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Different Responses of Two Endangered Sister Tree Species to Climate Change: A Comparison Between Island and Continental Populations in Tropical Asia

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Keywords: climate change | continental species | ecological niche modeling | habitat loss | Island species | species conservation | *Trigonobalanus*

ABSTRACT

Climate change is widely recognized as a major threat to biodiversity and a critical factor contributing to the decline in species and populations. However, it remains uncertain whether species from continental and island environments, especially endangered ones, will respond similarly or differently to climate change. The strategies employed by these species to cope with climate change, and the corresponding conservation management approaches, remain poorly understood. In this study, we employed ecological niche models to project future shifts in the distribution patterns of two endangered sister species, *Trigonobalanus doichangensis* and *T. vericillata*, which are distributed across continental and island regions of tropical Asia. We analyzed potential changes in their distribution under four different climate change scenarios for the 2050s and 2070s. Our results indicate that temperature is a significant driver for the continental species *T. doichangensis*, whereas precipitation predominantly influences the island species *T. vericillata*. Moreover, we found that the potential future distribution range of the continental species *T. doichangensis* is likely to exceed that of the island species *T. vericillata*, suggesting that the continental species *T. doichangensis* may have a stronger capacity for adapting to climate change. We recommend that conservation areas be established to maintain habitat stability in regions most affected by climate change. A comprehensive assessment of the endangered status of both species is also essential. Overall, this study underscores the distinct responses of island and continental species to climate change, thereby enhancing our understanding of their adaptive strategies and informing targeted conservation efforts.

Summary

This study investigates how climate change will impact endangered species differently, specifically focusing on two sister species of *Trigonobalanus* in tropical Asia. Using ecological niche models, we project how their distribution may change under various climate scenarios for the 2050s and the 2070s. Key findings include the following: (1) Temperature primarily affects the continental species *T. doichangensis*, whereas precipitation influences the island species *T. vericillata*. (2) The continental species *T. doichangensis* may have a larger future distribution range, suggesting better adaptability to climate change. This research emphasizes the need for: (1) The establishment of conservation areas in regions most affected by climate change. (2) The reassessment of the endangered status of both species. This study highlights the importance of understanding how different species respond to climate change to develop effective conservation strategies.

- **Practitioner Points**
  - The island species, *T. vericillata*, is likely to be more severely affected by future climate change compared to the continental species, *T. doichangensis*.
  - Temperature is a key factor influencing the continental species *T. doichangensis*, while precipitation plays a more significant role for the island species *T. vericillata.*
  - The continental species *T. doichangensis* and island species *T. verticillata* are both expected to shift to higher elevations in the future.

1 | Introduction

In recent decades, the intensification of greenhouse gas emissions has exacerbated climate change, significantly contributing to biodiversity loss (Urban 2024; Iordan et al. 2023; Shin et al. 2022; Sunday 2020; Bellard et al. 2012; Bálint et al. 2011). The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) indicates that the global surface temperature between 2011 and 2020 was 1.09°C higher than that observed between 1850 and 1900, alongside an increasing trend in rainfall (Eyring et al. 2021). The impacts of climate change on species have become increasingly evident and complex, driven by various factors such as invasive species (Chen et al. 2024; Mainka and Howard 2010), pollution (Yarahmadi 2024; Hernández-Yáñez et al. 2016), and habitat loss (Exposito-Alonso et al. 2022; Wang et al. 2022).

Species typically respond to climate change by expanding, contracting, or migrating their distribution ranges (Manes et al. 2021; Rather et al. 2021; Meng, Zhou, Jiang, et al. 2019). Species with wide distributions are more likely to find suitable refugia in parts of their range, which helps them cope with the impacts of climate change (Yu et al. 2019). Conversely, narrowly distributed species are more susceptible to accelerated habitat fragmentation, increasing their risk of extinction (Leimu et al. 2010; Manes et al. 2021). For example, Tang et al. (2021) demonstrated that species with broader geographical ranges, like the widely distributed *Ostrya* species, can expand their ranges in response to climate change, whereas narrowly distributed species face a higher extinction risk due to habitat loss. Sheth and Angert (2014) found that species with broad geographical ranges, such as the North American *Mimulus*, exhibit greater genetic variation, making them less vulnerable to climate change. These studies have primarily focused on continental species, emphasizing the differential impacts of climate change on species with varying distribution ranges (Xu et al. 2023; Xu et al. 2019; Yu et al. 2019). However, the responses of island species to climate change remain comparatively understudied. Notably, global surveys across 273 biodiversity regions indicate that island species face a 100% risk of extinction due to climate change, whereas mountain species face an 84% risk (Manes et al. 2021). Given these findings, it is crucial to understand whether continental and island species respond differently to climate change, particularly in terms of their distribution ranges.

Because of their isolated evolution, island species are often ill-prepared for changing environments (Matthews and Triantis 2021). Due to "island syndrome," which limits the dispersal ability of many island species, they are more susceptible to disturbance, especially regional endemics (Carlquist 1974). Furthermore, island species generally exhibit lower genetic variation than continental species, which exposes them to more complex and less predictable temperature and precipitation patterns, such as those caused by the El Niño Southern Oscillation or monsoons (Pouteau and Birnbaum 2016). Importantly, the surrounding ocean restricts the ability of island species to migrate to more favorable habitats as environmental conditions deteriorate. This means that these species must either adapt to changing conditions or retreat to potential refuges on the island (e.g., high-elevation islands with complex landscapes that can create microclimates; Pouteau and Birnbaum 2016; Whittaker and Fernández-Palacios 2007). Given these unique characteristics, we hypothesize that widely distributed island species may be more vulnerable to future climate change, whereas narrowly distributed continental species could be less impacted. However, there is limited literature on this subject, and it remains unclear whether this conjecture is correct.

The genus *Trigonobalanus* includes three species, two of which are found in tropical Asia and one in South America. Specifically, *T. excelsa* is distributed in South America, and *T. verticillata* and *T. doichangensis* are distributed in tropical Asia (Sun et al. 2007; Meng, Zhou, Li, et al. 2019). Interestingly, the two sister species in tropical Asia exhibit distinct geographic distributions: one occupies an island habitat, while the other occupies a continental region (Supporting Information S1: Figure A1). *T. verticillata* is widely distributed across three biodiversity hotspots in Southeast Asia and is classified as an island species within the genus (Zhu and Zhou 2017). In contrast, *T. doichangensis* is confined to Yunnan, China, and Thailand, classifying it as a continental species (Hu et al. 2022; Meng, Zhou, Li, et al. 2019). The unique distribution pattern of *Trigonobalanus* in tropical Asia presents a valuable opportunity to study the differential responses of narrow- and wide-ranging species to climate change in both island and continental environments.

