# Diversity, distribution, and conservation status of wild edible fruit species in Sumatra, Indonesia: A case study in western and eastern Bukit Barisan Mountains

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## Abstract

Bukit Barisan Mountains in Sumatra, Indonesia is home to a diverse range of plant species. However, this area has been subjected to intense human pressure resulting in various biological resources such as wild edible fruit species (WEFs) being under threat. The study aimed to 1) investigate the diversity of WEFs in the Bukit Barisan Mountains, Sumatra; 2) evaluate the suitable habitat and potential geographic distribution of WEFs in the Bukit Barisan Mountains, Sumatra; and 3) determine the conservation status of WEFs in Sumatra. This study was conducted in four provinces of Sumatra, Indonesia, including Sumatera Barat, Jambi, Riau, and Bengkulu, which are divided into two zones: the western of Bukit Barisan Mountains and the eastern of Bukit Barisan Mountains. At each study area, a line transect of 1,000 meters was laid from the forest's edge into the forest. WEFs discovered along the transect were collected and given local names. A total of 326 WEFs belonged to 74 botanical families and 170 genera were recorded. Of the 326 species, 125 species are found in the western of the Bukit Barisan Mountains and 228 species in the eastern Bukit Barisan Mountains. Our study highlights nearly half of the WEFs found in the Bukit Barisan Mountains are listed as threatened on the IUCN red list.


## Introduction

Tropical forests, which cover approximately 7% of the Earth's land surface and 30% of total forest areas, have wet and warm climates with higher biodiversity due to higher productivity, more species interactions, greater ecological specialization, and more opportunities for speciation (Mittelbach et al. 2007; Chu et al. 2019). This ecosystem is home to more than half of the world's estimated 10 million plant, animal, and insect species (Myers 1988). Tropical forests play an important role in the regulation of nutrient cycling and soil formation (Šamonil et al. 2010), flood mitigation (Calder and Aylward 2006), water and air purification (Song et al. 2016), and the provision of food (Navia et al. 2021; Navia and Suwardi 2022; Syamsuardi et al. 2022) and medicinal plants (Begossi et al. 2002). Approximately 1.6 billion people worldwide rely on forests to varying degrees for a living, with 350 million people living in or near forests relying on them heavily (World Bank 2001).

Wild edible fruit species (WEFs) are one of the forest resources that are widely used by people in their daily lives. WEFs provide vitamins, minerals, and dietary fiber is essential in the human diet (Mahapatra and Panda 2012; Suwardi et al. 2022a). Several wild fruits have been reported to be more nutritious than cultivated fruits (Aberoumand and Deokule 2009; Navia et al. 2022). Several WEFs are also known to contain significant biological activities in a wide range of traditional medicines (Li et al. 2016). WEFs have also been shown to improve household food security in both rural and urban areas under normal conditions, as well as during crop insufficiency (Broegaard et al. 2017). WEFs have also been used by local communities in various regions as a source of additional income for rural households (Suwardi et al. 2020).

Indonesia has the largest tropical rainforest in Southeast Asia, accounting for more than 10% of the world's flowering plant species (Von Rintelen et al. 2017), and is recognized as one of the centers of plant genetic diversity in the world, particularly for tropical fruit (Uji 2007). The majority of these species are found on Sumatra island (148 species) (Uji 2007), and a large portion of them grow wild in tropical forests (Dodo 2015). The Bukit Barisan mountain range in Sumatra, which is part of the Sundaland biodiversity hotspot, is considered to have a high species richness, as well as a high number of endemic and endangered plant species, including WEFs. Moreover, information on WEFs diversity in the Bukit Barisan Mountains is scarce. The Bukit Barisan Mountains, as another Sundaland biodiversity hotspot, has been subjected to intense human pressure (Verma et al. 2020), with on average, over 70% of protected land under intense human pressure and this far exceeds the global average of approximately 30% (Jones et al. 2018). As a result, the number of threatened plants in Indonesia is increasing every year (Dodo and Hidayati 2020), including in Sumatra. Monitoring the changing diversity and distribution of WEFs, as well as the status of rare or threatened species, is thus critical for conservation in order to protect WEFs that are becoming increasingly threatened or extinct in the future. This study aims to 1) investigate the diversity of WEFs in the Bukit Barisan Mountains, Sumatra; 2) evaluate the suitable habitat and potential geographic distribution of WEFs in the Bukit Barisan Mountains, Sumatra; and 3) determine the conservation status of WEFs in Sumatra.

