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Species Distribution Modeling of *Ficus fistulosa* Reinw. ex Blume in Java, Indonesia Using a MaxEnt-Based Approach in the BCCVL–EcoCommons Platform

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ABSTRACT

Ficus fistulosa is a keystone species in tropical forests, playing a crucial role in ecosystem stability and biodiversity conservation. Comprehending its distribution pattern is crucial for effective conservation and management efforts. This study employs species distribution modeling (SDM) to predict the potential habitat of *F. fistulosa* in Java Island, Indonesia. The approach that was utilized included the collection of data on the occurrence and environmental conditions of *F. fistulosa*, the modeling of species distribution by the utilization of the maximum entropy algorithm (MaxEnt), and the evaluation of the accuracy of the model. We used climate data (temperature, precipitation) from WorldClim version 2.1. A total of 19 bioclimatic variables, identified as Bio1 to Bio19, were used. Future projections were generated using the Shared Socioeconomic Pathway (SSP585) scenario, representing a high-emission and fossil-fuel-intensive development trajectory. The bioclimatic variables for this scenario were obtained from the UKESM1-0-LL General Circulation Model (GCM) with a spatial resolution of 30 arc-seconds (~1 km²) via the EcoCommons climate dataset repository. The Area Under the Curve (AUC) value was employed to evaluate the reliability of the model produced. Model validation indicates high predictive performance, with key environmental variables such as precipitation, temperature seasonality, and elevation significantly influencing habitat suitability. The results highlight priority conservation areas and suggest that future land-use changes and climate variability may impact the species distribution. The area of highly suitable habitats will significantly decrease by the year 2100, especially in highland and hydrologically critical regions. Moderate suitable areas decrease to 14.3%, high suitability areas reduce to 25.6%, and very high suitability areas shrink to 8.6%. These findings offer significant insights for biodiversity conservation strategies and ecological management of *F. fistulosa* in Java Island. Integrating *F. fistulosa* into climate-adaptive restoration is essential for preserving biodiversity and enhancing ecosystem resilience.

1. INTRODUCTION

Indonesia possesses one of the largest areas of tropical forests in the world, harboring exceptionally high biodiversity and serving as a critical hotspot for global conservation. Although they occupy a relatively small fraction of Earth's surface (< 10%), tropical forests support an estimated two-thirds of global species richness [1]. The tropical forests of Indonesia provide habitat for numerous plant and animal species, many of which are endemic and essential for sustaining ecosystem equilibrium [2]. However, the tropical forest in Indonesia declined from 113,500 hectares in 2020-2021 to 104,000 hectares in 2021-2022. This represents an 8.4% decrease and marks a historical low for deforestation in Indonesia since tracking began in 1990 [3].

On the other hand, the decrease in the tropical forests in Indonesia was probably due to climate change. Climate change would alter temperature, precipitation, and habitat availability, which in turn impacts the survival, reproduction, and migration of species. Many species are forced to shift their ranges, while others face heightened risks of extinction due to habitat degradation and environmental inadequacy. Anticipating these changes is crucial for biodiversity conservation, ecosystem management, and the development of effective adaptation strategies. Climate change may pose a significant threat to global species biodiversity within the next century [4]. Tree species vary in their reactions to anticipated climate change. Species are adapting their phenology, behavior, morphology, and geographic distribution in response to climate change [4, 5]. The majority of the species would suffer a lot of suitable habitat area [6]. Climate change has caused species distributions to ascend to greater elevations

[7]. Many of these changes are associated with increased temperatures and reduced precipitation [8]. Thus, understanding and predicting the future distribution of species has become increasingly important in the context of global climate change.

The genus *Ficus* plays a crucial role in many tropical rainforest ecosystems and has been proven to be a keystone resource for both animals and populations [9-11]. *Ficus* fruit was identified as a vital source of food for frugivores [12-14]. *Ficus* trees may grow a lot of fruit all year round [15, 16]. The majority of plant species depend on frugivorous mammals for seed dispersion [17]. The frugivorous vertebrates that frequent fruiting *Ficus* trees include bats, birds, and monkeys [15, 18]. In addition to their advantages for animal life, *Ficus* trees could potentially function as more effective facilitators for forest restoration compared to other existing tree species in disturbed landscapes. *Ficus* trees facilitate the regeneration of plant communities that reflect the overall environment [19]. *Ficus* species considerably contribute to the preservation of the hydrological cycle, influencing the soil water content and soil capacity to retain water [20]. *Ficus* species are recommended for land rehabilitation in Kuningan Regency, Indonesia, due to their adaptability and contribution to soil restoration [21, 22].

Within the varied members of the genus, *Ficus fistulosa*, often known as *wilodo*, stands out as a species of significant ecological relevance in tropical montane forests. *F. fistulosa* serves as a keystone species in tropical montane forests due to its significant influence on the ecosystem. In Mount Merbabu, Indonesia, *F. fistulosa* grows at an altitude of 1,500-2,500 meters above sea level and is recommended as a restoration species [23, 24]. As a member of the Moraceae family, *F. fistulosa* is known for its vital role in maintaining biodiversity, especially as a food source for many frugivores, including birds and primates [13]. Additionally, *F. fistulosa* is recognized for its ability to store and regulate water, making it a crucial component in water retention areas. This characteristic is particularly beneficial in watershed areas and highland regions, where the species can play a key role in ensuring water availability to downstream ecosystems. The capacity of this species to retain water is not only important for maintaining soil moisture and reducing erosion but also for regulating hydrological cycles, contributing to flood control and groundwater recharge in surrounding lowland areas. The ability of *F. fistulosa* to endure in ecologically unfavorable conditions enables this species to serve as a restoration plant in the shrub area of Gunung Ciremai National Park, Indonesia [25]. *F. fistulosa* is also a promising candidate for the development of antivirals against HIV, Hepatitis C, diarrhea, diabetes, malaria, antioxidants, and antimicrobials in the context of herbal therapy [26-30].

