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CLIMATE-DRIVEN RANGE SHIFTS THREATEN KEYSTONE ENDEMIC FIGS OF JAVA: COMPLEMENTING IUCN RED LIST ASSESSMENT WITH SPECIES DISTRIBUTION MODELLING TO GUIDE CONSERVATION PRIORITIES

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ABSTRACT

RISNA, R. A., LUGHADHA, E. N., PRASETYO, L. B., SUTOMO, AIDI, M. N., BUCHORI, D., PLUMMER, J., LATIFAH, D., YUSWANDI, A. Y. & YUDISTIRA, A. I. 2026. Climate-driven range shifts threaten keystone endemic figs of Java: complementing IUCN Red List assessment with species distribution modelling to guide conservation priorities. *Reinwardtia* 25(1): 49–63. — This study evaluates the extinction risk and climate-driven habitat dynamics of two endemic figs of Java, *Ficus trachycoma* Miq. and *F. miqueliana* C.C.Berg. Both species are poorly known, with no confirmed field records for more than six decades. Conservation status was assessed under IUCN Red List criteria, with extent of occurrence (EOO) and area of occupancy (AOO) calculated using validated herbarium records. *Ficus trachycoma* is restricted to a single 19th-century locality, with an EOO and AOO of 4 km², a single known location, and continuing decline in habitat, qualifying it as Critically Endangered. *Ficus miqueliana* has been more widely recorded, with an AOO of 20 km² and an EOO of about 600 km², ≤5 locations, and continuing decline in habitat, meeting the thresholds for Endangered. Species distribution modelling using MaxEnt and CMIP6 climate projections (SSP2-4.5 and SSP5-8.5) was applied to predict current and future habitat suitability. The models performed with high accuracy (AUC = 0.912–0.935, TSS = 1.0) and identified slope (52–73% contribution), temperature seasonality, and precipitation in the wettest, warmest, and coldest quarters as key predictors of occurrence. *Ficus miqueliana*'s current suitable habitat is 16,233 km² (12.4% of Java) in fragmented lowland, and foothill forests. CMIP6 projections (MIROC6, SSP2-4.5/SSP5-8.5 for 2050s and 2090s) forecast net contractions with upslope shifts: mid-century losses of 9–11% in Java, late-century persistence in montane refugia under moderate emissions but severe fragmentation under high emissions. These findings demonstrate that both endemic figs are highly vulnerable to environmental change. Applying IUCN Red List assessments alongside species distribution modelling provides a replicable framework for evaluating extinction risk in data-limited species and identifies priority areas for climate-adaptive conservation planning on Java.

Key words: Climate change, connectivity, extinction risk, habitat suitability, MaxEnt.

ABSTRAK

RISNA, R. A., LUGHADHA, E. N., PRASETYO, L. B., SUTOMO, AIDI, M. N., BUCHORI, D., PLUMMER, J., LATIFAH, D. & YUSWANDI, A. Y. 2026. Pergeseran jangkauan akibat perubahan iklim mengancam jenis penting tumbuhan ara endemik Jawa: melengkapi penilaian IUCN Red List dengan pemodelan sidtribusi jenis sebagai petunjuk prioritas konservasi. *Reinwardtia* 25(1): 49–63. — Penelitian ini mengevaluasi risiko kepunahan dan dinamika habitat akibat perubahan iklim pada dua jenis ara endemik Jawa, *Ficus trachycoma* Miq. dan *F. miqueliana* C.C.Berg. Kedua jenis ini kurang dikenal, tanpa catatan lapangan terkonfirmasi selama lebih dari enam dekade. Status konservasi dinilai menggunakan kriteria *IUCN Red List*, dengan perhitungan *extent of occurrence* (EOO) dan *area of occupancy* (AOO) berdasarkan data herbarium yang tervalidasi. *Ficus trachycoma* dijumpai terbatas pada satu lokasi dengan AOO dan EOO 4 km², dan menerusnya penurunan kualitas habitat, sehingga memenuhi kriteria Kritis (Critically Endangered). *Ficus miqueliana* menempati AOO 20 km² dan EOO sekitar 600 km² pada ≤5 lokasi dan terjadinya degradasi habitat sehingga memenuhi kriteria Terancam (*Endangered*). Pemodelan distribusi *F. miqueliana* menggunakan MaxEnt dan proyeksi iklim CMIP6 (SSP2-4.5 dan SSP5-8.5) diterapkan untuk memprediksi kesesuaian habitat saat ini dan masa depan. Model menunjukkan akurasi tinggi (AUC = 0,912–0.935; TSS = 1.0) dan mengidentifikasi kemiringan lereng (kontribusi 52–73%), musim, suhu, serta curah hujan pada kuartal terbasah, terpanas, dan terdingin sebagai prediktor utama keberadaan. Habitat yang sesuai bagi *Ficus miqueliana* saat ini mencakup 16.233 km² (12,4% dari Jawa), terutama pada hutan dataran rendah dan kaki bukit yang terfragmentasi. Proyeksi CMIP6 (MIROC6, SSP2-4.5/SSP5-8.5 untuk pertengahan dan akhir abad ke-21) memperkirakan kontraksi dengan pergeseran ke arah pegunungan: kehilangan habitat pada pertengahan abad hingga 9–11% dari Jawa, serta keberlanjutan di refugia montana pada emisi moderat namun fragmentasi parah pada emisi tinggi. Temuan ini menegaskan kerentanan tinggi jenis terhadap perubahan lingkungan. Penggunaan asesmen IUCN Red List dengan pemodelan distribusi jenis memberikan kerangka kerja yang dapat direplikasi untuk mengevaluasi risiko kepunahan pada jenis dengan data terbatas, serta mengidentifikasi area prioritas bagi perencanaan konservasi adaptif iklim di Jawa.

Kata kunci: Konektivitas, MaxEnt, pemodelan kesesuaian habitat, perubahan iklim, risiko kepunahan.

INTRODUCTION

The genus *Ficus* L. (Moraceae) is one of the most ecologically significant and taxonomically diverse plant groups in tropical ecosystems, comprising *ca.* 900 species worldwide (POWO, 2024), of which at least 367 species are distributed across the Malesia region (Berg *et al.*, 2006). Indonesia, particularly the island of Java, is a biogeographic hotspot for *Ficus* diversity, hosting 75 species (Berg *et al.*, 2006; Yusuf, 2011) with two confirmed Java endemics: *Ficus miqueliana* C.C.Berg and *F. trachycoma* Miq. These species are known only from historical herbarium records, with no confirmed wild observations for over six decades (GBIF, 2022a; 2022b). Their restricted distribution and long absence from field surveys raise urgent questions about their current status and vulnerability to environmental change.