## Materials And Methods

# Study area

This study was conducted in four provinces of Sumatra, Indonesia, including Sumatera Barat, Jambi, Riau, and Bengkulu (Fig. 1). The study area was divided into two zones: the western Bukit Barisan Mountains and the eastern Bukit Barisan Mountains (Table 1).

Table 1
List of the study area

| Zone | Study areas (Districts) | Coordinates |
|---|---|---|
| Western Bukit Barisan Mountains | Pasaman Barat | 0°19'46.7"N; 99°37'30.9"E |
| | Padang Pariaman | 0°40'04.7"S; 100°21'42.5"E |
| | Pesisir Selatan | 1°23'08.1"S; 100°37'20.1"E |
| | Mukomuko | 2°55'11.4"S 101°43'44.1"E |
| | Lebong | 2°56'32.3"S 102°06'11.1"E |
| | Rejang Lebong | 3°25'38.5"S 102°35'31.8"E |
| | Bengkulu Tengah | 3°42'56.0"S 102°31'50.6"E |
| Eastern Bukit Barisan Mountains | Pasaman | 0°42'33.2"N; 100°00'40.5"E |
| | Solok | 1°00'47.8"S; 100°53'46.9"E |
| | Lima Puluh Kota | 0°16'25.9"S; 100°47'47.8"E |
| | Kampar | 0°02'24.7"S 100°58'10.1"E |
| | Indragiri Hulu | 0°46'00.6"S 102°27'07.4"E |
| | Merangin | 1°49'45.5"S 102°30'20.2"E |
| | Bungo | 1°43'05.0"S 101°52'22.8"E |
| | Tebo | 1°11'36.7"S 102°33'59.0"E |

Figure 1. [near here]

Table 1. [near here]

# Data collection

The sampling of WEFs was conducted from Jun to Oct 2022. A line transect method was employed. At each study area, a line transect of 1,000 meters was laid from the forest's edge into the forest. WEFs discovered along the transect were collected and given local names.

The botanical name was identified at the Anda Herbarium of Universitas Andalas, West Sumatra, Indonesia. The botanical names have been updated using The Plants of the World online (http://www.plantsoftheworldonline.org).

# Modeling of potential geographic distribution

The geographical distribution data (longitude and latitude) of WEFs was obtained from field investigation in four provinces of Sumatra, Indonesia, i.e. Sumatera Barat, Jambi, Riau, and Bengkulu. A total of 1,976 distribution points of WEFs were collected (Fig. 2). All data were entered into Microsoft Excel version 2018 programs and saved in "CSV" format for future analysis.

Figure 2. [near here]

The elevation and climate variables were obtained from the Global Climate Database (https://www.worldclim.org/, accessed on January 18, 2023). For 19 environmental variables, the spatial resolution was 2.5 arc minutes. The variables with contribution rates of 0 were deleted, and SDM tools in ArcGIS software were used to remove variables with high correlation (Pearson's |r| 0.80) (Liu et al. 2021). As a result, nine environmental variables were selected (Table 2).

Table 2
Environmental variables in the MaxEnt model

| Code | Description | Unit |
|---|---|---|
| Bio3 | Isothermality | % |
| Bio4 | Temperature seasonality | % |
| Bio12 | Annual precipitation | mm |
| Bio13 | Precipitation of wettest month | mm |
| Bio14 | Precipitation of driest month | mm |
| Bio15 | Precipitation seasonality | % |
| Bio18 | Precipitation of warmest quarter | mm |
| Elev | Elevation | m |

Table 2. [near here]