Despite its ecological significance, *F. fistulosa* has become increasingly rare in the wild, especially on the densely populated island of Java. Habitat loss due to land-use changes, deforestation, and agricultural expansion has led to a rapid decline in its population, particularly in critical watershed areas. This decrease is troubling considering the species' function in sustaining environmental stability in these areas. The decreasing presence of *F. fistulosa* has prompted an urgent need for conservation efforts aimed at identifying suitable habitats that can support its recovery. Furthermore, understanding and predicting the future distribution of species has become increasingly important in the context of global climate change. It is also very important to anticipate these changes, which is crucial for biodiversity conservation, ecosystem management, and the development of effective adaptation strategies. One approach utilized for projecting the future distribution of species is species distribution modeling (SDM). SDM utilizes species occurrence data and environmental variables to assess the probable distribution of species under present and future climatic conditions [31].

In terms of *F. fistulosa*, SDM can be used to predict the map of potential habitats for *F. fistulosa* on Java Island, relating to the effects of climate change. Numerous research has examined the effects of climate change on the geographical distribution of native tree species through the application of species distribution models (SDM). For example, Islam et al. [32] created SDM using MaxEnt to predict the effect of climate change on the spatial redistribution of *F. benghalensis* and *F. hispida* in Bangladesh. Fungjanthuek et al. [33] constructed an SDM utilizing MaxEnt to evaluate habitat suitability and predict potential habitats of *F. squamosa* and *F. heterostyla* in China.

Given the importance of preserving this species for its ecological and hydrological functions, SDM offers a valuable approach to guide conservation efforts and habitat restoration initiatives [34]. By predicting areas where *F. fistulosa* could thrive, targeted actions can be taken to protect and restore suitable habitats, particularly in upland areas where the species can contribute significantly to the sustainability of water catchment areas. SDMs are the most common type of model used in ecology, evolution, and conservation. They can be used to guide conservation efforts and management strategies, prioritize conservation actions, assess the effects of global change, and figure out how environmental factors affect species responses [35, 36].

This study applies the SDM framework to explore the potential geographic distribution of *F. fistulosa* in Java. By combining ecological knowledge with predictive modeling, this research's objectives are (1) to simulate the current potential geographic distribution of *F. fistulosa* in Java, (2) to predict its future distribution under the SSP585 scenario in 2100, (3) to identify the key environmental factors influencing its distribution, and (4) to provide scientific recommendations for conservation planning.

2. RESEARCH METHODS

2.1 Species description

F. fistulosa is a tree that produces a nutritious fruit. The unripe fruits are green and brownish and have a spherical shape with some attenuation on the top and bottom. They are approximately the size of a thumbnail [16, 37]. *F. fistulosa* is an evergreen tree and has both male and female parts. The bark is dark brown. The stipules are 1–2 cm long and ovate-lanceolate. The leaves are arranged in an alternating pattern, and the petiole is 1.5 to 4 cm long. The leaves are hairy or hirsute, and the leaf blade is obovate to oblong, measuring 10-20 × 4-8 cm, papery, and has sparse pubescence or yellow tubercles on the abaxial side. Figs are on short, cone-shaped branchlets on the main branches. When they are ripe, they are reddish orange and about 1.5 to 2 cm in diameter. *F. fistulosa* is a species distributed in China, Taiwan, Bangladesh, Cambodia, Laos, Myanmar, Thailand, Vietnam, Malesia, Sumatra, Borneo, Lesser Sunda, Java, Philippines, Sulawesi, Papua, New Guinea [38]. Figure 1 presents the sketch of the

F. fistulosa herbarium.

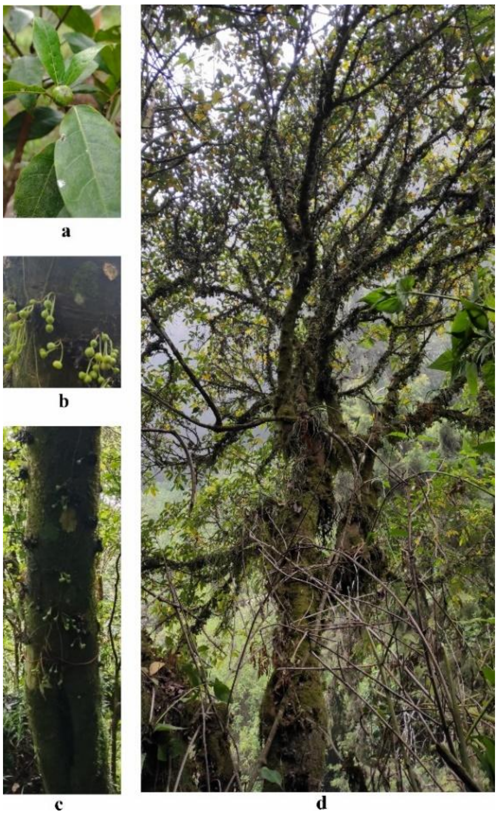


Figure 1. (a) leaves, (b) fruits, (c) trunk, and (d) trees of *F. fistulosa* Reinw. ex Blume

The SDM was conducted using the Biodiversity and Climate Change Virtual Laboratory (BCCVL)-EcoCommons platform (www.ecocommons.org.au), which integrates the MaxEnt algorithm under a standardized configuration framework [39]. The SDM employed occurrence data from the field and geographic coordinates from the Global Biodiversity Information Facility (GBIF/www.gbif.org) as input data. After re-screening the GBIF database (accessed on August 07, 2024), we found a total of 252 occurrence records of *F. fistulosa* across Indonesia, with 76 verified presence points located on Java Island (Figure 2). A total of 76 occurrence records of *F. fistulosa* were used after removing duplicate coordinates within the same 30 arc-second (~1 km²) grid cell of the environmental layers, thereby reducing spatial autocorrelation. The modeling employed 19 bioclimatic variables from the WorldClim v2 database. To address potential multicollinearity, the platform automatically screened predictors based on pairwise correlation ($|r| > 0.7$), and only variables with low intercorrelation and meaningful ecological relevance were retained in the final model. Among these, Bio9, Bio6, and Bio16 in the current projection and Bio6, Bio12, and Bio1 and Bio9 in the future projection, contributed the most to model performance.

