0.29
Precipitation Annual	prec_ann	−0.17	−0.23
Precipitation - Dec/Jan/Feb	prec_djf	−0.15	−0.22
Precipitation - Mar/Apr/May	prec_mam	−0.14	−0.15
Precipitation - Jun/Jul/Aug	prec_jja	−0.12	−0.17
Precipitation - Sep/Oct/Nov	prec_son	−0.18	−0.23
Maximum Temp Annual	tmax_ann	−0.18	0.26
Maximum Temp - Dec/Jan/Feb	tmax_djf	−0.17	0.27
Maximum Temp - Mar/Apr/May	tmax_mam	−0.14	0.31
Maximum Temp - Jun/Jul/Aug	tmax_jja	−0.2	0.23
Maximum Temp - Sep/Oct/Nov	tmax_son	−0.2	0.21
Mean Temp Annual	tmean_ann	−0.24	0.13
Mean Temp - Dec/Jan/Feb	tmean_djf	−0.24	0.13
Mean Temp - Mar/Apr/May	tmean_mam	−0.22	0.17
Mean Temp - Jun/Jul/Aug	tmean_jja	−0.24	0.1
Mean Temp - Sep/Oct/Nov	tmean_son	−0.24	0.1
Minimum Temp Annual	tmin_ann	−0.25	0.01
Minimum Temp - Dec/Jan/Feb	tmin_djf	−0.25	0
Minimum Temp - Mar/Apr/May	tmin_mam	−0.25	0.03
Minimum Temp - Jun/Jul/Aug	tmin_jja	−0.25	0
Minimum Temp - Sep/Oct/Nov	tmin_son	−0.25	−0.01
Proportion of variance		**0.63**	**0.29**
Cumulative proportion		**0.63**	**0.92**

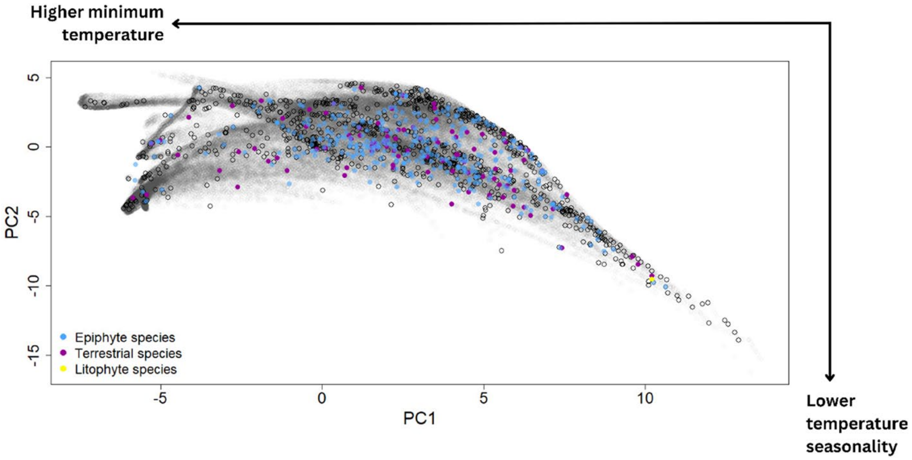

Fig. 2 Principal component analysis of climatic conditions found in Honduras. Grey circles represent all climatic conditions. Different coloured dots represent epiphytic (blue), terrestrial orchids (purple), and lithophytic species (yellow). The closed coloured circles represent the species means, whereas the black open circles individual species records. The arrows describe the general climate space for each axis

between the current and projected space was 47.1% (Table 2; Fig. 5). When comparing the current (43,100.09 km²) and future (7,419.84 km²) projections of climatically suitable areas (Fig. 4), we observed a total reduction of 35,680.26 km², corresponding to an 83% decrease.

Epiphytes represented a higher proportion of the species in our database (75.6%). This shift in climate is likely to result in a displacement of 88–238 (20–54%) species of orchids depending on the climate scenario and years (Tables 2 and 3). The largest displacement observed under RCP2.6 was for the year 2069 ($n=87$ species), and under RCP8.5 for the year 2099 ($n=238$ species). Across scenarios, the percentage of epiphytic species displaced, relative to the total number of records in the dataset, was higher than for terrestrial species under both RCP2.6 (17% vs. 4%) and RCP8.5 (42% vs. 13%). When considering displacement within each group, a slightly greater proportion of epiphytes were affected under both (21.32% under RCP2.6 and 54.95% under RCP8.5) compared to terrestrial orchids (16.50% and 53.40%, respectively; Table 4). The only lithophytic species in our dataset did not experience climatic niche displacement under either of the scenarios analysed. For a comprehensive list of species that were included in the model and their resulting displacement classification, please refer to the additional data provided here: https://zenodo.org/records/13752943.