MaxEnt version 3.4.3 was used to simulate the potential distribution of WEFs (Phillips et al. 2006) and was downloaded from (https://biodiversityinformatics.amnh.org/, accessed on 18 January 2023). The distribution data and environmental variables were entered into MaxEnt software, and the following parameters were set: 25% of the distribution points were set as test data, 75% as training data, 10 repetitions with a maximum of 500 iterations, the convergence threshold was set to $1 \times 10^{-6}$ for each training repetition, and the output was in Logistic format. To describe the distribution changes of WEFs, the simulated results were reclassified in ArcGIS 10.8 using the natural breakpoint method (Esri, Redlands, CA, USA). The natural discontinuous point method was used to divide the suitable area into 4 grades, i.e. highly suitable habitat ($0.5 \leq P \leq 1.0$), moderately suitable habitat ($0.3 \leq P \leq 0.5$), poorly suitable habitat ($0.1 \leq P \leq 0.3$), and unsuitable habitat ($0.0 \leq P \leq 0.1$) (Songer et al. 2021). Finally, ArcGIS 10.8 was used to create maps of suitable habitats under the current climate. Each grade's grid number was counted, and the proportion of suitable area for each grade was calculated. To assess the model's prediction accuracy, subject work characteristics (ROC), the area under the curve (AUC), and true skill statistics (TSS) were used. AUC values near 1 indicate that the model prediction effect is better. The model prediction accuracy evaluation criteria were divided into four grades: poor (AUC ≤ 0.80), general (0.80 < AUC ≤ 0.90), good (0.90 AUC ≤ 0.95), and best (0.95) (Liu et al. 2021). TSS assesses a model's overall accuracy based on its random accuracy, assigning a score between − 1 and 1, with values near 1 indicating optimal performance (Allouche et al. 2006). TSS values greater than 0.5 are considered adequate for informing model performance (Silva et al. 2022).

# Data analysis

# Species richness indices

The richness of WEFs was determined using Margalef's diversity index calculated using the following formula (Clifford and Stephenson 1975):

$$D_{Mg} = \frac{S-1}{lnS}$$

1 ………………………………………………………………..…………………..…………

where, N = population = the total number of individuals in the sample and S = the number of species recorded

# Diversity index

The diversity of WEFs was determined using the Shannon-Wiener Index (*H*') calculated using the following formula (Barbour et al. 1987):

$$H\prime = -\sum_{i=1}^{s} Pi \ln Pi$$

2 ……………………………………………………………………….…………

where, H'= Shannon-Wiener Diversity Index, s = number of species, Pi = the proportion of individuals or abundance of the i species expressed as the proportion of the total abundance, ln = natural logarithm of Pi.

Hutcheson's t-test with PAST ver. 4.03 was used to examine differences in WEFs diversity between sites.

# Evenness index

The evenness index (E) was calculated using the following formula (Magurran 2004):

$$E = \frac{H\prime}{H_{max}} = \frac{H\prime}{LnS}$$

3 ……………………………………………………………………..……….

Where: E = Evenness, H'= Shannon-Wiener Diversity Index, S = total number of species in the sample, ln = natural logarithm.

# Dominance index

A high uniformity index and low diversity indicate a species' dominance over other species. The dominance index was used in this study with the following formula (Odum 1996):

$$C = \sum_{i=1}^{s} Pi^2$$

4 ……………………………………………………………………………….

Where: C = Dominance Index, Pi = the proportion of individuals in WEFs, I = 1, 2…, n

Welch's t-test with PAST ver. 4.03 was used to examine differences in species dominance between sites.

# Similarity index

To assess the similarities in plant species among the study areas, the Jaccard similarity coefficient (CJ) was employed using the following Cabrera-Meléndez et al. (2022):

$$CJ = \frac{c}{a+b+c}$$

5 …………………………………………………………………….………….

where, a = the number of species present only at site A; b = the number of species present only at site B; and c = the number of species present at both sites A and B.