Moreover, these two species are vital for timber production and contribute significantly to local vegetation and related economies (Meng, Zhou, Li, et al. 2019). Unfortunately, both species are currently listed as threatened on the IUCN Red List of

Threatened Species (https://www.iucnredlist.org/). Overexploitation driven by the demand for construction materials, cash crops, and agricultural tools has led to the extensive habitat destruction of these two species (Sun et al. 2006; Zheng et al. 2009). Broad-leaved trees, such as *Trigonobalanus*, play a key role in maintaining ecological balance and preserving regional species diversity (Ge and Xie 2017). However, the biodiversity hotspots where these species occur are facing severe habitat loss due to land-use changes and are highly susceptible to the impacts of global warming (Costello et al. 2022). Therefore, predicting the potential effects of climate change on the distribution of these species is critical. Such predictions are essential for understanding the adaptive capacities of species to environmental changes and identifying potential migration corridors. This knowledge will be instrumental in developing more effective conservation strategies, ultimately safeguarding biodiversity, maintaining ecosystem stability, and ensuring the continued provision of essential ecological services.

In this study, we sought to predict the current and future potential distributions of *Trigonobalanus* species. Our primary objectives were twofold: first, to identify the key environmental factors that significantly influence the potential distribution of *Trigonobalanus* species across Asia; and second, to predict how the distribution patterns of species with narrow versus wide ranges may shift under future climate change scenarios.

2 | Materials and Methods

2.1 | Species Data

We obtained occurrence records from the literature, the Global Biodiversity Information Facility (https://www.gbif.org/), the National Specimen Information Infrastructure (http://www.nsii.org.cn/), the Chinese Virtual Herbarium (http://www.cvh.ac.cn/), Sichuan University Herbarium (http://mnh.scu.edu.cn/list/introduction/), New York Botanical Garden (https://sciweb.nybg.org/science2/hcol/vasc/index.asp.html/), and Kew Royal Botanic Garden (http://apps.kew.org/herbcat/gotoHomePage.do), as well as our field surveys conducted in 2017 and 2021. All occurrence records were reviewed and cross-checked using *Flora of China* (http://www.efloras.org/) and *The Plant List* (http://www.theplantlist.org/) to ensure accuracy and eliminate errors or problematic entries. To reduce the potential influences of overfitting biases, occurrence records for each species were thinned (10 km) using SDMtools in ArcGIS 10.7 (Zhou et al. 2021). This resulted in a total of 44 occurrence records selected for our study (20 for *T. doichangensis* and 24 for *T. verticillata*; Supporting Information S1: Table A1; Figure A1).

2.2 | Environmental Data

Environmental data were obtained from the WorldClim database (https://www.worldclim.org), which includes 19 bioclimatic variables for the present period (1970–2000) and projections for the 2050s (2040–2060) and 2070s (2060–2080), as well as elevation variables (Supporting Information S1: Table A2). Detailed descriptions of these environmental variables are provided in Supporting Information S1: Table A2. Future climate data were based on the Community Climate System Model (CCSM4), with a total of four representative concentration pathways (RCPs) considered: RCP2.6, RCP4.5, RCP6.0, and RCP8.5, which represent low, medium, high, and highest concentration greenhouse gas emissions scenarios, respectively (van Vuuren et al. 2011). Map data were sourced from the Resource and Environment Science and Data Center (https://www.resdc.cn/Default.aspx).

To avoid the influence of highly correlated variables, Pearson's correlation analysis was performed to select the final bioclimatic variables. Using the Band Collection Statistics tool in ArcGIS, any pair of variables with a correlation coefficient $|r| \geq 0.8$ was assessed, and the variable with the lesser contribution to the model was omitted. Variables with minimal effects on species distribution and growth were removed, while those with potential ecological relevance to the species were retained (Supporting Information S1: Figure A2). The elevation factor was incorporated directly into the analysis and assumed to remain constant over the coming decades (Zhang et al. 2023). As a result, nine environmental variables were retained to simulate the potential distribution of *T. doichangensis*, and seven environmental variables were retained for *T. verticillata* (Tables 1 and 2).

2.3 | Species Distribution Modeling

Ecological niche models (ENMs) are valuable tools for investigating species distribution patterns (Peterson et al. 2011; Warren and Seifert 2011). Among various modeling methods, the MaxEnt model, which is based on maximum entropy theory, is particularly noted for its exceptional performance in predicting species geographic distribution (Ab Lah et al. 2021; Zeng et al. 2023; Elith et al. 2011). Numerous studies have demonstrated the reliability of the MaxEnt model in simulating potential species distributions (He et al. 2023; Li et al. 2023; Shi et al. 2023; Gao et al. 2022).

Species distributions were predicted using MaxEnt v3.4.1 (Elith et al. 2011). Twenty percent of occurrence data were randomly selected as the test data set, while the remaining 80% were used as the training data set (Orefice and Innocenti 2024). Background points were set to 10,000, with the maximum number of iterations of the model set to 1000 and the number of repetitions set to 10. Other parameters were set to default values (i.e., regularization multiplier = 1, convergence threshold = 10^{-5}; Syfert et al. 2013). The jackknife test was used to identify the most dominant environmental factors, and the threshold value for each environmental factor was determined from the response curve. The area under the receiver operating characteristic curve (AUC) was used to evaluate the reliability of the model's predictions. The AUC value ranges from 0 to 1, with higher values indicating greater reliability in model predictions (Elith et al. 2006; Fielding and Bell 1997).

The outputs from the Maxent model were converted into raster format and reclassified to identify potentially suitable areas. The

TABLE 1 | Present contributions and suitable ranges of the main environmental variables for *T. doichangensis*.