The model applied BCCVL's default-tuned MaxEnt settings, with automatic feature selection, regularization multiplier = 1.0, and maximum iterations = 500. Model convergence was achieved with a regularized training gain of 1.8581 and an unregularized training gain of 2.7057, indicating stable model fitting. Habitat suitability thresholds were determined using the 10-percentile training presence (0.1442) and equal sensitivity and specificity (0.1828) criteria. The MaxEnt thresholds (10-percentile and equal sensitivity–specificity) were used solely for evaluating model discrimination performance, whereas the suitability classes used for area calculations followed the equal-interval classification of Li et al. [40], independent of any MaxEnt threshold.

Model performance was evaluated by randomly partitioning the dataset into 75% training and 25% testing subsets with five-fold cross-validation. The mean test AUC value (≈ 0.90) indicated excellent model accuracy and strong discriminatory capacity.

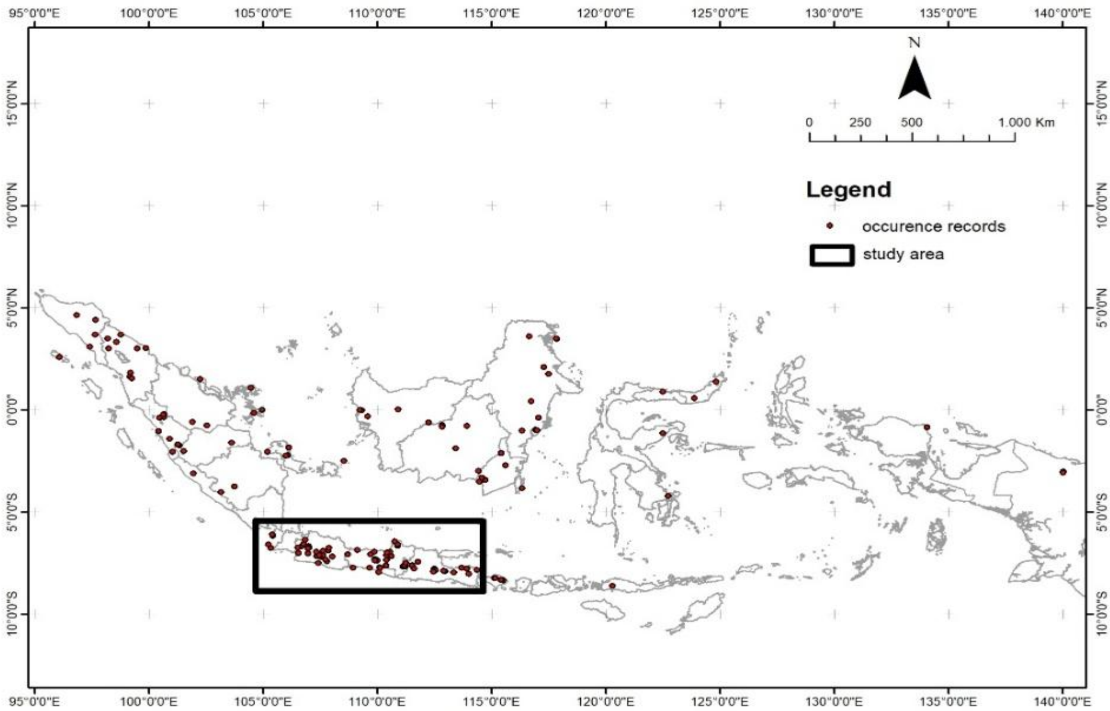


Figure 2. A total of 252 occurrence records of *F. fistulosa* across Indonesia, with 76 verified presence points located on Java Island

The bioclimatic characteristics of the environment were utilized in the process of developing the species distribution model for *F. fistulosa*. The bioclimatic variables were sourced from WorldClim version 2.1, an interpolation dataset from 1970–2000 with a spatial resolution of 1 km, which was used to generate the current prediction. For future prediction, WorldClim v2.1, future climate Bioclimatic Variables 2081–2100, UKESM1-0-LL SSP585 was employed. Future projections were generated using the Shared Socioeconomic Pathway (SSP585) scenario, representing a high-emission and fossil-fuel-intensive development trajectory. The SSP585 scenario assumes continued population growth, high economic development driven by energy-intensive industries, and limited climate change mitigation, leading to an approximate radiative forcing of 8.5 W/m² by 2100. This scenario corresponds to a projected global mean temperature increase of about 4.3°C by 2100 relative to pre-industrial levels, reflecting a "business-as-usual" pathway. This pathway was selected to represent a worst-case climate projection for assessing the potential future distribution and habitat suitability of *F. fistulosa* under extreme warming conditions. The bioclimatic variables for this scenario were obtained from the UKESM1-0-LL General Circulation Model (GCM) with a spatial resolution of 30 arc-seconds (~1 km²) via the EcoCommons climate dataset repository. A total of 19 bioclimatic variables, identified as Bio1 to Bio19, were used (Table 1). MaxEnt is relatively robust to correlated predictors due to its internal regularization mechanism, which penalizes unnecessary model complexity and reduces the influence of redundant variables. This approach helps prevent overfitting even when the full set of bioclimatic variables is used. In addition, the BCCVL implementation of MaxEnt employs cross-validation and standardized regularization settings that further mitigate the potential effects of predictor collinearity. The BCCVL–EcoCommons platform does not provide a built-in correlation matrix or a variable-screening tool prior to model execution. Consequently, unless users perform external preprocessing steps—which were not available in the workflow adopted here—the full bioclimatic dataset is typically used. Therefore, all 19 bioclimatic variables were included in both the current and future distribution models.

Table 1. Information about the data collected from WorldClim Version 2.1

1	Bio1	Annual mean temperature
2	Bio2	Mean diurnal range
3	Bio3	Isothermality
4	Bio4	Temperature seasonality
5	Bio5	Maximum temperature of the warmest month
6	Bio6	Minimum temperature of the coldest month
7	Bio7	Temperature annual range
8	Bio8	Mean temperature of the wettest quarter
9	Bio9	Mean temperature of driest quarter
10	Bio10	Mean temperature of the warmest quarter
11	Bio11	Mean temperature of the coldest quarter
12	Bio12	Annual precipitation
13	Bio13	Precipitation of the wettest month
14	Bio14	Precipitation of the driest month
15	Bio15	Precipitation seasonality
16	Bio16	Precipitation of the wettest quarter
17	Bio17	Precipitation of the driest quarter
18	Bio18	Precipitation of the warmest quarter
19	Bio19	Precipitation of the coldest quarter

Using the maximum entropy model (MaxEnt) method available on the Biodiversity and Climate Change Virtual Laboratory (BCCVL) within the Ecocommons platform, species distribution modelling analysis was conducted. The Area Under the Curve (AUC) value was employed to evaluate the reliability of the model produced [41]. The Receiver Operating Characteristic (ROC) method was employed to evaluate the model's efficacy. ROC works by comparing sensitivity and specificity. Sensitivity shows how well the model can predict presence, and specificity shows how well it can predict absence [39]. The assessment outcomes are presented as AUC values (Table 2) [41-43].