Discussion

In this work we assessed how much of the Honduran climatic space is occupied by different orchid species, to evaluate which regions are most likely to face significant changes under various climate change scenarios, and how many orchids are likely to be displaced in the future under different climate scenarios. We found that between 71 and 183 epiphytic and 17–55 terrestrial orchids in Honduras are likely to be displaced outside their current climate niche between 2049 and 2099. This represents between 20 and 54% of the species

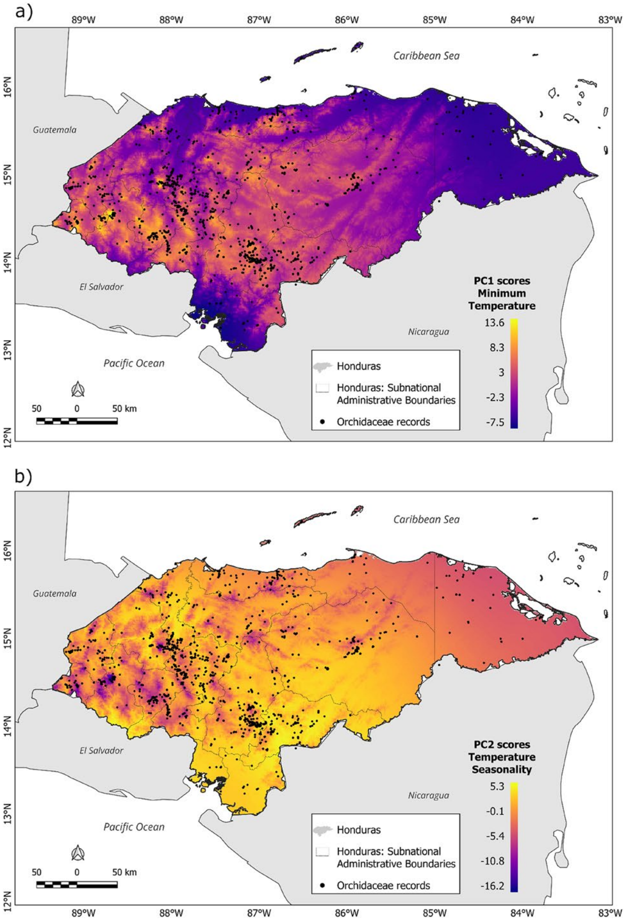

Fig. 3 Spatial distribution of component scores of the climatic conditions across Honduras. To visualise the climate conditions associated with each grid cell, a principal component analysis was performed, and the results were mapped back to the corresponding cells. PC1 loadings mostly reflected variation in minimum temperature (**a**), while PC2 described mostly temperature seasonality (**b**)

we analysed. These numbers are comparable to recent work by Pie et al. (2022) that showed for Honduran ferns that between 36 and 67 epiphytes (6–10%) and 92–324 terrestrial ferns (14–50%) are likely to be displaced by the year 2049–2099. Epiphytic species in Honduras appear to be at slightly greater risk of displacement compared to terrestrial orchids, which aligns with previous studies suggesting that epiphytes are more sensitive to climatic changes (Richards 2021; Males et al. 2023). This difference between terrestrial and epiphytic species still holds true when we compare the percentage of displaced species within each life-form across two major plant groups: ferns and orchids. For example, when comparing epiphytic orchids within this study, we found that 16–55% of species were displaced, compared to 23–60% of terrestrial. Similarly, 30–56% of epiphytic ferns and 17–61% of terrestrial ferns showed displacement in the study by Pie et al. (2022).