Ficus, or figs, is widely recognized as a keystone resource in tropical forests due to its asynchronous fruiting phenology, which supports a diverse assemblage of frugivores and pollinators throughout the year (van Vankelburg & Bunyapraphatsara, 2002; Chantarasuwan, 2014; Mackay *et al.*, 2018). Recent studies reaffirm their ecological centrality in both natural and urban landscapes. *Ficus* species provide essential food resources for 54 frugivore species in the Pakke Wildlife Sanctuary, India, highlighting their critical role in sustaining frugivore populations (Gogoi *et al.,* 2023). *Ficus* also plays a crucial role in maintaining biodiversity and microclimatic stability in urban green spaces in Bogor, West Java (Peniwidiyanti *et al.*, 2022). The loss of such species can disrupt ecological networks and impair forest regeneration, particularly in ecosystems where anchor trophic networks are present. Fragmentation in tropical forests can lead to the breakdown of plant-animal mutualism, reducing ecosystem resilience and regeneration capacity (Marjakangas *et al.,* 2020). These disruptions are espe-

Table 1. Occurrence data of *F. miqueliana* and *F. trachycoma* from the Global Biodiversity Information Facility (GBIF) database.

No.	Collector names	Codes	Locations	Years	Coordinates	Remarks
Ficus miqueliana C.C.Berg						
1	Koorders SH	24612*	Banyumas, Central Java	No data	-7.52 S 109.28 E	*ca*. 1898–1900
2	Koorders SH	9380	Ngebel, Madiun, East Java	1896	-7.63 S 111.52 E	Wood sample
3	Koorders SH	9380*	Ngebel, Madiun, East Java	1896	-7.63 S 111.52 E	Herbarium sheets
4	Koorders SH	38811B	Ngebel, Madiun, East Java	1896	-7.79 S 111.62 E	Wood sample
5	Koorders SH	38811B	Ngebel, Madiun, East Java	1896	-7.79 S 111.62 E	Herbarium sheets
6	Koorders SH	20669B	Besuki, East Java	1889	-7.75 S 113.68 E	Herbarium sheets
7	Koorders SH	38773B	Ngebel, Madiun, East Java	1900	-7.79 S 111.62 E	Herbarium sheets
8	Jacob, M.	4818*	Mt. Raung, Besuki, East Java	1957	-8.25 S 114.08 E	Herbarium sheets
9	Jacob, M.	4841	Mt. Raung, Besuki, East Java	1957	-8.25 S 114.08 E	Herbarium sheets
10	Jacob, M.	4834	Mt. Raung, Besuki, East Java	1957	-8.25 S 114.08 E	Herbarium sheets
11	Jacob, M.	4834	Mt. Raung, Besuki, East Java	1957	-8.25 S 114.08 E	Herbarium sheets
12	Jacob, M.	4834	Mt. Raung, Besuki, East Java	1957	-8.25 S 114.08 E	Extra herbarium sheets
Ficus trachycoma Miq.						
1	Teysmann	-	Bogor	1860	No data	Collected from Hortus Botanicus Bogoriense
2	Zollinger	456	Mt. Gede	No data	No data	Holotype at National Herbarium Nederland

cially pronounced for endemic taxa with narrow ecological niches, which face heightened extinction risks under combined pressures of habitat loss and climate change (Tejedor-Garavito *et al.*, 2015; Urban, 2015).

Assessing the conservation status of species is essential for safeguarding biodiversity and guiding conservation priorities, particularly under the Convention on Biological Diversity's Global Strategy for Plant Conservation (Sharrock *et al.*, 2018; IUCN Standards and Petitions Committee, 2024). Extinction risk, quantified through standar-dized criteria, has revealed that nearly half of all tree species may be threatened globally due to their relatively limited ecological range and exposure to human pressure (Silva *et al.,* 2022; Bachman *et al.,* 2024). Additionally, endemic plant species and those known from few occurrence records are typically more threatened than widespread species (Jose, 2025), highlighting the urgency of integrating spatial modelling into conservation planning for these vulnerable taxa. Within the genus *Ficus*, where approximately 66.26% (487 species) of species have assessment on the IUCN Red List of Threatened Species, with 82 currently listed as threatened (IUCN, 2024). However, no formal assessment exists for the Javan endemics *F. miqueliana* C.C.Berg and *F. trachycoma* Miq., despite their ecological importance and paucity of occurrence records.

To strengthen conservation evaluations, species distribution modelling (SDMs) can provide spatially explicit insights into habitat suitability and potential range shifts under climate change scenarios. While more widely applied to data-rich species, SDMs can also prove valuable when applied to rare, data-sparse species, enabling researchers to integrate occurrence records with environmental predictors to identify priority areas for conservation and anticipate future risks (Qazi *et al.*, 2022; Rathore & Sharma, 2023).

Therefore, this study aims to 1) assess the conservation status of *F. miqueliana* and *F. trachycoma* under the IUCN categories and criteria, 2) model the current and future habitat suitability of *F. miqueliana* under climate change scenarios, 3) identify potential shifts and refugia, and 4) provide evidence-based recommendations for these Javan endemic figs.

MATERIALS AND METHODS

Study Site

This study covers Java Island, Indonesia, which is located between 5°50′- 8°30′S and 105°15′- 114°30′E (Fig.1) with a total area of approximately 132,523 km^2. The island has an altitudinal range from sea level to 3,676 m asl., with mountains stretching from west to east in the central part of the island. Many of these mountains are volcanoes. Lowland areas are primarily situated in the northern and southern parts of the island. The general land use is categorized as forests, settlements, agriculture, industrial and infrastructure areas, but Setiawan & Yoshino (2014) detailed it into 25 classes including forest. The remaining terrestrial forest area is estimated to be around 12,000 km^2 and mostly situated at high altitude in 2005 (Prasetyo *et al.,* 2009), but continuing to decline during the last two decades, especially in East Java Province (Global Forest Watch, 2023). The study was carried out from December 2023 to December 2024.