Environmental variables	Description	*T. doichangensis*			
		Present contribution/%	Permutation importance/%	Suitable ranges	Optimum peak
Bio2	Mean Diurnal Range (Mean of monthly (max temp–min temp)) (°C)	64.8	75.2	≥ 11.6	—
Bio18	Precipitation of Warmest Quarter (mm)	13.2	6.9	613.0–1336.8	809.7
Bio3	Isothermality (BIO2/BIO7) (×100)	9.3	13	48.7–55.8	51.6
Bio13	Precipitation of Wettest Month (mm)	4.5	2.9	247.6–350.5	297.6
Elevation	Elevation (m)	3.9	1	778.8–2191.9	1354.7
Bio19	Precipitation of Coldest Quarter (mm)	2.1	0.4	29.6–67.1	42.1
Bio15	Precipitation Seasonality (Coefficient of Variation)	1.5	0.3	81.7–92.7	86.6
Bio14	Precipitation of Driest Month (mm)	0.6	0.2	4.6–16.8	10.5
Bio8	Mean Temperature of Wettest Quarter (°C)	0.1	0	19.3–26.1	23.5

TABLE 2 | Present contributions and suitable ranges of the main environmental variables for *T. verticillata*.

Environmental variables	Description	*T. verticillata*			
		Present contribution/%	Permutation importance/%	Suitable ranges	Optimum peak
Bio15	Precipitation Seasonality (Coefficient of Variation)	32.9	30.3	≤ 27.8	15.4
Elevation	Elevation (m)	32.3	28.4	667.4–1710.0	1165.7
Bio8	Mean Temperature of Wettest Quarter (°C)	12	5.1	9.8–23.8	20.7
Bio4	Temperature Seasonality (standard deviation ×100)	11.5	8.9	0.2–0.6	0.3
Bio2	Mean Diurnal Range (Mean of monthly (max temp − min temp)) (°C)	6.6	20.8	≤ 9.0	7.4
Bio18	Precipitation of Warmest Quarter (mm)	2.9	4.5	536.7–1050.8	700.9
Bio12	Annual Precipitation (mm)	1.9	2	≥ 2057.3	2399.1

cloglog output from MaxEnt represents climate suitability on a scale from 0 to 1, with higher values indicating more favorable conditions for species survival (Lee et al. 2021). A 10% training presence cloglog threshold was used to classify suitability levels: unsuitable area (< 10% training presence cloglog threshold), low suitability (10% training presence cloglog threshold–0.6), medium suitability (0.6–0.8), and high suitability (0.8–1). In addition, response curves for environmental variables were used to assess the suitability range of environmental variables for species growth. A presence probability greater than 0.5 indicates that the corresponding environmental variable range is suitable for species survival (Zhao et al. 2021).

3 | Results

3.1 | Maxent Performance and the Importance of Environmental Variables

The results indicated that the AUC values exceeded 0.9 (*T. doichangensis*: 0.984, *T. verticillata*: 0.974), implying high reliability in the simulation outcomes, which effectively reflected the responses of both island and continental species to climate change.

For the continental species *T. doichangensis*, the analysis revealed that the mean diurnal range (Bio2), isothermality

(Bio3), and precipitation of the warmest quarter (Bio18) were the most influential factors affecting its predicted distribution. The cumulative contribution of these three variables was 87.3% (Table 1). Other factors, such as precipitation of the wettest month (Bio13), elevation, and precipitation of the coldest quarter (Bio19), had a moderate influence, contributing 10.5% to the model (Table 1). In contrast, precipitation seasonality (Bio15), precipitation of the driest month (Bio14), and mean temperature of the wettest quarter (Bio8) had the least influence on the predicted distribution of *T. doichangensis* (Table 1). Overall, temperature was found to have the greatest impact on the potential distribution of the continental species, followed by precipitation and elevation (Table 1).

For the island species *T. verticillata*, the dominant environmental factors influencing species distribution were precipitation seasonality (Bio15), mean temperature of the wettest quarter (Bio8), temperature seasonality (Bio4), and elevation. These four factors collectively contributed 88.7%, with the next most influential variables being mean diurnal range (Bio2, 6.6%), precipitation in the warmest quarter (Bio18, 2.9%), and annual precipitation (Bio12, 1.9%). The three highest permutation importance values were precipitation seasonality (Bio15), mean diurnal range (Bio2), and elevation. In total, precipitation factors accounted for the greatest cumulative contribution (37.7%), followed by temperature factors (30.1%), and elevation (32.3%). Precipitation had the greatest influence on the potential distribution range of island species, followed by elevation, while temperature factors had the least influence (Table 2).

3.2 | Present Potential Habitat

The current potential distribution of the continental species *T. doichangnsis* is mainly in southwest Yunnan, China, eastern Myanmar, and some scattered areas in northern Laos and northern Thailand. Low-, medium-, and high-suitability areas account for 60.17%, 16.34%, and 23.49%, respectively. Current high-suitability areas are primarily located in Yunnan, China, and eastern Myanmar (Figure 1a). The current potential distribution of the island species *T. verticillata* includes Hainan (China), south-central and central Vietnam, Malaysia, Sulawesi, Sumatra, Java, northeastern Kalimantan, and the Philippines. The low-, medium-, and high-suitability areas account for 76.89%, 12.15%, and 10.96%, respectively. Current high-suitability areas are mainly in northern Sumatra, Sulawesi, scattered areas in northern Java, northeast Kalimantan, and the southern Philippines (Figure 1b).

3.3 | Potential Future Distribution Pattern of the Continental Species *T. doichangensis*

For the narrowly distributed continental species *T. doichangensis*, the potential suitable areas across different periods were primarily centered in southwest Yunnan, eastern Myanmar, northern Laos, and northern Thailand, with southwest Yunnan and northern Laos being the most suitable (Figure 2a–h).

Under different climate scenarios, the potential high- and medium-suitability areas exhibited significant changes. Under low-concentration (RCP2.6) and medium-concentration (RCP4.5) greenhouse gas emissions scenarios, the potential high-suitability areas initially decreased and then increased. In contrast, under high-concentration (RCP6.0) and highest-concentration (RCP8.5) emissions scenarios, the potential high-, medium-, and low-suitability areas decreased significantly (Figure 2a–h).

Overall, the potential distribution areas of the narrowly distributed continental species *T. doichangensis* are expected to expand significantly, particularly in regions bordering southwest China, eastern Myanmar, northern Thailand, and northern Laos (Figures 3 and A4).