Table 2. Model performance values

AUC Score	Model Performance
0.9-1	Excellent
0.8-0.9	Good
0.7-0.8	Fair
0.6-0.7	Poor

The predictions were represented as grid cell suitability on a scale from 0 to 1, with 0 indicating extremely low distribution probability and 1 representing very high distribution probability. Li et al. [40] identified five distinct threshold ranges for classifying species suitability areas: 0–0.2 for unsuitable areas, 0.2–0.4 for low suitability areas, 0.4–0.6 for moderate suitability areas, 0.6–0.8 for medium suitability areas, and 0.8–1 for high suitability areas.

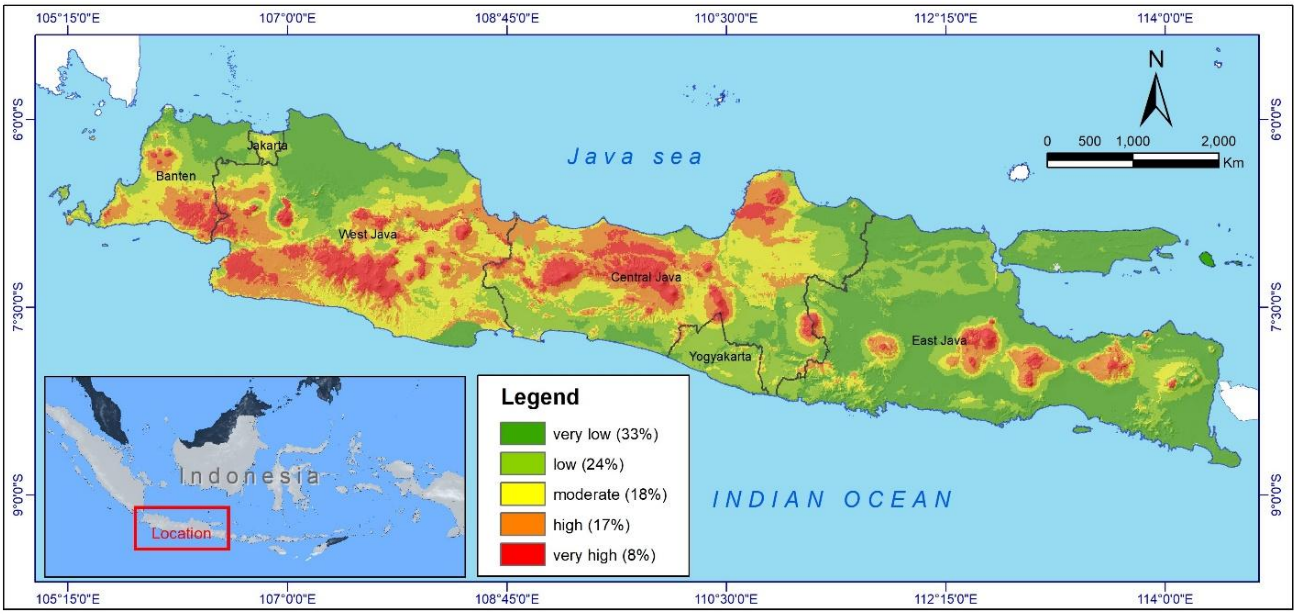
The main output of SDM is a map that shows the predicted distribution or habitat suitability of *F. fistulosa*. The resultant raster file is further processed in QGIS or ARCGIS. A base map of Java Island is added as an overlay. It is important to note that this map does not represent the actual presence of the species; instead, it serves as a prediction of suitable habitat distribution based on environmental variables (specifically the current and future climate conditions) included in the model [44].

3. RESULTS AND DISCUSSION

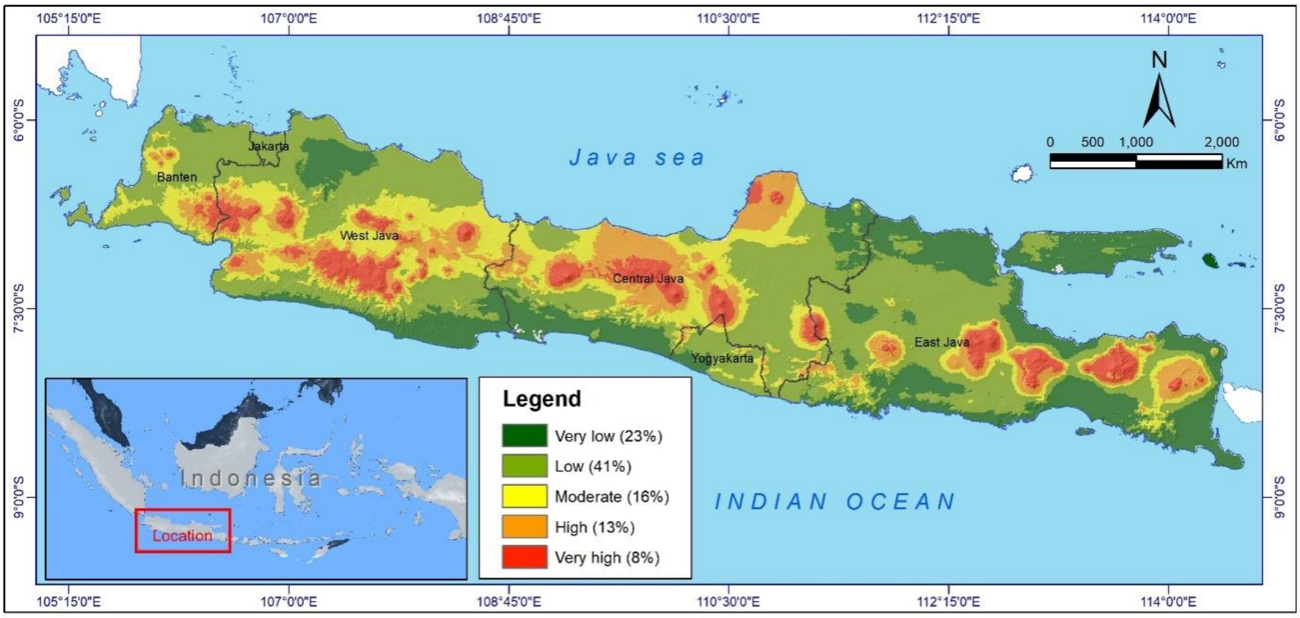
The species distribution model for *F. fistulosa* on Java Island reveals distinct distribution patterns under current conditions and future projections for the year 2100 (Figure 3). The current distribution map (Figure 3(A)) indicates that suitable habitats for the species are concentrated in specific areas, primarily in regions with favorable environmental factors, such as high humidity and mid-to-low elevations. High suitability areas are predominantly found in western and central Java, suggesting a preference for regions relatively less disturbed by human activities.