Species Data Collection

Occurrence records of *F. miqueliana* and *F. trachycoma* were obtained from the Global Biodiversity Information Facility global database (GBIF.org, 2022a). Records were filtered to remove duplicates and occurrences of cultivated specimens. Each occurrence point was georeferenced using QGIS 3.28.4 (QGIS Development Team, 2023). Location names were validated using Geonames (GeoNames, 2022), whilst accepted species names were checked using the World Checklist of Vascular Plants (WCVP) database on Plants of the World Online (POWO, 2024). A herbarium study was also conducted at Herbarium Bogoriense (BO), National Research and Innovation Agency (BRIN).

Projecting Deforestation and its Impact on Habitat

To assess the potential impact of deforestation on the habitat of *F. miqueliana*, a species assumed to be forest-dependent, we conducted a spatial analysis of forest cover change. All geoprocessing and spatial modeling were performed using QGIS software v.3.38 (QGIS Development Team, 2023).

The primary analysis involved projecting future forest cover and evaluating its effect on species habitat. First, we utilized the MOLUSCE (Modeling Land Use and Surface Coupled Environment) plugin within QGIS to model forest cover change for the years 2050 and 2090 across Java. The model was calibrated using historical land cover data from MAPBIOMAS Collection 4.0 (Mapbiomas, 2025) and several predictor variables. These variables included human population density data on WorldPop hub (WorldPop, 2025) and Euclidean distances to rivers, roads, and built-up areas, the latter of which were derived from OpenStreetMap data (OSM, 2025). The resulting land cover projections were then reclassified into a binary schema of 'forest' and 'non-forest' to delineate potential areas of forest loss.

Subsequently, to quantify the impact on *F. miqueliana*, we intersected the projected forest loss maps with the species' potential habitat map. This intersection identified specific areas of "suitability contraction"—locations where suitable habitat is projected to be lost due to deforestation. Finally, to evaluate the vulnerability of these habitats within protected zones, the suitability contraction maps were clipped using the official conservation area boundary map from the Sistem Informasi Geospasial Kementerian Lingkungan Hidup dan Kehutanan (SIGAP) (Kementerian Kehutanan RI, 2024). This final step yielded a spatially explicit quantification of projected suitable habitat loss within the designated conservation areas of Java.

Complementarity with Red List Assessment

The species distribution modelling approach was selected to complement the IUCN Red List conservation status assessment. While bioclimatic modelling techniques are acceptable to inform Red List assessments, their direct use for creating the official distribution map or calculating the key metrics of Extent of Occurrence (EOO) and Area of Occupancy (AOO) is not permitted (IUCN Standards and Petitions Committee, 2024). Therefore, our modelling results are intended to provide complementary information on potential habitat shifts and threats, which can inform qualitative assessments of a species' long-term viability, rather than to replace the standard IUCN mapping and quantification protocols.

RESULTS

Conservation status assessment

Ficus miqueliana is known from historical collections dating from 1896 (S. H. Koorders) through 1957 (Banyumas, Central Java), with no confirmed recent field reports. From the ini-

Table 2. Summary of model evaluation under multiple climate scenarios.

Models	AUC	TSS
Current	0.912	1.0
SSP2-4.5 (2041 – 2060)	0.929	1.0
SSP5-8.5 (2041 – 2060)	0.924	1.0
SSP2-4.5 (2081 – 2100)	0.935	1.0
SSP5-8.5 (2081 – 2100)	0.921	1.0

tial retrieval of 12 records from the GBIF database (Table 1), subsequent filtering to remove duplicates and specimens cultivated in botanic gardens yielded three unique georeferenced points. These three records represent distinct threat-defined locations across East and Central Java. Based on Criterion B of the IUCN Red List, the species meets the following quantitative thresholds: the Area of Occupancy (AOO) was calculated as 20 km^2 and the Extent of Occurrence (EOO) was estimated at 600 km^2. Thus, *F. miqueliana* qualifies for the Endangered (EN) category under criteria B1 (EOO < 5,000 km^2) and B2 (10 km^2 < AOO <500 km^2), and sub-criterion (a) (≤ 5 locations), and sub-criteria (b)(iii) (continuing decline in habitat quality).

Ficus trachycoma is known from a single herbarium record collected in 1864 from Cibodas, Mount Gede, West Java. When restricted to a single historical collection, assigning a data-adequate extinction risk category is challenging. However, close scrutiny of the specimen label limits the collection locality to an area within +/- 275 m elevation of the Cibodas Botanic Garden. Taking a precautionary approach, as recommended by IUCN standards (IUCN Standards and Petitions Committee, 2022), the species is assumed to be severely restricted and may not occur naturally at less-disturbed, higher elevations on Mt. Gede volcano. Based on this extreme limitation and plausible threat, the species is proposed as Critically Endangered (CR) under criteria B1ab (iii)+2ab(iii). This assessment was supported by estimates for EOO and AOO of 4 km^2 which meet thresholds for CR under criterion B1 (EOO < 100 km^2), and B2 (AOO < 10 km^2), respectively, and sub-criteria a (one location) and b(iii) (continuing decline in habitat).

Habitat suitability modelling

Model evaluation and predictive performance

Species distribution models (SDMs), particularly those using presence-only algorithms such as MaxEnt, require a minimum number of occurrence records to produce statistically robust and ecologically meaningful predictions. In the case of *F. trachycoma,* which has only one known occurrence point, modelling its potential distribution is not feasible due to insufficient environmental representation. A single occurrence point cannot capture the environmental breadth or niche of the species, leading to unreliable or biased predictions. According to van Proosdij *et al.* (2016) SDMs should not be attempted for species with fewer than three records, especially for narrowly-distributed species, and even greater numbers of records are required for such species in certain biomes (Sampaio & Cavalcante, 2023). Therefore, *F. trachycoma* was excluded from modelling to maintain methodological integrity and avoid unsupported spatial extrapolation; only *F. miqueliana* can be modeled for current and future distribution.

MaxEnt evaluation models (Table 2) exhibited excellent discriminatory performance across climate scenarios, with AUC values ranging from 0.912 (current) to 0.935 (SSP2-4.5 2081–2100) and consistent TSS=1.0. Although these results indicate perfect threshold-independent discrimination, careful interpretation is required. Slope was identified as the dominant predictor contributing the distribution of *F. miqueliana*'s distribution across climate scenarios (Table 3). Slope consistently contributed to each scenario (25.8–72.8%), with permutation importance reinforcing its role (up to 52.4%). Temperature seasonality (BIO4) and precipitation variables in wettest, warmest, and coldest quarters (BIO16, BIO18, BIO19, respectively) emerged as secondary drivers, peaking at 30% contribution in SSP2-4.5 in 2041–2060 and notable permutation values, while isothermality (BIO03) and topographic aspect showed scenario-specific influence up to 28.5%. Model performance underscored these variables' independent explanatory power, with soil factors (BD, OCD, SOC) exhibiting negligible effects throughout. Precipitation in driest quarter (BIO17) consistently contribute negligibly.