3.4 | Future Potential Distribution Pattern of the Island Species *T. verticillata*

For the widely distributed island species *T. verticillata*, areas of high suitability decreased under the four climate scenarios, especially in Kalimantan. Additionally, some unsuitable habitats in Sulawesi were transformed to low-suitability areas. From the present to the 2050s, potential high-suitability habitats were transformed into medium- and low-suitability habitats under all four climate scenarios (Figures 1b and 4a–d).

Overall, the island species *T. verticillata* is expected to experience range contraction in its potential distribution areas (Supporting Information S1: Figure A4). The primary areas of range contraction are Hainan, China, south-central and central Vietnam, and the coastal areas of western Sumatra, Java, northeast Kalimantan, and Malaysia (Figure 5).

4 | Discussion

4.1 | The Impact of Dominant Environment Variables on Continental and Island Species

Temperature, precipitation, and elevation are crucial climatic factors that influence species distribution and ecosystems (Punyasena et al. 2007). Our study revealed that precipitation and temperature conditions significantly shape species distribution patterns. Specifically, the cumulative contribution of temperature factors affecting the potential distribution of the continental species *T. doichangensis* was 74.2%, while precipitation factors contributed 37.7% to the potential distribution of the island species *T. verticillata*.

For mountain species inhabiting high-elevation areas, low temperatures limit plant growth and development, thereby influencing species distribution. Hence, temperature plays a crucial role in constraining the distribution and development of mountain species (Dong et al. 2023; Yu et al. 2019). The continental species *T. doichangensis* is distributed in lower montane evergreen broad-leaved forests (Mao et al. 2010; Zhu and Ashton 2021). The high suitability of *T. doichangensis* clustered in high-elevation areas also indicates that species at high elevations are sensitive to temperature changes. With climate change, lower temperatures at high elevations are likely to drive continental species to migrate upward in search of

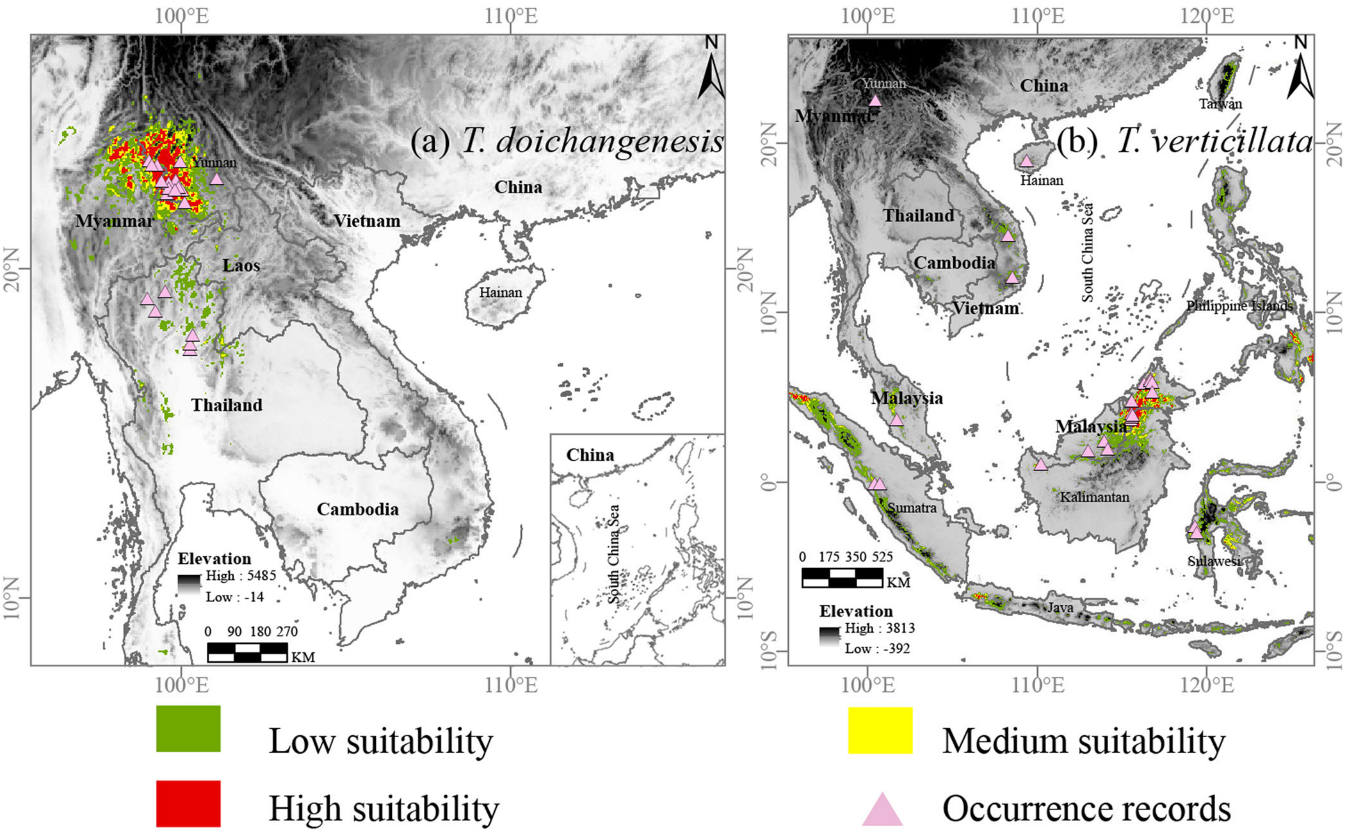

FIGURE 1 | Potential distribution pattern of (a) *Trigonobalanus doichangenesis* and (b) *T. verticillata* in the present (1970–2000).