In contrast, the future distribution projection for 2100 (Figure 3(B)) highlights potential shifts in suitable habitats due to climate change impacts. A noticeable reduction in suitable habitat areas is projected, particularly in regions subject to high anthropogenic pressures. However, the model also indicates the emergence of new potential habitats, although on a more limited scale. These changes illustrate how vital it is to protect this species, especially in areas with high habitat suitability under both current and future conditions.

Table 3 presents the area sizes for each category of habitat suitability for *F. fistulosa* in Java Island under current conditions and future projections for the year 2100. The current model indicates that the majority of the land area falls under the "very low" and "low" suitability categories, with areas of 4,466,785.54 hectares and 3,178,748.78 hectares, respectively. Moderately suitable habitats account for 2,448,065.56 hectares, while "high" and "very high" suitability areas comprise 2,276,465.72 hectares and 1,084,348.43 hectares, respectively.



(A) Current



(B) Future projection 2100

Figure 3. Species distribution model for *Ficus fistulosa* in Java Island, Indonesia

Table 3. Area size for each category of habitat suitability for *F. fistulosa* in Java Island

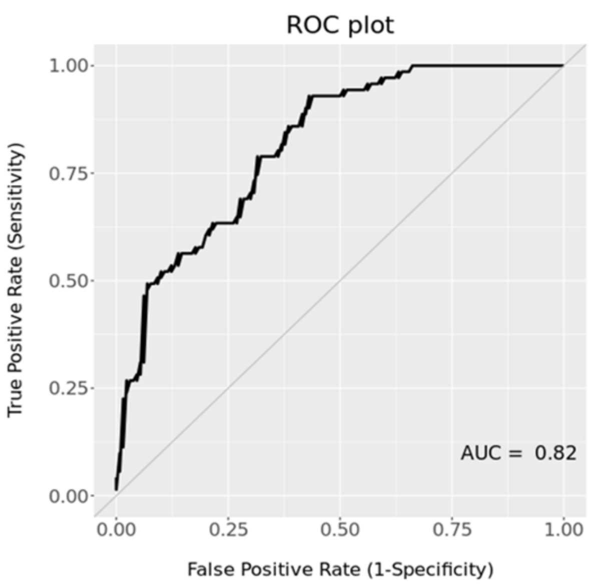
No.	Category	Current	Future	Change (%)
1	Very low	4,466,785.54	2,940,463.71	-34.2
2	Low	3,178,748.78	5,273,062.65	+65.9
3	Moderate	2,448,065.56	2,098,033.01	-14.3
4	High	2,276,465.72	1,692,645.67	-25.6
5	Very high	1,084,348.43	990,591.25	-8.6

The future projections for 2100 demonstrate significant shifts in habitat suitability. Areas categorized as "low" increase to 5,273,062.655 hectares (65.9%), while all higher categories (moderate, high, and very high suitability) decline. “Moderate” suitable areas decrease slightly to 2,098,033.015 hectares (14.3%), and “high” suitability areas reduce to 1,692,645.674 hectares (25.6%). The "very high" suitability category shows the most significant reduction, shrinking to 990,591.257 hectares (8.6%) (Table 3). This indicates a general decline in optimal habitats, accompanied by an expansion of marginally suitable zones. This shows that a transition in climatic zones, where formerly ideal conditions for *F. fistulosa* growth are expected to deteriorate in the future.

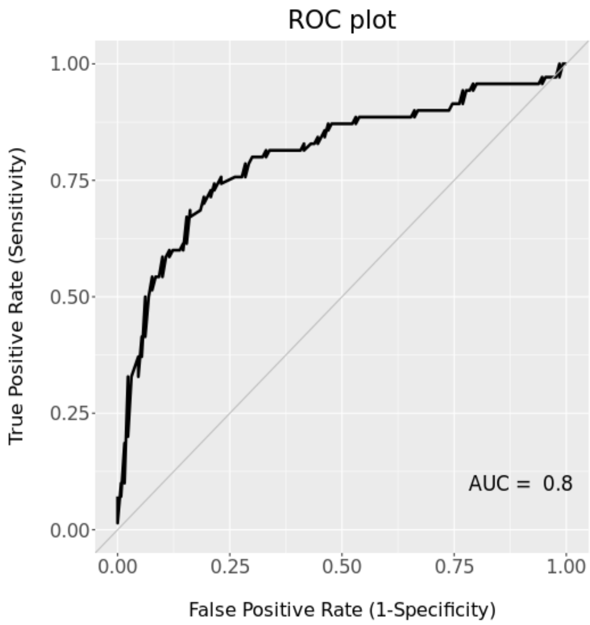
It is suggested that climate change is the main cause of the changes in habitat suitability for *F. fistulosa*. Climate change impacts things like temperature and precipitation in the area. These projected changes carry significant ecological consequences. *F. fistulosa* are essential resources that support a variety of frugivores, such as birds, bats, and monkeys. The loss of highly suited habitats could make it harder for these animals to get food, which could undermine their food security and possibly destabilize networks of mutualistic seed-dispersal. Additionally, *F. fistulosas* is crucial for regulating water flow, as it helps keep water in the soil and stops erosion. A decrease in optimal distribution could reduce these ecosystem services, leading to downstream effects on watershed stability, flood control, and groundwater recharge. From a conservation and restoration point of view, the results show how important it is to include *F. fistulosa* in climate-adaptive management plans right now. Restoration initiatives should focus on planting in regions that are moderately to highly suitable, especially in mid- to high-elevation zones where the climate is more likely to be stable over time. Also, keeping ecological corridors open between habitats that are broken up will be important for natural dispersal and range adjustments.