Table 3. MaxEnt modelling results.

Environmental variables	Percent contribution					Permutation importance				
	Current	SSP2-4.5 (2041–2060)	SSP5-8.5 (2041 –2060)	SSP2-4.5 (2081–2100)	SSP5-8.5 (2081–2100)	current	SSP2-4.5 (2041 –2060)	SSP5-8.5 (2041 –2060)	SSP2-4.5 (2081–2100)	SSP5-8.5 (2081–2100)
BIO03 (isothermality)	0	0	0	9.1	0	0	0	0	0	0
BIO04 (temperature seasonality)	0.5	29.8	3.8	39.4	3.5	0	37.7	16.9	44.3	7.9
BIO16 (Precipitation of Wettest Quarter)	0.1	4.8	0	0	0	0	26.7	29.9	0	28.7
BIO17 (Precipitation of Driest Quarter)	0	0	0	0	0	0	0	0	0	0
BIO18 (Precipitation of Warmest Quarter)	0	0	0	24.0	0	0	0	0	43.7	0
BIO19 (Precipitation of Coldest Quarter)	13.2	0	8.4	0	20.9	19.1	0	9.3	0	28.1
Aspect	15.2	9.9	14.9	1.6	12.7	28.5	3.2	9.8	0	13.1
Slope	71.1	55,5	72.8	25.8	62.9	52.4	32.5	34.1	12	22.2
BD (Bulk density)	0	0	0	0	0	0	0	0	0	0
OCD (Organic Carbon Density)	0	0	0	0	0	0	0	0	0	0
SOC (Soil Organic Carbon)	0	0	0	0	0	0	0	0	0	0

Current and future habitat suitability projection

The MaxEnt model for current bioclimatic condition predicts a highly fragmented distribution of suitable habitat for *F. miqueliana* across Java (Fig. 1). Across the island, suitable habitat is concentrated in the following ecological zones: humid lowland forests of West Java, foothill zones of Central Java, and southern montane slope of East Java. These areas are characterized by a stable temperature regime and low temperature seasonality, aligning with the species' known ecological preferences.

Under current conditions, the suitable habitat of *F. miqueliana* comprised approximately 16,233 km² (12.4% of the total 131,302 km² of Java Island), predominantly absent from 115,069 km² (Table 4; Fig. 2). The suitable habitat was concentrated in lowland and foothill forests. This baseline supports the characterization of *F. miqueliana* as a low- to mid-elevation endemic fig. The modelling results indicated that the species is sensitive to future climate trajectories, with marked differences between moderate (SSP2-4.5) and high-emission (SSP5-8.5) scenarios across Java (Table 4; Fig. 3).

Future projections indicated net contractions. By mid-century (2041–2060 or 2050s), both scenarios project substantial reductions in suitable habitat. Under SSP2-4.5, the suitability habitat was reduced to 11,974 km² (9.0% of the total Java Island), with the range contracted to 4,439 km² and only 6,747 km² of expansion. This indicates a net decline and moderate contraction, with habitat shifting upslope. A similar contraction occurs under SSP5-8.5, where the suitable area decreases to 13,820 km² (10.5%), coupled with 4,104 km² expansion and minimal contraction among scenarios (2,413 km^2).

By the late century (2081–2100 or 2090s), trajectories diverge sharply. Under SSP2-4.5, *F. miqueliana*'s suitable habitat covered only 9,058 km² (6.9%), with severe but relatively balanced between contraction and expansion (7,175 and 7,612 km^2, respectively). In contrast, SSP5-8.5 projected minimum expansion (2,915 km^2), maintained 12,764 km² (9.7%) remaining suitable. The model predicts persistence only in isolated montane patches, severe-

Table 4. Size of predicted habitat transition summary (km^2).

Scenario	Present	Contraction	Expansion	Absent	Spatial trend
Current climate	16,233	-	-	115,069	Lowland and foothill habitats.
SSP2-4.5 (2041-2060)	11,794	4,439	6,747	108,322	Upslope shift to montane zones
SSP2-4.5 (2081-2100)	9,058	7,175	7,612	107,457	Continued upslope shift with increased fragmentation
SSP5-8.5 (2041-2060)	4,439	2,413	4,104	110,965	Initial upslope shift with fragmentation
SSP5-8.5 (2081-2100)	12,764	3,469	2,915	112,154	Severe contraction to isolated montane refugia

ly reducing connectivity and elevating extinction risk.

Figure 4 visualizes the spatial overlap between forest loss-driven habitat contraction for *Ficus miqueliana* and designated conservation areas across Java under different climate scenarios. The maps delineate areas of habitat contraction due to forest loss (brown), persistent suitable and unsuitable habitat (green), with conservation area boundaries (*e.g.* national parks) clearly demarcated. The visualization demonstrates that habitat contraction occurs within designated protected zones, indicating that forest loss compounds climate-induced habitat reduction. The spatial extent of contraction varies across scenarios, with notable fragmentation visible in both SSP2-4.5 and SSP5-8.5 projections, particularly in lowland and foothill regions.

In 2050s, low emission SSP2-4.5 (Fig. 4A) model shows habitat contraction due to forest loss is most severe in western and central Java conservation area. In contrast, SSP5-8.5 with high emission (Fig. 4B) shows more fragmented loss with smaller, scattered patches of contraction in the same regions, suggesting reduced pressure on protected habitats under extreme warming climate. By the 2090s, SSP2-4.5 indicates worse habitat contraction across central and eastern Java protected areas (Fig. 4C), while the high emission SSP5-8.5 (Fig. 4D) shows more moderate habitat contraction. In this period, habitat suitability contraction outside PA boundaries was also extensive that need strong conservation measures against deforestation. These findings imply that current protected areas (PA) are insufficient and require a dual, scenario-specific strategy. Under SSP2-4.5 pathway, the extensive and contiguous habitat suitability loss within PAs signals an immediate need for enhanced in-situ protection.