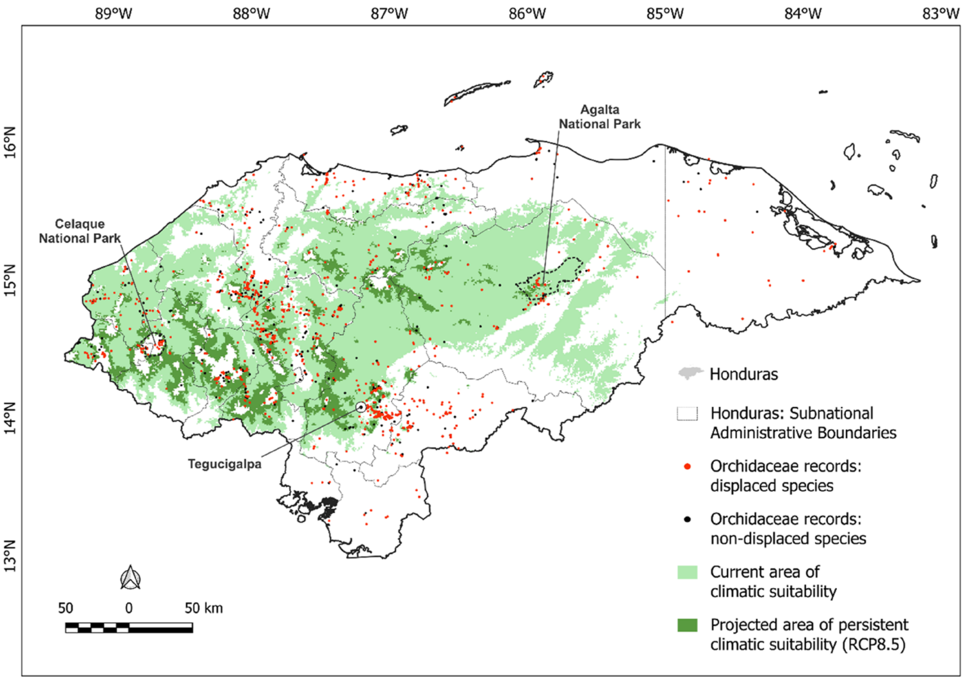

Fig. 4 Climatically suitable areas for Honduran orchids under current (43,100.09 km²; light green) and future conditions projected to persist until 2099 under RCP8.5 (7,419.84 km²; dark green). Climatic suitability was defined based on the intersection of intervals calculated from the mean ± standard deviation of six key climatic variables (tmin_djf, tmin_jja, tmin_ann, tmax_mam, tmax_djf, dtr_son; see Tables 1 and 3). The comparison indicates a reduction of 35,680.26 km², representing an 83% loss in suitable area. Black dots represent non-displaced species occurrences; red dots indicate displaced records

This difference between terrestrial and epiphytic species slightly shifts when we compare the percentage of displaced species within each life-form across two major plant groups: ferns and orchids. For example, 30–56% of epiphytic ferns and 17–61% of terrestrial ferns showed displacement in the study by Pie et al. (2022). Among the orchids analysed in this study, on the other hand, 21–55% of epiphytic species were displaced, compared to 17–53% of terrestrial species. Our results support previous hypotheses about epiphytes' heightened climatic sensitivity. As plants anchored in the forest canopy without access to soil resources, epiphytes occupy a uniquely climate-defined ecological niche compared to co-occurring growth forms such as their host trees (Benzing 1998). In addition to being more tightly coupled to atmospheric conditions, our findings show that epiphytes also exhibited narrower climatic niches than terrestrial species, as indicated by their lower variance in occupied climate space. This reinforces the idea that epiphytes are not only more exposed to climatic fluctuations, but also operate within more restricted environmental bounds, potentially increasing their vulnerability under future climate scenarios.

The greater vulnerability of epiphytes is reinforced by other studies showing that even modest increases in temperature and reductions in water availability can significantly impair their growth and physiological performance (Males et al. 2023; Acevedo et al. 2020). Groups such as bromeliads and orchids have shown stress responses to elevated temperatures and drought, potentially leading to range contractions and increased extinction risk (Acevedo et al. 2020). These effects are intensified by climatic extremes, with temperature variability further elevating local vulnerability (Acevedo et al. 2020). Moreover, subtle shifts in microclimatic conditions, such as changes in vapor pressure deficit, can modify epiphyte community composition (Hsu et al. 2023). Beyond direct climatic impacts, epiphytes are also affected by indirect effects mediated through host tree dynamics. As canopy dwellers, they depend entirely on suitable phorophytes, whose distributions are also shifting in response to climate change (Nascimbene et al. 2020). This challenge may be intensified by the spread of invasive species, which may replace native hosts and further reduce the availability of suitable substrates (Nascimbene et al. 2020).