The reduction in areas of moderate, high, and very high suitability can also be attributed to altitudinal changes. *F. fistulosa* presently flourishes in tropical montane forests at elevations of 1,500–2,500 meters above sea level. Nonetheless, climate-induced warming is anticipated to shift favourable circumstances to higher elevations. As altitude rises, the available land area diminishes, hence restricting the possible range expansion of *F. fistulosa*. As a result, low suitability zones are increasing, whereas ideal habitats are diminishing, indicating the loss of stable climatic niches.

The validation model using the ROC plot demonstrates the predictive presentation of SDM for *F. fistulosa* in Java Island, both for the current condition and future projections (Figure 4). The AUC value for the current model is 0.82, while for the future projection, the AUC is slightly lower at 0.80. An AUC value close to 1.0 indicates that the model has good accuracy in distinguishing between suitable and unsuitable areas for this species.



Current projection



Future projection

Figure 4. Model accuracy using ROC plot for *F. fistulosa* in current and future projections in Java, Indonesia

The ROC plot for the current condition shows a curve that is significantly separated from the random diagonal line, indicating that the model has good sensitivity and specificity in predicting *F. fistulosa*'s habitat. Meanwhile, although the future projection shows a slight decrease in AUC, the curve still follows a trend that reflects the model's ability to identify potential habitats in the future. This decrease in AUC might be attributed to environmental uncertainties, land-use changes, or climate factors affecting the species' distribution.

In general, these results show that the MaxEnt model utilized is good for predicting where *F. fistulosa* will be found on Java Island. The slight difference in AUC values between the current and future conditions indicates potential habitat changes that need to be considered in conservation strategies. These results can help policymakers make decisions about protecting habitats and lessening the impacts of climate change and human activities on the species' natural ecosystem.

The response curves (Figure 5) of the bioclimatic variables indicate the relationship between each environmental element and the possibility of *F. fistulosa* presence in Java Island under both current and future conditions. The response curves reveal how *F fistulosa* responds to environmental gradients represented by the 19 bioclimatic variables. These patterns describe the sensitivity of the species to climatic factors that shape its potential distribution across Java. Several variables show a particularly strong influence on habitat suitability, especially temperature and precipitation-related factors.

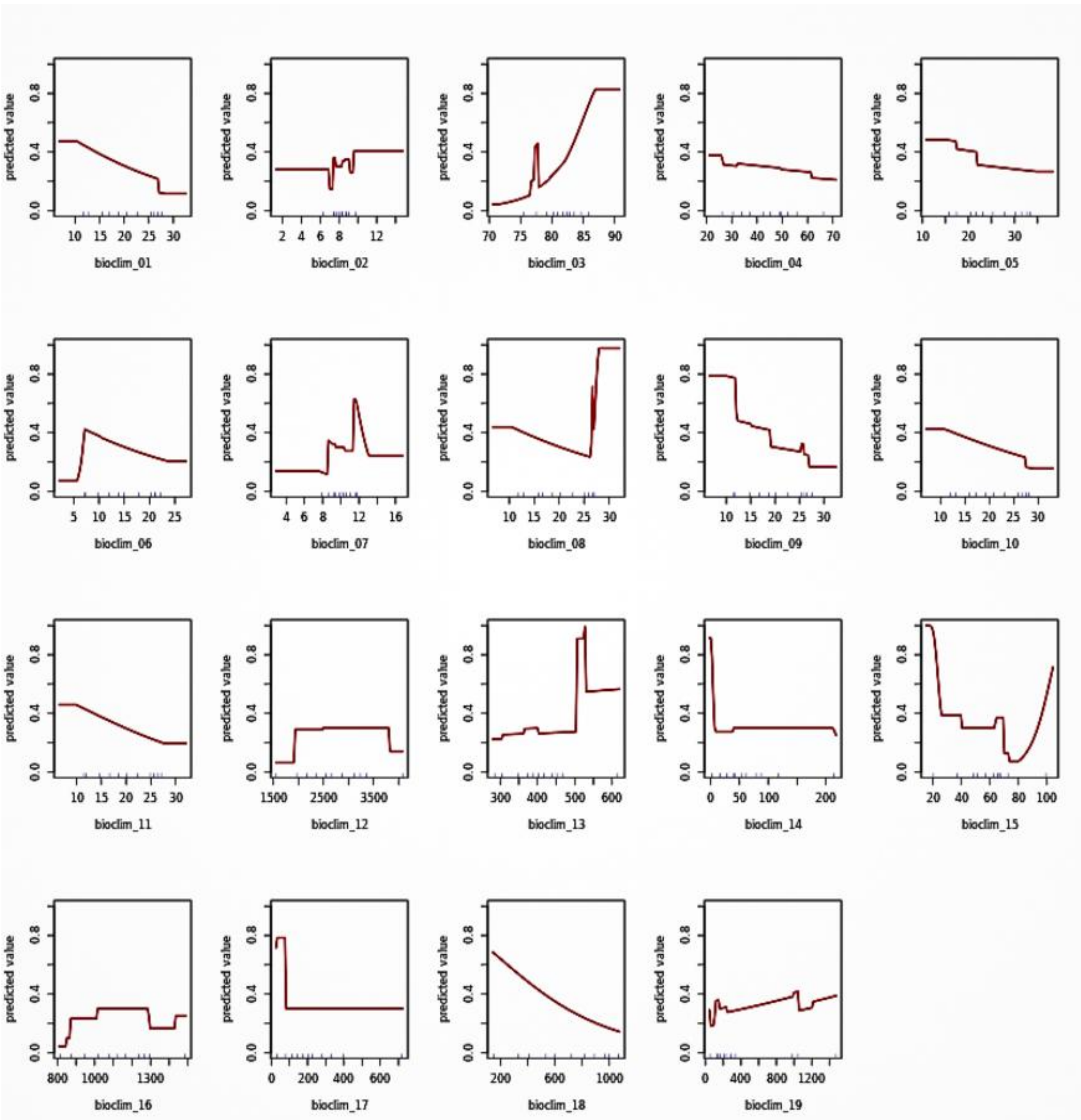
In the current scenario, some bioclimatic variables show a clear threshold effect, where habitat suitability sharply increases or decreases beyond specific climatic values. This suggests that *F. fistulosa* has optimal environmental conditions within a certain range of temperature and precipitation. However, in the future projections, several response curves exhibit shifts or fluctuations, indicating potential changes in species' climatic preferences due to environmental changes.