DISCUSSION

Conservation Status of Javan Endemic Figs

The proposed conservation statuses of *F. miqueliana* (Endangered) and *F. trachycoma* (Critically Endangered) highlight the high degrees of extinction risk faced by Javan endemic figs. *Ficus miqueliana* is threatened by ongoing habitat loss and the future impacts of climate change. The status of *F. trachycoma* is more challenging to ascertain on account of record scarcity, however, several lines of evidence may be used to infer habitat loss and a highly restricted distribution. The threat of agricultural and settlement expansion in the immediate vicinity of the Cibodas Botanic Garden is taken as evidence for its restriction to a single threatened location. Additionally, given the proximity of the type collection to a major botanic garden, the prolonged absence of collections over the intervening 150+ years suggests that this plant is likely very rare, if indeed it is still present in the vicinity of the type locality. Therefore, these conditions warrant immediate field verification to identify any remaining populations and to implement precautionary protection measures to prevent the potential loss of this species before it can be better understood and conserved.

The assessment of these two species underscores critical conservation concerns for Java's endemic flora. The diagnosis of restricted distribution, few known locations, and ongoing habitat degradation suggests a pervasive pattern of population decline, consistent with documented trends for other range-restricted tropical trees (Tejedor-Garavito *et al.,* 2015, Bachman *et al.,* 2024). As keystone species, the potential extinction of these figs could severely disrupt ecological networks, particularly fig-frugivore interactions that are vital for

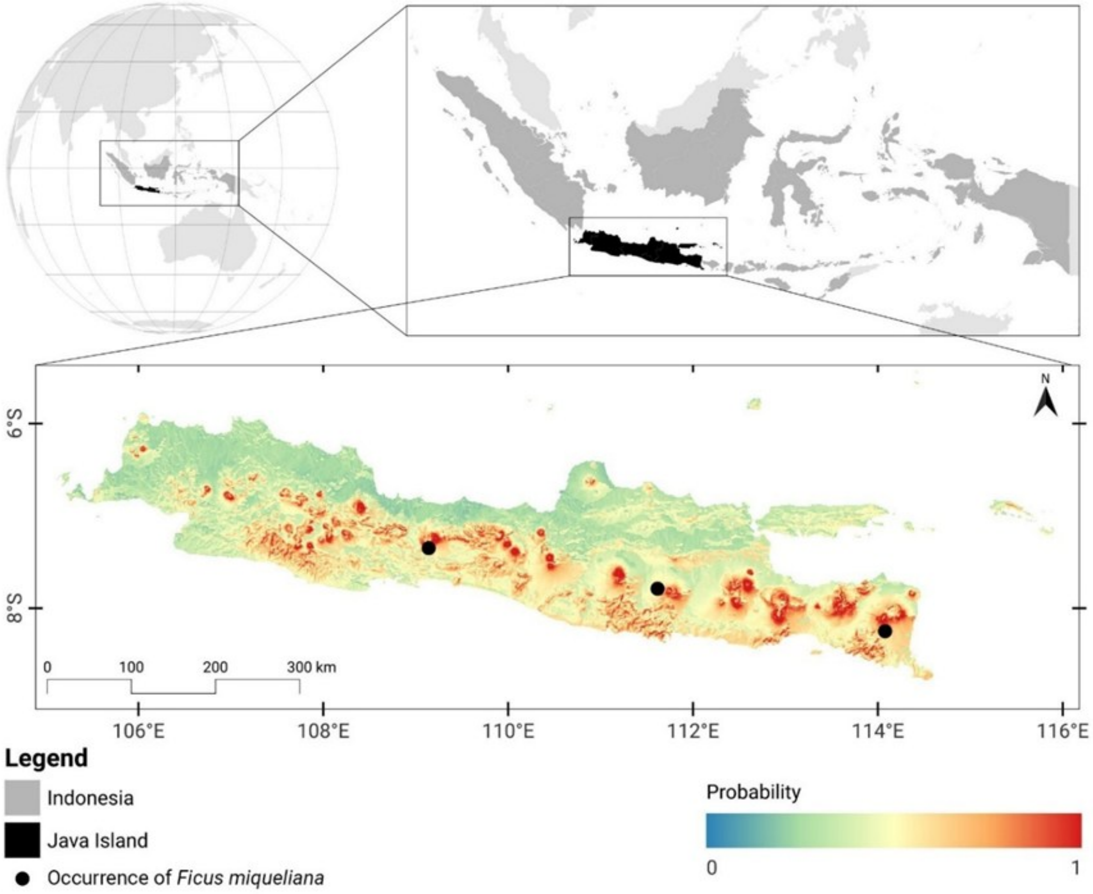

Fig. 1. Predicted habitat suitability of *Ficus miqueliana* in current bioclimatic condition.

sustaining forest regeneration (Marjakangas *et al.,* 2020). Therefore, the assessed status for both species warrants formal inclusion in national threatened species lists and demands the immediate implementation of precautionary protection measures.

Environmental Drivers

The dominance of slope as the primary predictor (52–73% contribution) in MaxEnt models aligns with its role in modulating microclimatic stability, soil drainage, and erosion resistance, thereby shaping habitat suitability for forest species across current and future SSP scenarios. Slope influences microclimatic conditions critical to plant growth by affecting sunlight exposure, water retention, and soil stability, in which topographic gradients explained substantial distributional variance in heterogeneous landscapes (Liao *et al.*, 2025). Our findings, which identify temperature seasonality (bio4) and precipitation metrics of the warmest and coldest quarter (bio18, bio19) as important drivers, are consistent with Prasetyo *et al.* (2022). They also found these same variables to be among the most important predictors for teak growth on Java, underscoring the overarching influence of seasonal climate dynamics on species distribution in the region. Temperature seasonality captures thermal variability constraining phenological cycles. At the same time, precipitation of the wettest, warmest, and coldest quarters defines hydrological niches, with permutation importance highlighting their scenario-specific gains in predictive power (Li *et al.*, 2024). The inclusion of all uncorrelated variables, despite negligible contributions from soil factors (BD, OCD, SOC), follows established MaxEnt protocols to capture comprehensive ecological niches, mitigate overfitting risks from post-hoc exclusion, and enable robust validation of independent predictor effects, as premature filtering may omit subtle interactions or future scenario relevance.