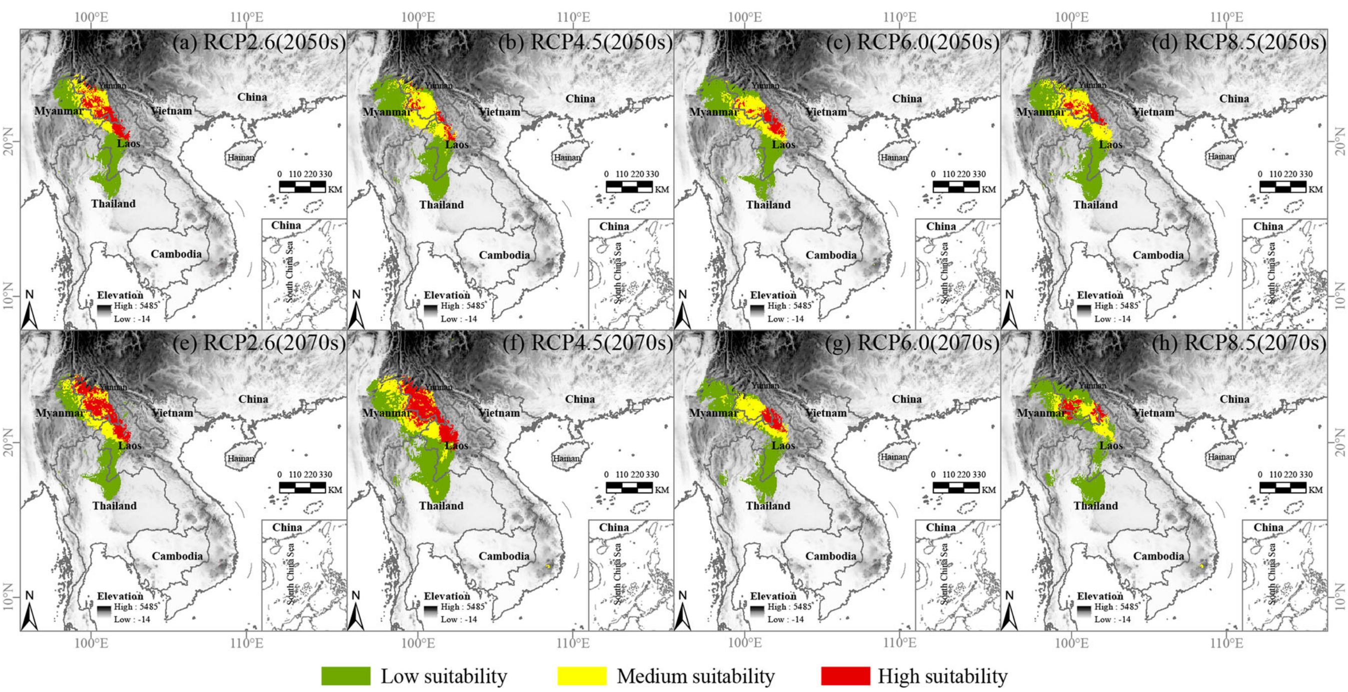

FIGURE 2 | Distribution of potentially suitable areas of *Trigonobalanus doichangenesis* in different periods (2050s and 2070s) and climate scenarios (RCP2.6, RCP4.5, RCP6.0, and RCP8.5), representing low, medium, high, and highest concentration greenhouse gas emissions scenarios, respectively.

suitable habitats. Although precipitation and elevation had less impact on the distribution of continental species in our study, these factors remain important for species growth and distribution.

The island species in our study predominantly thrives in Southeast Asia, a region characterized by the prevalence of monsoons. The Asian monsoon has a direct impact on rainfall and temperature patterns in these regions, creating a regular seasonal cycle between dry and wet periods (Jiang et al. 2017; Tan, Malabrigo, et al. 2020). These climatic fluctuations affect plant growth, development, and reproduction, facilitating better adaption to seasonal changes (Sun et al. 2020). With climate change, an increase in extreme weather events, such as droughts and heavy rainfall can be expected (Reichstein et al. 2013; Wang et al. 2024), which will likely have significant consequences for the distribution of island species.

Furthermore, our study highlights the significant impact of topographic factors on both continental and island species. Interestingly, when excluding other factors (e.g., land-use change, human activities), the influence of topography on island species is considerably greater than that on continental species. We speculate that changes in the upper and lower elevation ranges may have contributed to this result. Affected by climate change, both the upper and lower limits of the species' elevation distribution is expected to shift (Zu and Wang 2022). The elevation range of island species is lower than that of continental species, meaning that island species have a greater upward migration potential than continental species (Tables 1 and 2).

4.2 | Differences in Climate Response Between Continental and Island Plant Species

Species survival is closely linked to climate change, with some researchers suggesting that species with narrower thermal niche breadths, smaller geographic ranges, or smaller body sizes are at a greater risk of extinction (Malanoski et al. 2024). However, our study demonstrated an opposite viewpoint: under scenarios of low and moderate greenhouse gas emissions, the highly suitable distribution area for the continental species in this study is expected to first decrease and then increase in the future. In contrast, under scenarios of high emissions, highly suitable areas are expected to continue shrinking. This suggests that continental species with narrow distribution ranges may not be able to adapt to rapid climate change and migrate to the most suitable areas quickly (Figure 2).

Additionally, with global warming, temperature restrictions on vegetation distribution in certain regions may be lifted, facilitating the further expansion of species (Zhong et al. 2023). Temperatures increases are driven by rising greenhouse gas concentrations (Wang et al. 2024). Hence, even if continental species can adapt to escalating temperature conditions to a certain extent, the decline in highly suitable habitats remains unavoidable.

Unlike continental species, island species are generally more sensitive to climate change and often lack the ability to adapt quickly or migrate to more suitable areas. This is evident in the study by Tanaka et al. (2012), which predicted that climate change would reduce the potential habitats of *Abies* species in Japan. Our findings support this view, with the suitable area for the island species *T. verticillata* predicted to decrease (Figures 4 and A4).