## Results

# Diversity of wild edible fruit plants

A total of 326 WEFs belonged to 74 botanical families and 170 genera were recorded (Table S1). Of the 326 species, 125 species are found in the western Bukit Barisan Mountains and 228 species in the eastern Bukit Barisan Mountains. However, a total of 202 species were discovered only in the eastern

Bukit Barisan Mountains, while 37 WEFs were discovered only in the western Bukit Barisan Mountains. *Artocarpus elasticus* Reinw. ex Blume, *Artocarpus integer* (Thunb.) Merr., *Artocarpus odoratissimus* Blanco, *Baccaurea lanceolata* (Miq.) Müll.Arg., *Baccaurea sumatrana* (Miq.) Müll.Arg., *Bellucia pentamera* Naudin, *Curculigo capitulata* (Lour.) Kuntze, *Mangifera foetida* Lour, *Miconia crenata* (Vahl) Michelang, *Passiflora foetida* L., *Pometia pinnata* J.R. Forst. & G. Forst., *Rubus moluccanus* L., and *Syzygium pycnanthum* Merr. & L.M.Perry, were the most frequently recorded species in all surveyed studies (Table S1). Among the families, Moraceae and Phyllanthaceae are the most specious families in the western Bukit Barisan Mountains, with 17 species each, while Moraceae is the most specious family in the eastern of the Bukit Barisan Mountains (Fig. 3).

Figure 3. [near here]

The species richness index was higher in the eastern Bukit Barisan Mountains ($D_{Mg}$ = 40.740) than in the western Bukit Barisan Mountains ($D_{Mg}$ = 18.060). Merangin has the highest species richness index value ($D_{Mg}$ = 17.80), while the lowest was discovered in the Pasaman Barat ($d$ = 2.91) (Table 1). The species diversity index ($H'$) value of WEFs was higher in the eastern Bukit Barisan Mountains ($H'$ = 4.841) than in the western Bukit Barisan Mountains ($H'$ = 4.076). Hutcheson's t-test reveals significant differences in the Shannon diversity between the western and eastern Bukit Barisan Mountains ($t_{value}$ = 13.494, df = 1962; $P < 0.05$).

In the fifteen study areas, the dominance index ($D$) value of WEFs ranged from 0.02 to 0.157, indicating a low level of dominance, and the population of each plant species is more evenly distributed. The dominance index was higher in the western Bukit Barisan Mountains ($D$ = 0.027) than in the eastern Bukit Barisan Mountains ($D$ = 0.016). Welch's t-test shows significant differences in species dominance between the western and eastern Bukit Barisan Mountains ($t_{value}$ = 60.282, df = 1557; $P < 0.05$). In addition, the evenness index ranged from 0.471 to 0.979 (Table 3). Padang Pariaman had a higher evenness index value (0.979), indicating that the ecosystem in the area is more stable. The evenness index was higher in the western Bukit Barisan Mountains ($E$ = 0.479) than in the eastern Bukit Barisan Mountains ($E$ = 0.441).

Table 3
Species richness, diversity, dominance, and evenness of wild edible fruit species in the study area

| Zone | Study Area | No. of species | Dominance Index ($D$) | Shannon-Wiener Index ($H'$) | Evenness Index ($E$) | Margalef Index ($D_{Mg}$) |
|---|---|---|---|---|---|---|
| Western Bukit Barisan Mountain | Pasaman Barat | 8 | 0.157 | 1.972 | 0.898 | 2.919 |
| | Padang Pariaman | 31 | 0.034 | 3.412 | 0.979 | 8.580 |
| | Pesisir Selatan | 76 | 0.067 | 3.578 | 0.471 | 13.930 |
| | Mukomuko | 52 | 0.029 | 3.733 | 0.804 | 10.620 |
| | Lebong | 69 | 0.032 | 3.823 | 0.663 | 13.000 |
| | Rejang Lebong | 53 | 0.032 | 3.671 | 0.741 | 10.430 |
| | Bengkulu Tengah | 45 | 0.043 | 3.424 | 0.682 | 8.891 |
| | Combine | 123 | 0.027 | 4.076 | 0.479 | 18.060 |
| Eastern Bukit Barisan Mountain | Pasaman | 42 | 0.025 | 3.714 | 0.977 | 10.770 |
| | Solok | 48 | 0.047 | 3.500 | 0.690 | 9.869 |
| | Lima Puluh Kota | 41 | 0.042 | 3.426 | 0.750 | 8.764 |
| | Kampar | 84 | 0.023 | 4.122 | 0.735 | 16.290 |
| | Indragiri Hulu | 79 | 0.027 | 3.950 | 0.657 | 14.240 |
| | Merangin | 94 | 0.020 | 4.238 | 0.737 | 17.800 |
| | Bungo | 81 | 0.024 | 4.068 | 0.722 | 15.520 |
| | Tebo | 57 | 0.028 | 3.821 | 0.801 | 12.190 |
| | Combine | 287 | 0.016 | 4.841 | 0.441 | 40.740 |