Future Range Shifts and Vulnerability Under Climate Change

Ficus miqueliana's future suitable habitat declines 10–43% across SSP scenarios relative to current baselines, driven by topographic-climatic mismatches amplifying contraction over expansion. This result is consistent with MaxEnt's slope and temperature seasonality dominance under warming trajectories. SSP2-4.5's steeper losses by

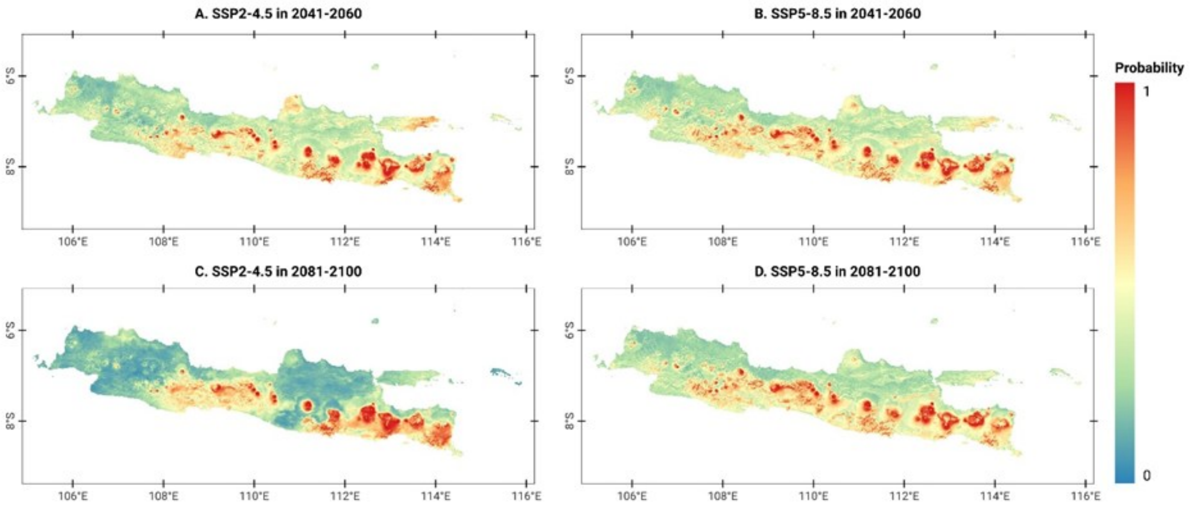

Fig. 2. Predicted future habitat probability of *F. miqueliana* in Java under different climate change scenarios: A) SSP2-4.5 in 2041–2060; B) SSP5-8.5 in 2041–2060; C) SSP2-4.5 in 2081–2100; D) SSP5-8.5 in 2081–2100.

2090s signaled moderate emissions' delayed impacts on niche stability, whereas SSP5-8.5's relative stability underscores high-emission resilience via expanded margins, though net contractions highlight vulnerability in rugged terrain (Liao *et al.*, 2025). The spatial trend toward montane zones also aligns with established elevational migration patterns observed in plant species (Chen *et al.*, 2012). These range shifts strongly suggest that refugia should be mapped with a view to assisted migration; however, any such conservation interventions must be implemented with caution, taking into account the risk of model overfitting due to limited sample size (Radosavljevic & Anderson, 2014).

These climatic sensitivities have significant implications for the species' future under changing climate scenarios. The contrasting outcomes highlight that *F. miqueliana*'s persistence is contingent on emission pathways and habitat continuity. Moderate warming may facilitate upslope migration into montane refugia, echoing patterns in other tropical montane taxa (Feeley *et al.*, 2023). However, under high-emission scenarios, the species faces a combination of range collapse, habitat fragmentation, conditions often associated with elevated extinction risk in narrow-range tropical trees (Tejedor-Garavito *et al.*, 2015; Bachman *et al.*, 2024).

We highlighted the net present change in *F. miqueliana*'s habitat consistently declines across all scenario (Table 4). The gross values of habitat expansion range (2,915–7,612 km^2) compared to contraction (2,413–7,175 km^2) may indicates potential dispersal constraints, consistent with theoretical limitations on tropical plant migration rates (Corlett & Westcott, 2013). The projected fragmentation into isolated montane refugia raises concerns about genetic diversity loss and local extinction risk, particularly given the species' already restricted distribution (12.4% of the study area).

Looking forward, model outputs suggest that under moderate climate trajectories (SSP2-4.5), suitable habitat may expand upslope into montane refugia by the late century (Fig. 3). In contrast, under high-emission pathways (SSP5-8.5), the species faces severe contraction and fragmentation, with only small isolated patches persisting. This apparent "expansion" in the modeled scenarios does not imply natural recovery, as colonization of new areas depends on the species' dispersal capacity and the maintenance of habitat connectivity along elevational gradients. Consequently, the smaller historical EOO relative to the present predicted distribution may reflect a history of range decline. At the same time, future projections highlight that persistence will depend on rediscovery, the protection of remaining foothill and montane forests, and the establishment of ecological corridors that enable upslope migration. These findings highlight the urgency of precautionary conservation. The historical contraction of *F. miqueliana*, together with projected climate-driven range shifts, increases its extinction risk. Immediate action is needed to secure refugia and maintain elevational connectivity.

A direct comparison of paired scenarios reveals a counterintuitive pattern between emission severity and forest loss-driven habitat contraction. For