Notably, some variables maintain a relatively stable response pattern, suggesting that certain climatic factors may continue to be critical factors of habitat suitability. Meanwhile, other curves show more pronounced variations, which could be attributed to climate change effects, like increasing temperatures or modified precipitation patterns.

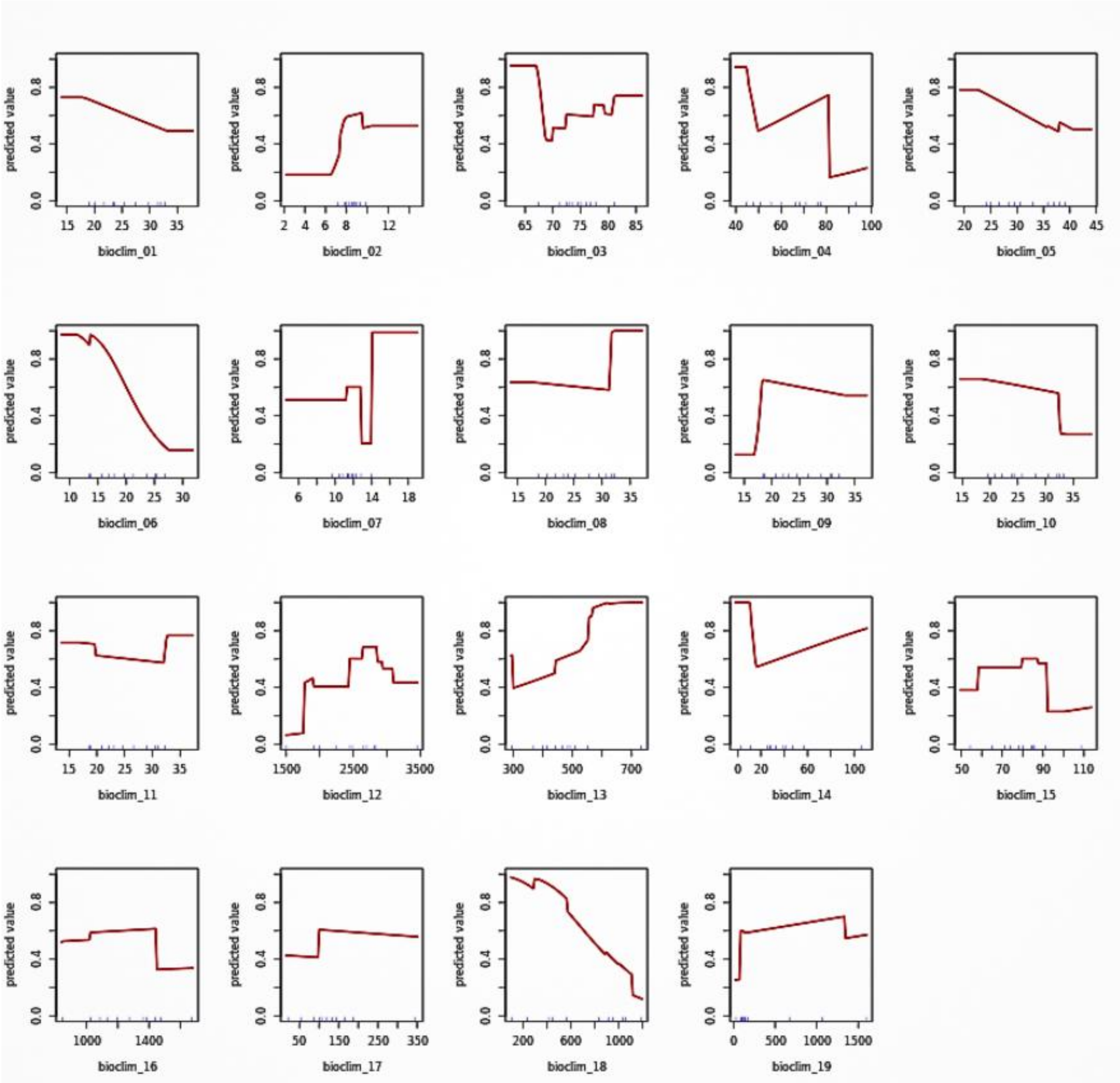
These results emphasize the importance of understanding how bioclimatic factors influence *F. fistulosa* distribution over time. The changes in response curves show that we need to use adaptive conservation measures to make sure this species can survive in the long run, especially if climate change and habitat loss occur.

Figure 6 shows the relative contribution of each bioclimatic variable to the SDM of *F. fistulosa* in Java, considering both current and future climatic scenarios. These contributions indicate the importance of different environmental factors in determining the species' suitable habitat.

In the current scenario, *bioclim_09* exhibits the highest contribution, suggesting that this variable plays a crucial role in influencing the distribution of *F. fistulosa*. Habitat suitability for *F. fistulosa* rises sharply at moderate mean temperatures of around 22-26℃ and declines outside this range. This trend indicates that the species performs best in warm but not excessively hot dry-season conditions typical of monsoonal and sub-humid tropical forests. Temperature significantly influenced the rate of stomatal conductance and photosynthesis. Fig cultivars exhibited adaptive behavior to manage harsh conditions, including elevated temperatures [45]. The preference for stable warmth suggests that *F. fistulosa* has adapted to microhabitats with moderate thermal stress during the driest months. These results are comparable to those of other *F. altissima* in Guangxi, China habitats that thrive ideally at a temperature of 20-25℃ [46]. Other variables, such as bioclim_06, bioclim_16, and bioclim_10, also contribute significantly, indicating their strong influence on habitat suitability. Conversely, variables like bioclim_14 and bioclim_18 have minimal impact, implying they are less critical in determining the species' presence.