According to the IPCC Sixth Assessment Report (Costello et al. 2022), approximately 80% of forecasts concerning terrestrial (in this context, non-freshwater and non-marine) species evaluated within biodiversity hotspots indicate a detrimental influence from climate change, with roughly 50% facing a very high risk of extinction, including most endemic species (moderate confidence). Beyond habitat loss and species range contractions, alterations in precipitation patterns are anticipated to be a significant factor affecting species in tropical and subtropical regions (moderate confidence) (Maharaj and New 2013; Vogiatzakis et al. 2016). We found that for orchids in Honduras, minimum temperature and temperature seasonality were identified as the most relevant climatic factors, with predictions suggesting a warming trend in minimum temperatures and a decline in seasonal variablity. In comparison, Pie et al. (2022) showed that when using the same methodology as employed here, niche displacement of ferns in Honduras is mostly driven by changes in low temperature and high precipitation. This demonstrated a clear separation in the required climate niche space between orchids and ferns that could be explained by their difference in climate tolerance. For example, orchids generally are better able to maintain internal water balance under drought conditions due to their ability to store water in their pseudobulbs and leaves, reduced water loss, and Crassulacean Acid Metabolism (CAM) (Zhang et al. 2018).

Table 2 Predicted consequences of climate space shifts according to different climate change scenarios. The total area represents the size of the climate space compared to the current one, while the overlap shows the relative portion of that space that aligns with the present climate

	Outside				Within				Total area	Area overlap
	All	Epiphyte	Terrestrial	Lithophyte	All	Epiphyte	Terrestrial	Lithophyte		
Present	3	3	0	0	434	330	103	1	100	100
RCP2.6_2049	72	57	15	0	365	276	88	1	102	79.8
RCP2.6_2069	87	70	17	0	350	263	86	1	102.5	76.6
RCP2.6_2099	76	61	15	0	361	272	88	1	101	77.2
RCP8.5_2049	80	65	15	0	357	268	88	1	100.6	75.8
RCP8.5_2069	130	104	26	0	307	229	77	1	103.3	62.6
RCP8.5_2099	238	183	55	0	199	150	48	1	100	47.1

Whereas many ferns have higher dependency on water supply but often need to employ more drought avoidance strategies (Campany et al. 2021).

Understanding the impact of climate change on species distribution in mountainous regions is challenging due to the complex topography of these environments. Unlike typical pyramidal mountains, real-world mountains often feature intricate landscapes with varying slopes, ridges, and valleys (Elsen and Tingley 2015). These geometrical constraints can influence how species respond to climate shifts as they migrate to different elevations. Higher elevation areas have been identified as particularly vulnerable to species loss due to climate change, as mid- to high elevation communities are often at the limit of their available climate range, and any small changes in local conditions could restrict their ability to move (Kong et al. 2014). For example, high environmental heterogeneity has been shown to harbour a disproportionate diversity of species, primarily in mountains at lower latitudes (Gutiérrez-Rodríguez et al. 2022; Suissa et al. 2021), such as those found in Honduras (Reyes-Chávez et al. 2021b).

Interestingly, our results indicate that some of the highest regions in Honduras, such as Celaque National Park, fall outside the projected area of climatic suitability (Fig. 2). This appears to be due to a mismatch between the climatic envelope of Celaque (Fig. 1) and the suitability thresholds defined for variables such as tmax_mam, tmin_jja, and tmax_djf. For instance, the minimum temperature in the warmest quarter (tmin_jja) at Celaque averages 14.25 °C (see support material), which is below the lower suitability threshold of 15.58 °C. Similarly, the maximum temperature in winter (tmax_djf) averages 19.27 °C at Celaque, while the model-defined envelope starts at 23.06 °C. These values consistently fall below the lower bounds of the suitability range, suggesting that the cool temperatures typical of high-elevation areas are not adequately captured in the model.

We believe this discrepancy is related to a sampling bias in our occurrence data. Although some records exist at high elevations, the mean elevation across all occurrence points is only 995 m, while Celaque ranges from 975 to 2,870 m. Consequently, higher elevations and their associated climatic conditions may have been underrepresented, resulting in suitability thresholds biased towards lower altitudes. This likely inflated the modelled values for suitable minimum and maximum temperature and led to the exclusion of cooler highland areas such as Celaque from the projected suitable range.