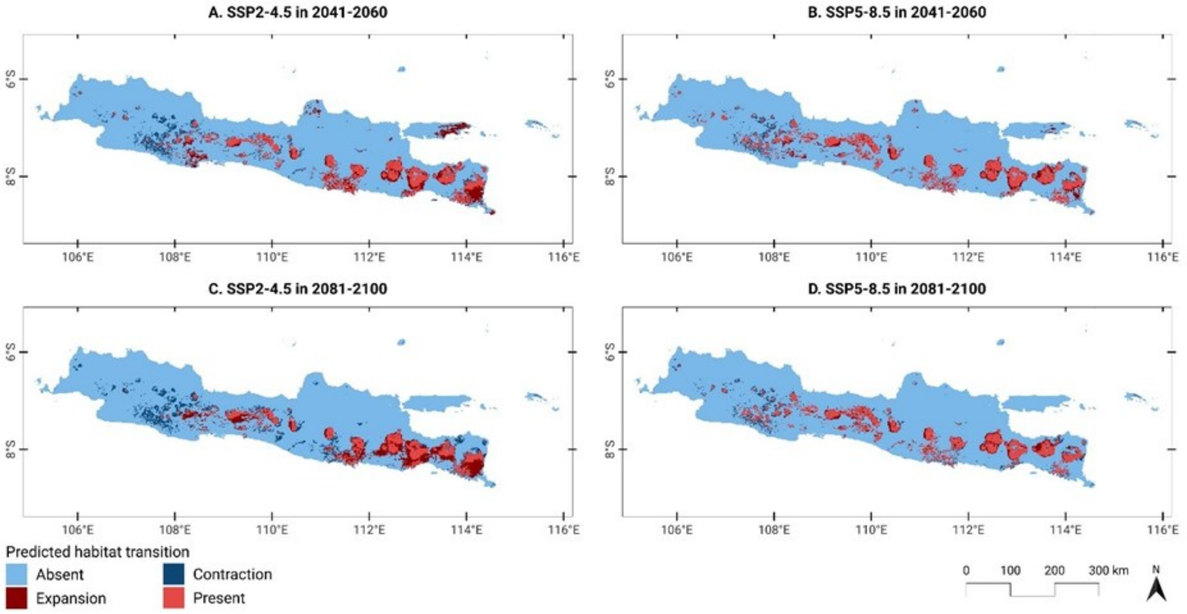

Fig. 3. Predicted habitat transition across climate scenarios in 2041–2060 and 2081–2100 compared to the current condition as baseline. Absent = no change in unsuitable habitat; contraction = suitable in the current became unsuitable in the future; expansion = unsuitable in current condition, became suitable in the future; present = no change in suitable habitat between current and future.

the 2041–2060 period (Fig. 4A *vs.* 4B), the high-emission SSP5-8.5 scenario projects less habitat contraction compared to the medium-emission SSP2-4.5 scenario. This trend persists into the 2081-2100 period (Fig. 4C *vs.* 4D), where SSP5-8.5 again shows lower contraction than SSP2-4.5. This discrepancy suggests that the relationship between climate warming and forest loss is not linear; the more extreme warming under SSP5-8.5 may lead to rapid vegetation shifts that initially reduce the rate of targeted forest loss within the species' specific niche, whereas the intermediate warming of SSP2-4.5 allows for prolonged human activities (*e.g.* selective logging, agriculture expansion) to degrade habitats gradually. The implication is that conservation efforts must consider that intermediate climate pathways may pose a more insidious threat through sustained, incremental habitat loss, rather than the abrupt changes associated with high-emission scenarios. This aligns with observations that gradual environmental change can facilitate more persistent and pervasive anthropogenic pressures (Barlow *et al.*, 2018).

Implications for Conservation

The spatial patterns presented in Fig. 4 corroborate the range shift trends detailed in Table 4, highlighting the synergistic threats of climate change and deforestation. The occurrence of habitat contraction within conservation areas underscores the limitations of static protected area boundaries in mitigating biodiversity loss under dynamic environmental change. The pronounced contraction in lowland protected areas aligns with the species' projected upslope shift, suggesting that current reserves may not encompass future suitable habitats. This spatial evidence reinforces the conclusion that forest loss intensifies climate-driven habitat fragmentation, emphasizing the critical need for integrated conservation strategies that address both deforestation and climate adaptation to ensure the long-term persistence of *Ficus miqueliana.*

From a conservation perspective, our modelling results underscore three urgent priorities. First, targeted field surveys are essential to verify extant populations and assess their elevational range, especially in predicted refugia zones. Second, protection of montane forests should be prioritized to secure future habitat, complemented by ex-situ measures such as seed banking to mitigate catastrophic loss. Third, maintaining connectivity across elevational gradients will be critical to facilitate upslope migration and ensure gene flow. Without such integrated measures, the species may face irreversible decline, particularly under high-emission scenarios where suitable habitat becomes fragmented and isolated.

Given the high extinction risk for both Javan endemic figs, an integrated, climate-adaptive conservation strategy must be implemented, addressing the dual pressure of habitat loss and climate change. This strategy is recommended on three complementary pillars. Firstly, an immediate field