Many species begin migrating to higher latitudes and elevations in response to climate change, leading to changes in distribution areas (Meng, Zhou, Jiang, et al. 2019; Zhou et al. 2021). Our results show that both continental and island species are forecast to shift towards higher elevations (Figures 2 and 4). Surveys of natural forest habitats in Southeast Asia have suggested that biodiversity in this region is highly vulnerable to climate change, especially in the Indo-Burma region and central Malaysia, where many species are increasingly moving to higher elevations in response to climate warming, which increases the risk of habitat loss (Namkhan et al. 2022). Rising greenhouse gas emissions will accelerate climate change (Tan, Wu, et al. 2020). Our study indicates that, as greenhouse gas emissions increase, both island and continental species are expected to experience varying degrees of contraction in their potentially highly suitable areas (Figures 1, 2 and 4). Because habitat availability decreases with elevation, the shift of island species to higher elevations under climate change poses a significant extinction risk (Figure 4). Interestingly, our results also suggest that continental species may migrate to lower latitudes (Figure 2). Although there is ample evidence of species migrating to higher latitudes or elevations in response to climate change, evidence of their migration to lower latitudes is limited (Franco et al. 2006). We propose that the observed movement towards lower latitudes is likely attributable to niche conservation, prompting plants to migrate towards habitats that are more conducive to their survival. It is important to note that in subtropical and tropical regions, there are no high-elevation areas acting as buffer zones, such as the high mountain ranges in the Himalaya–Hengduan Mountains, which can provide microclimatic refuges and reduce extinction risks (Meng, Zhou, Jiang, et al. 2019). Therefore, mountaintops in low-latitude tropical regions are likely to serve as refugia. However, we did not observe significant low-latitude migration in island species, leading us to speculate that island species may lack similar buffer zones.

Based on our analysis of the potential distribution patterns of continental and island species, our findings align with our initial hypothesis that widely distributed island species are likely to be more significantly impacted by future climate change, while narrowly distributed continental species may experience fewer effects. Specifically, our study of the widespread island species *T. verticillata* in Southeast Asia indicated a less favorable future distribution (Figures 1, 4 and A4). In contrast, the continental species *T. doichangensis*, which currently has a limited distribution in Yunnan, China, and Thailand, shows promising future distribution trends (Figures 1, 2 and A4).

One possible explanation for our findings is the role of genetic diversity, which is critical to the evolutionary history and future adaptability of species (Jump et al. 2009). Low genetic diversity can impede a species' ability to adapt to environmental changes, and we speculate that the observed distribution patterns in our study may be influenced by the genetic diversity of the species involved. In earlier studies, we found that the genetic diversity and gene flow of the continental species *T. doichangensis* were higher than those of the island species *T. verticillata* (Hu et al. 2022; unpublished data). Moreover, studies on the genus *Geodorum* have shown that narrowly distributed species tend to have higher genetic diversity (Zhu et al. 2023). Therefore, we suggest that, in addition to ecological factors, intrinsic characteristics of species, such as genetic diversity, are crucial for their adaptation to climate change.

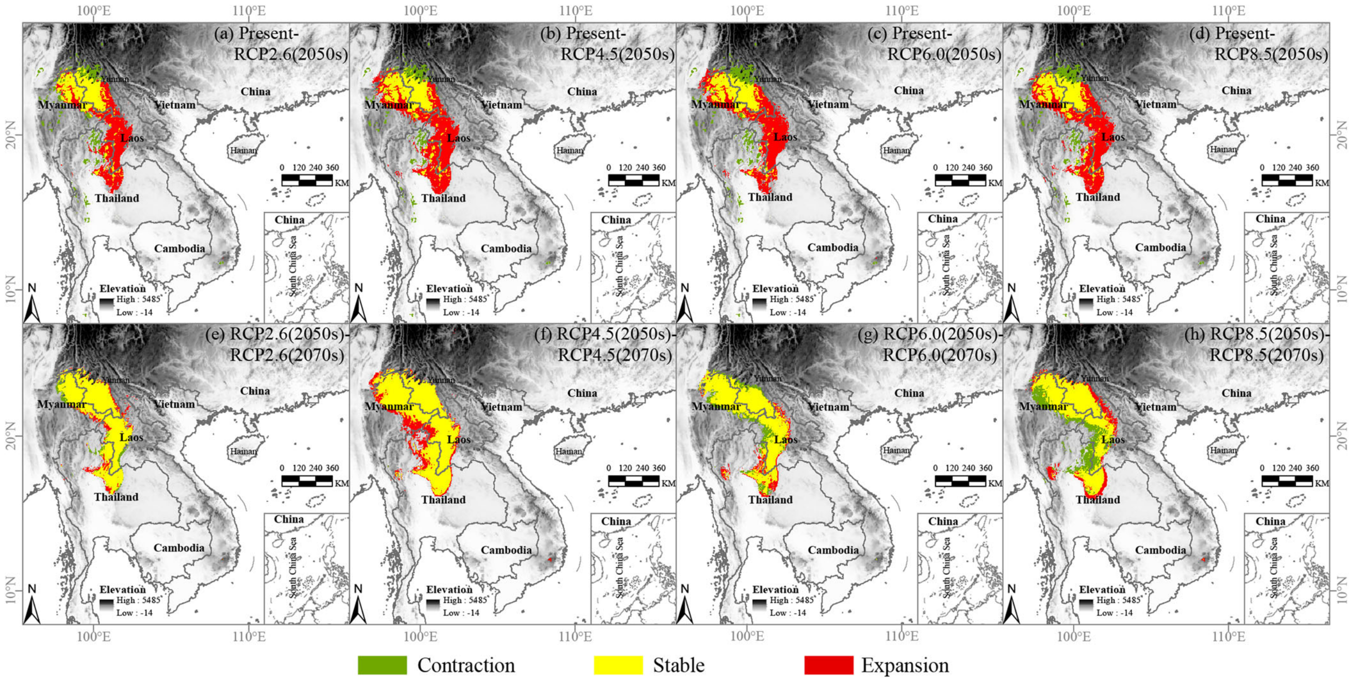

FIGURE 3 | Changes in the potential distribution pattern of *Trigonobalanus doichangensis* under different climate scenarios. Red represents unsuitable areas that are expected to become suitable. Yellow represents suitable areas that are expected to remain unchanged. Green represents suitable areas that are expected to become unsuitable. Climate scenarios include RCP2.6, RCP4.5, RCP6.0, and RCP8.5, representing low, medium, high, and highest concentration greenhouse gas emissions scenarios, respectively.