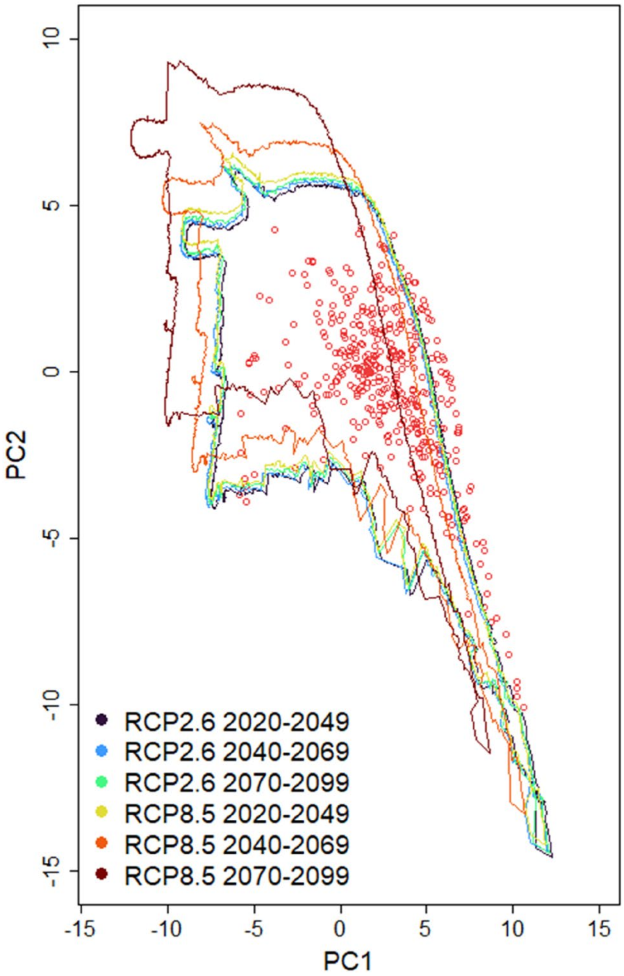

Fig. 5 Principal component analysis showing the outline of all climate change projections for the Honduran climate space for the years 2020–2049, 2040–2069, and 2070–2099. Red empty circles represent the species mean. Note the red circles that fall outside the concave hull for some scenarios between PC1 5 to 12 and PC2 5 to −10

Table 3 Mean, standard deviation, lower limit (mean − SD), and upper limit (mean + SD) for the six Climatic variables identified as most relevant by the PCA. These values were used to define the Climatic suitability envelopes for Honduran orchids

Statistic	tmin_djf	tmin_jja	tmin_ann	tmax_mam	tmax_djf	dtr_son
Mean	15.11	18.24	16.96	29.72	26.09	9.59
SD	2.72	2.66	2.67	3.17	3.03	1.44
Lower limit	12.39	15.58	14.29	26.55	23.06	8.16
Upper limit	17.83	20.89	19.63	32.89	29.12	11.03

Table 4 Summary of displaced Orchid species for two climate change scenarios that have been identified to result in the highest displacement of species according to different growth forms. RCP2.6 refers to the year 2069 and RCP8.5 refers to the year 2099. Please refer also to Table 2

Growth form	Present	RCP2.6			RCP8.5		
		Displaced	Growth form group (%)	Total (%)	Displaced	Growth form group (%)	Total (%)
Epiphyte	333	71	21.32	16.25	183	54.95	41.88
Terrestrial	103	17	16.50	3.89	55	53.40	12.59
Lithophyte	1	0	0.00	0.00	0	0.00	0.00
Total	**437**	**88**		**20.14**	**238**		**54.46**

The effect of altitudinal bias in the occurrence data is further supported by the fact that climatic conditions in Celaque fall consistently below the modelled suitability thresholds. If more records had been collected from higher elevations, the lower bounds of the envelope might have been even lower. This would likely have increased the mismatch between current and future climatic conditions, as future projections show increasing temperatures that already exceed the upper limits of suitability. In other words, a suitability envelope that more accurately captures the colder conditions of high-elevation regions would likely amplify the projected loss of climatically suitable area under future climate scenarios.