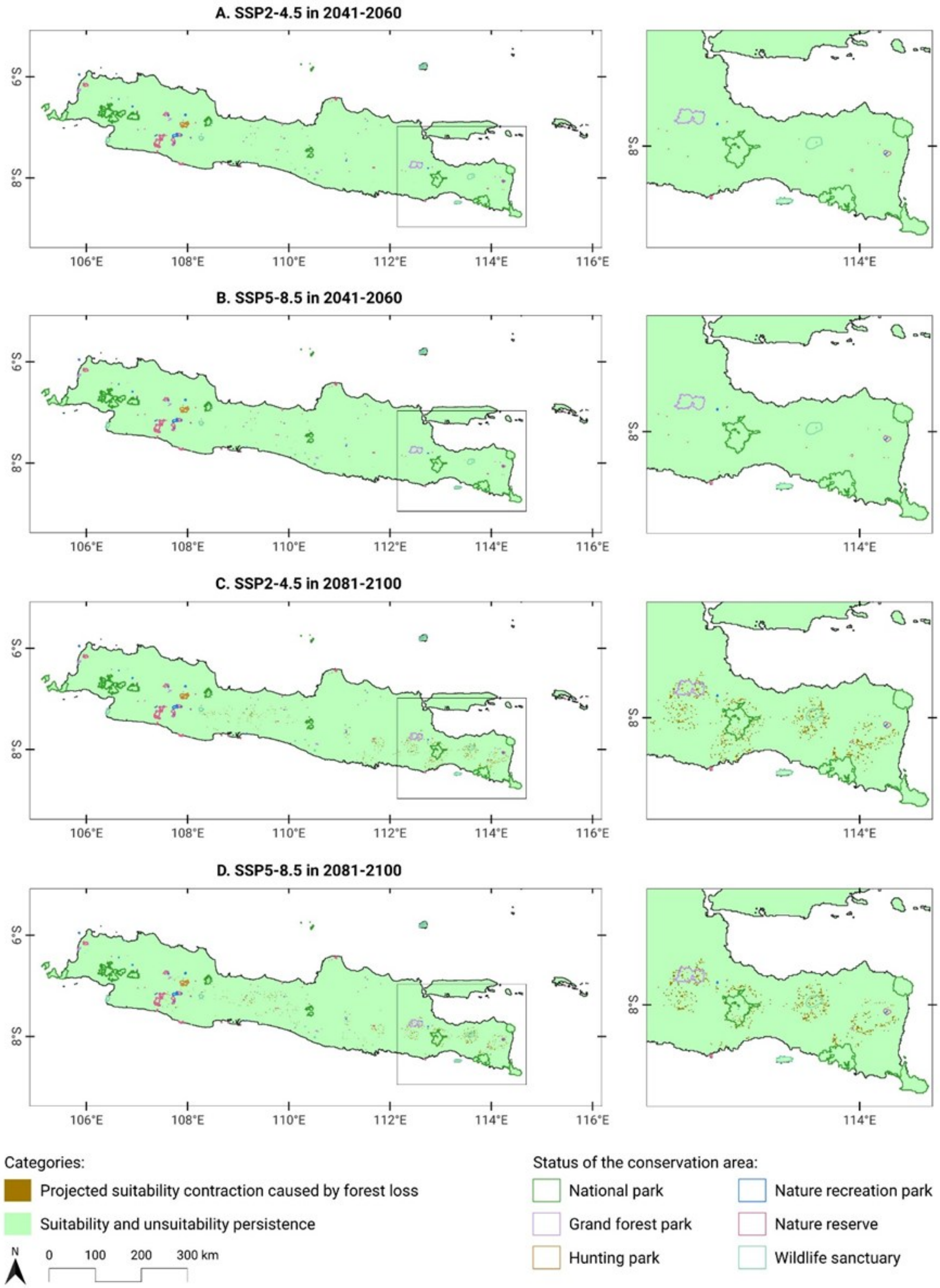

Fig. 4. *Ficus miqueliana*'s projected suitable habitat contraction caused by forest loss across conservation areas in Java.

verification and rediscovery programme is the highest priority. Targeted expeditions should prioritize climatically stable refugia predicted under the moderate emission scenario (SSP2-4.5, 2041–2060), where *F. trachycoma* may persist undetected and where *F. miqueliana* retains habitat continuity. These surveys will provide critical data on current population status, ecological requirements, and confirm the validity of model-identified refugia. Empirical work shows that SDM-guided surveys repeatedly improve detection efficiency and have led to rediscoveries or range extensions for rare taxa, making this the immediate operational priority (Sofaer *et al.,* 2019).

Secondly, an integrated ex-situ and in-situ protection must be established. For *F. miqueliana*, this involves formally designating current and projected refugia as key biodiversity areas for immediate in-situ protection. In parallel, ex-situ conservation measures – including seed banking, tissue culture, and other living collections – are essential to safeguard against catastrophic loss, especially under the high-emission pathway where the species is predicted to persist only in isolated montane fragments. The feasibility of this ex-situ approach is strongly supported by the biology of the *Ficus* genus; seeds of more than 50 fig species are known to be orthodox, making them highly suitable for long-term storage in seed banks (Anilkumar *et al.*, 2008; SER, INSR & RGBK, 2025). Seed banks and living collections are proven, cost-effective components of integrated conservation strategies and are essential when in-situ populations are fragmented or extremely small (Hoyle *et al.,* 2023).

Thirdly, a landscape-level management strategy is required. The predicted upslope migration underscores the need to maintain elevational connectivity across Java's fragmented forest landscapes. This involves management that extends beyond static protected areas, integrating buffer zones, ecological corridors, and restoration in production landscapes to facilitate dispersal and gene flow. Such an approach aligns with climate-adaptive conservation principles, which emphasize dynamic spatial planning in response to shifting species distributions. Evidence from Borneo demonstrates that proactively identifying and securing priority corridors can mitigate the combined pressures of warming and forest loss, underscoring the urgency of integrating connectivity into long-term conservation planning (Struebig *et al.,* 2024).

Model Limitations and Future Research

The primary limitation of this study stems from the scarcity of the species occurrence records, which restricts model reliability despite high AUC and TSS values. These metrics, derived from training data, may reflect overfitting rather than true predictive power, necessitating spatially independent validation such as block cross-validation. Reliance on a single GCM (MIROC6) – although having strong performance in Southeast Asia (Nguyen *et al.,* 2024) and discrepancies between contribution and permutation importance further constrain robustness. The mismatch between historical EOO and modeled distribution signals ongoing range contraction from habitat loss, as evidenced by forest cover decline in East Java (Global Forest Watch, 2023).

Future research should prioritize field surveys to expand occurrence data and validate projections, incorporating multi-model ensembles for greater reliability. To maximize conservation impact, we recommend for scaling this approach beyond single-species assessment. Extending analyses to co-occurring *Ficus* species or community-level of key plant functional groups – such as *Ficus* and other keystone taxa – across the entire Java or even multiple islands. Such landscape-scale analyses would be critical for identifying shared climate refugia and establishing interconnected conservation networks that enhance ecosystem resilience, moving from species-specific to biodiversity-centric conservation planning.

CONCLUSION

This study provides assessments of extinction risk for two endemic figs of Java: *Ficus trachycoma* Miq. and *Ficus miqueliana* C.C. Berg, under the IUCN Red List Criteria Version 3.1. *Ficus trachycoma* is confirmed to face the highest extinction risk, meeting the criteria for Critically Endangered CR B1ab(iii)+2ab (iii). *Ficus miqueliana* is assessed as Endangered EN B1ab(iii)+2ab(iii). These assessments emphasize the urgent need for conservation measures to prevent further decline.

Complementing the conservation assessments, the habitat suitability model for *F. miqueliana* demonstrated high predictive accuracy, identifying temperature seasonality and precipitation during the wettest, warmest, and coldest quarter as the primary niche drivers. Its current suitable habitat is highly fragmented, covering approximately 16,233 km² of lowland and foothill forests in Java. Future projections under CMIP6 scenarios reveal considerable range contraction, indicates a pronounced contraction, fragmentation, and upslope displacement of suitable habitat. Under moderate emissions scenarios (SSP2-4.5), the species may find refuge in montane areas, continued to upslope shift with increased fragmentation. High-emission scenarios (SSP5-8.5) predict severe contraction and isolation into small, fragmented patches, that increased extinction risk. Understanding this climatic sensitivity is critical for anticipating the species' response to future environmental changes.

Based on these findings, conservation efforts must prioritize the verification of extant populations, protection of climatically stable refugia, and maintenance of elevational connectivity to facilitate upslope migration. An integrated, evidence-based conservation strategy that includes in-situ protection, ex-situ measures such as ex-situ banking, and connectivity restoration is essential to safeguard these keystone endemics against compound climate and land-use threats.

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