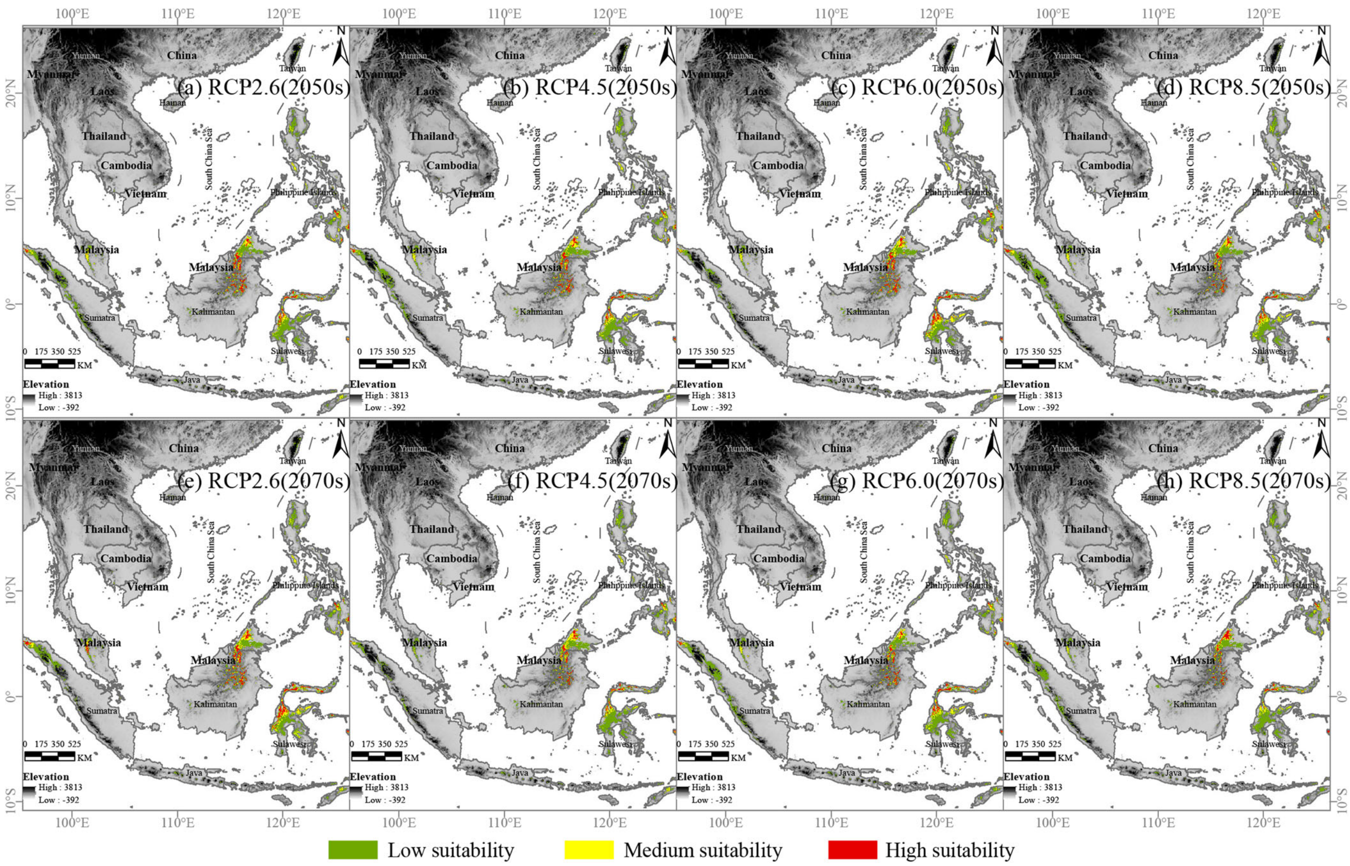

FIGURE 4 | Distribution of potentially suitable areas for *Trigonobalanus verticillata* in different periods (2050s and 2070s) and climate scenarios (RCP2.6, RCP4.5, RCP6.0, and RCP8.5), representing low, medium, high, and highest concentration greenhouse gas emissions scenarios, respectively.