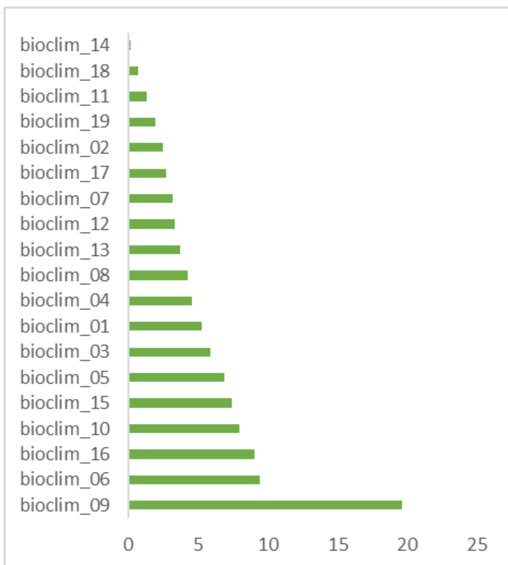
Current



Future

Figure 5. Current and future response curve of bioclimatic layers used in the model for *F. fistulosa* SDM

Under future climatic conditions, there is a shift in the relative importance of bioclimatic variables. While bioclim_06 remains a dominant predictor, bioclim_12 and bioclim_01 gain increased importance compared to the current scenario. This suggests that future climate change may alter the ecological drivers of *F. fistulosa* distribution, potentially leading to habitat shifts. The decrease in importance of certain variables, such as bioclim_09, highlights the dynamic nature of species-environment relationships under changing climatic conditions. Future climate forecasts indicate a minor shift in the response curve towards elevated temperature ranges, while the peak suitability narrows. This contraction indicates a decrease in thermal tolerance as heat stress escalates. Under projected climate-change scenarios, increasing temperatures during the dry season could substantially reduce habitat suitability, especially in lowland and mid-elevation areas. As drought and heat stress intensify, *F. fistulosa* populations are likely to migrate toward higher elevations or persist in wetter microsites. This result is in line with the findings of prior research on the elevational redistribution of species in other places, such as Mount Gongga, Tibet Plateau [47], Natma Taung National Park (NTNP), Myanmar [48]. This pattern highlights the species' reliance on thermally stable environments, such as riparian corridors, shaded forest edges, and moist slopes, where microclimatic fluctuations are reduced.



Current

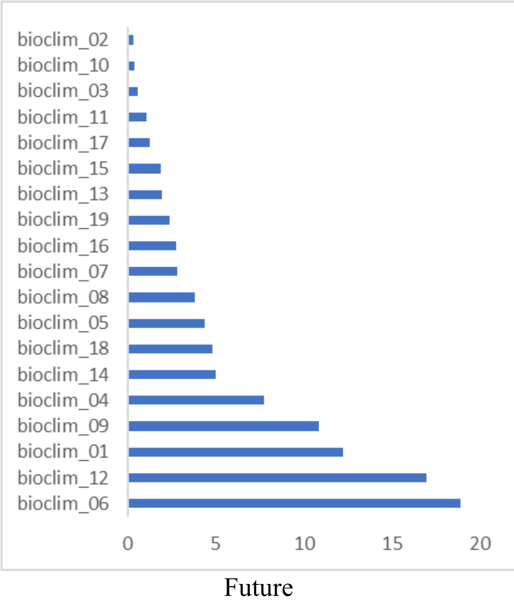


Figure 6. Contribution of each bioclimatic variable in the SDM of *F. fistulosa* in Java

These findings highlight how important it is to include predictions about climate change in plans to protect *F. fistulosa*. By identifying key environmental factors affecting its distribution, targeted conservation efforts can be developed to mitigate potential habitat loss and ensure the species' long-term survival in Java. Habitat loss and fragmentation can severely disrupt the mutualistic relationships between *F. fistulosa* and its animal dispersers by reducing both fruit availability and spatial connectivity among feeding sites. When these networks are disturbed, frugivorous birds and bats—key agents in seed dispersal—tend to show reduced movement, declining population densities, and weakened ecological functions. To mitigate the ecological consequences of fragmentation, conservation strategies should focus on restoring habitat connectivity through well-planned ecological corridors. Corridors linking riparian zones and forest fragments where *F. fistulosa* naturally occurs can facilitate animal movement, enhance seed dispersal, and stabilize pollination dynamics.

Overall, this model provides valuable insights into the spatial distribution of *F. fistulosa*, which can inform effective conservation planning and habitat management strategies on Java Island.

4. CONCLUSIONS

The study's results show that the SDM can help find the best habitats for *F. fistulosa* on Java Island by looking at both the current and future climate conditions. A high level of accuracy was attained by the model through the utilization of the MaxEnt algorithm, which was combined with bioclimatic and topographic factors. This was demonstrated by the AUC scores. The results suggest that the area of highly suitable habitats will significantly decrease by the year 2100, especially in highland and hydrologically critical regions. This decline of suitable habitats illustrates the vulnerability of *F. fistulosa* to the persistent impacts of climate change. These results have big effects on how we protect biodiversity and keep ecosystem services working in tropical forest areas. The species is ecologically significant as a keystone frugivore resource, and it plays a role in the hydrological cycle. Areas should be prioritized for conservation, including Mount Kelud (East Java), Mount Muria, Mount Slamet, Mount Dieng, Mount Rogojembangan (Central Java), Mount Ciremai, Mount Papandayan, Mount Tumpeng, and Mount Halimun (West Java). This study does not account for biotic interactions, land-use dynamics, or dispersal constraints, which may affect realized distributions. We suggested that future research integrate dynamic land-use data and biotic variables to improve model realism and predictive accuracy.

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