The effects of climate change on biodiverse areas are intensified by other human-induced factors, leading to increased vulnerability and decreased resilience of biodiversity to climate change (very high confidence = 9 out of 10 chances for being correct; Costello et al. 2022). Projections considering climate change alone might overestimate or underestimate the actual impacts on biodiversity (moderate evidence, high agreement across many species groups; Costello et al. 2022). It has previously shown that climate change can result in unbalanced loss of phylogenetic diversity in other species groups (Salariato et al. 2024). Compounded risk from climate and additional impacts such as land use change, overhunting, pollution, and invasive species can be also important (Ngo Bieng et al. 2022). The terrestrial hotspots anticipated to be most affected by global warming are typically those already suffering from habitat loss due to changes in land use (Warren et al. 2018). For life-forms such as epiphytes, the loss of available hosts, for example, could result in a complete extinction in local populations (Gradstein 2008). For example, habitat modification and changes in host community composition are of particular importance to epiphytes (Larrea and Werner 2010). Similarly, local extinction risk of terrestrial or epiphytic orchids can also be strongly affected by asymmetrical dispersal ability of species, such as issues of limited patch connectivity (Acevedo et al. 2020).

One of the key challenges when interpreting niche model simulations is that the analysis focuses mainly on species climate means, which should not be misinterpreted as results derived from species specific climate envelope models. However, niche models are powerful tools to enable us to identify potential vulnerable species that live near their climate niche limits. The quality of model results will ultimately depend on the representation of good spatial species occurrence data. For example, unrecorded or rare species are often underrepresented (Molano-Flores et al. 2023), which is also likely the case of the Honduran orchid database. Considerable collections biases have been found in Honduras, such as opportunistic collections performed close to main roads, collection hotspots located mainly in lowland forests and central parts of the country, and at altitudes between 800 and 1250 m.a.s.l. (Batke et al. 2022). These conditions may significantly impact the quality of epiphytic species occurrence data, given that most protected areas are situated above 1800 m.a.s.l. Epiphytic species are often inconspicuous and difficult to access during field surveys unless specifically targeted. It is not uncommon for surveys focused on specific taxonomic groups to substantially increase national and local records, even in well-surveyed and biodiverse regions (Reyes-Chávez and Diaz-Maradiago 2019). In addition, areas such as La Mosquitia have historically been less well sampled for several taxonomic groups due to access limitations, despite of been one of the most biodiverse areas of the country (Reyes-Chávez et al. 2021a). Similarly, areas such as the West of Honduras have been shown to harbour a higher richness of endemic orchid species (Vega et al. 2022). However, it is unlikely that more comprehensive surveys for these areas will be carried out soon due to financial limitations and a lack of incentives from local and national government bodies.

In summary, our study reinforces previous findings indicating that climate change can increase species vulnerability and cause shifts in their habitat suitability. Our analysis of orchid data in Honduras unveils a concerning trend: up to 54% of orchid species could face displacement due to climate shifts. To safeguard these species effectively, current, and future conservation endeavours must adopt landscape-wide strategies that prioritise the preservation of future habitat suitability. Orchids possess distinct niche requirements compared to other plant groups, necessitating conservation approaches that embrace a multi-taxa perspective to mitigate the repercussions of anticipated niche alterations. A crucial prerequisite for this entails establishing more robust and comprehensive species inventories, particularly in regions disproportionately susceptible to climate change. For instance, Honduras boasts over 150 orchid species awaiting thorough voucher collections, alongside a notable absence of detailed herbarium-based inventories for other significant plant taxa (*personal observations* by the authors).

Moving forward, the next pivotal step involves crafting species-specific climate envelope models for taxa identified as facing substantial risks of niche displacement in our study. Such models would empower conservation practitioners to formulate precise, targeted management strategies. By integrating these insights into actionable plans, we can strive to safeguard the rich biodiversity of vulnerable regions like Honduras amidst the ongoing challenges posed by climate change.

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Author contributions All authors contributed to this study design. Data collection was carried out by HV, WC-I, EM and KR-S. Analysis was performed by MM in collaboration with SB. The manuscript was written by SB, TD, and MM, with contributions from all other authors. All authors have read and approved the final manuscript.

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Data availability The orchid species dataset as well as the relevant analysis files and scripts are freely available and deposited on Zenodo (https://zenodo.org/records/13752943). For additional information please con tact the corresponding author.

Declarations

Competing interests The authors declare no competing interests.

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