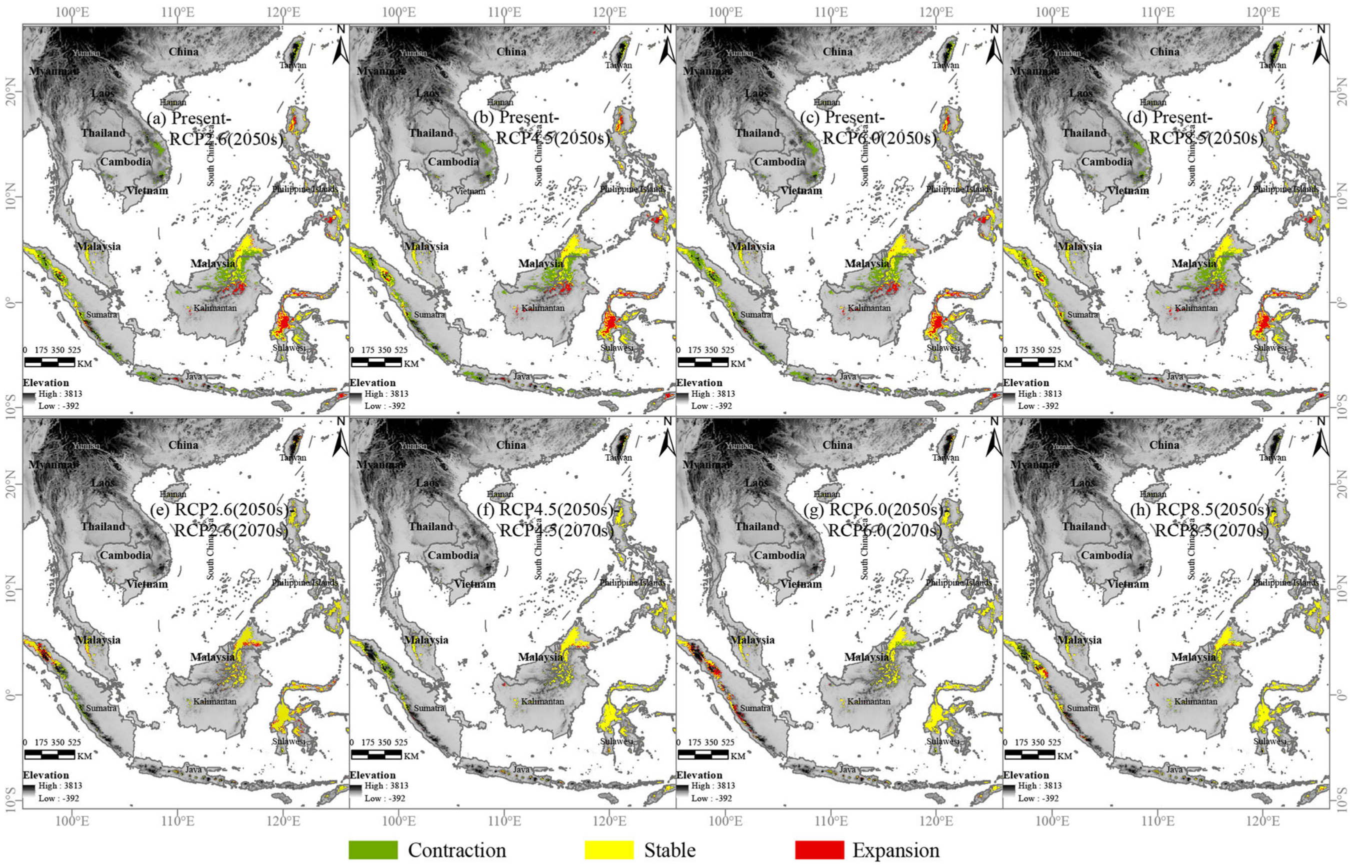

FIGURE 5 | Changes in the potential distribution pattern of *Trigonobalanus verticillata* under different climate scenarios. Red represents unsuitable areas that are expected to become suitable. Yellow represents suitable areas that are expected to remain unchanged. Green represents suitable areas that are expected to become unsuitable. Climate scenarios include RCP2.6, RCP4.5, RCP6.0, and RCP8.5, representing low, medium, high, and highest concentration greenhouse gas emissions scenarios, respectively.

Furthermore, island plant species face greater challenges in dispersing across geographical barriers than continental species. There is no evidence to suggest that *Trigonobalanus* species possesses the ability to disperse over long distances across oceans. As a result, island species generally exhibit weaker resilience to environmental risks than continental species. Therefore, we propose that continental species are likely to be more resilient to climate change than island species.

4.3 | Conservation Implications

In Asia, the genus *Trigonobalanus* plays a crucial role in maintaining ecological balance and preserving regional biodiversity, thereby supporting the rich biodiversity of Southeast Asia. To our knowledge, there are currently no studies on the future distribution of *Trigonobalanus*. Therefore, our study helps fill this gap. Our predictions indicate that southwest Yunnan, China, and eastern Myanmar are high-suitability areas for *T. doichangensis* (Figure 1a). Meanwhile, northern Sumatra, Sulawesi, scattered areas in northern Java, northeast Kalimantan, and the southern Philippines are high-suitability areas for island species of *T. verticillata* (Figure 1b). The natural habitats in these areas are optimal environments for species growth. We found that, except for Myanmar, Java, and the Philippines, where there was no population distribution, the remaining areas aligned with the real distribution areas of *T. doichangensis* and *T. verticillata*. These highly suitable habitats are predicted to experience varying degrees of fragmentation in the future, particularly for the island species (Figures 2 and 4). Therefore, we propose the establishment of protected areas (PAs) to maintain habitat stability in regions most affected by climate change, such as Sumatra. Additionally, our results suggest that some areas where island species are present, such as Hainan, China, and Vietnam, are at risk of disappearing in the future because of climate change (Figure 4). These areas, highly affected by climate change, should be prioritized for conservation, supplemented by ex situ conservation efforts to prevent potential extinction of island species.

High-elevation regions, particularly mountaintops in tropical areas, are predicted to serve as crucial refuges under climate change, offering microclimatic conditions that buffer extinction risks. Furthermore, our study suggests that the continental species *T. doichangensis* will likely exhibit greater adaptability to climate change than the island species *T. verticillata*. This implies that conservation efforts for *T. doichangensis* may yield more significant results, suggesting that this species should be given priority. Based on our fieldwork, there is an urgent need for a more comprehensive assessment of the endangered status of both *T. doichangensis* and *T. verticillata*, especially since the current threat status of *T. verticillata* may be more severe than that indicated by the IUCN (Near Threatened, https://www.iucnredlist.org).

5 | Conclusions

Based on the present and future potential distribution patterns of the two sister species distributed on islands and continental Asia, and by identifying the key factors influencing their distribution, we suggest that the mean diurnal range, isothermality, and precipitation of the warmest quarter are the dominant environmental variables affecting the distribution of the continental species *T. doichangensis*. For the island species *T. verticillata*, the dominant environmental variables are precipitation seasonality, elevation, mean temperature of the wettest quarter, and temperature seasonality.

Overall, temperature emerged as the critical factor influencing the distribution of the continental species *T. doichangensis* in Asia, whereas precipitation was the primary factor affecting the distribution of the island species *T. verticillata*. Moreover, our findings suggest that the potential distribution range of the narrowly distributed continental species *T. doichangensis* is likely to expand, whereas that of the widely distributed island species *T. verticillata* is expected to decrease. The potential distribution areas of both species, particularly higher elevations and mountaintops in low-latitude tropical regions, are expected to serve as refuges under climate change. We emphasize that the widely distributed island species *T. verticillata* will be more vulnerable to future climate change, whereas the narrowly distributed continental species *T. doichangensis* will be less affected. We recommend the establishment of conservation areas in regions most affected by climate change to maintain habitat stability and the implementation of comprehensive assessments of the endangered status of both species. In summary, our study underscores the distinct responses of continental and island species to climate change, thereby enhancing our understanding of how these species will respond to future environmental shifts.

Author Contributions

Ling Hu: methodology, conceptualization, data curation, formal analysis, investigation, software, visualization, writing – original draft, writing – review and editing. **Xiao-Yan Zhang:** writing – review and editing. **Yi-Gang Song:** writing – review and editing. **Shook Ling Low:** writing – review and editing. **Shu-Mei Xiao:** writing – review and editing. **Shi-Shun Zhou:** investigation, writing – review and editing. **Lang Li:** investigation, writing – review and editing. **Yun-Hong Tan:** investigation, writing – review and editing. **Hong-Hu Meng:** conceptualization, investigation, resource, supervision, project-administration, data curation, funding acquisition, writing – original draft, writing – review and editing. **Jie Li:** conceptualization, resource, supervision, project-administration, funding acquisition, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support this study are available in the Supporting material of this article.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.