Table 3. [near here]

# Comparison of species diversity among study areas

The coefficient Jaccard similarity index (CJ) compares the similarity of species across all areas of study. The species similarity index value between the western and eastern Bukit Barisan Mountains of 0.258. In the seven study areas of the western Bukit Barisan Mountains, the species similarity index value range from 0.026 to 0.671, and from 0.020 to 0.358 in eight study areas of the eastern Bukit Barisan Mountains (Fig. 4).

Figure 4. [near here]

Our funding reveals that the similarity is high, with a coefficient of similarity greater than 0.65, for Lebong–Rejang Lebong (CJ = 0.671) and Lebong-Mukomuko (CJ = 0.658). Low similarities, on another hand, were detected for Bungo–Tebo (CJ = 0.02).

# Geographic distribution potential of wild edible fruits under climate condition

The MaxEnt model was used to simulate and predict the potential habitat suitability and distribution of WEFs in the study area. Species showed different responses to the eight climatic variables studied. AUC values of training and test data were 0.861 and 0.866, respectively (Fig. 5), and the TSS value is 0.622, indicating that the models are useful for predicting the occurrence of species using the eight climatic variables and presence-absence data.

Figure 5. [near here]

The model prediction of habitat suitability of WEFs revealed a total suitable habitat of 7,763,828.02 ha, consisting of a highly suitable habitat of 1,322,471.45 ha, a moderately suitable habitat of 3,402,467.58 ha, and a poorly suitable habitat of 3,038,888.99 ha, with the greatest concentration of highly suitable areas primarily predicted in Sumatera Barat province (Fig. 6).

Figure 6. [near here]

Our findings revealed that the WEFs distribution was more influenced by elevation, temperature (temperature seasonality), precipitation (precipitation of wettest month, precipitation of wettest month, precipitation of warmest quarter, and precipitation seasonality), and isothermality (Table 4). The findings showed that the elevation (Elev) had the highest percent contribution (64.5%) and permutation importance (53.9%) to the simulation, which was the key variable affecting its distribution. It indicates that the presence of the probability of WEFs was higher when the elevation was 200–300 m a.s.l.

Table 4
Percent contribution and permutation importance of each variable defined by MaxEnt for wild edible fruit species

| Variable | Percent contribution | Permutation importance |
|---|---|---|
| Elev | 64.5 | 53.9 |
| Bio4 | 12.8 | 14.5 |
| Bio13 | 8.2 | 12.1 |
| Bio3 | 4.4 | 3.2 |
| Bio15 | 4.0 | 6.6 |
| Bio18 | 2.3 | 2.2 |
| Bio12 | 1.9 | 4.3 |
| Bio14 | 1.8 | 3.2 |

Table 4. [near here]

Temperature seasonality (Bio4) is a second important factor in the distribution of WEFs, with a percent contribution and permutation importance of 12.8% and 14.5%, respectively. The findings reveal that the presence of the probability of WEFs was higher when the temperature seasonality was 30–35%. Precipitation of wettest month (Bio13), on other hand, has a percent contribution and permutation importance of 8.2% and 12.1%, respectively, whereas the precipitation of driest month (Bio14) only has a percent contribution and permutation importance of 1.8% and 3.2%, respectively, and the precipitation of warmest quarter (Bio18) has a percent contribution and permutation importance of 2.3% and 2.2%, respectively. The presence of the probability of WEFs was higher when the precipitation of wettest month was 250–300 mm, the precipitation of driest month was 150–200 mm, and the precipitation of warmest quarter of 800–1000 mm, respectively. Precipitation seasonality (Bio15) has a percent contribution and permutation importance of 4.0% and 6.6%, respectively, and the presence of the probability of WEFs was higher when the precipitation seasonality was 30–35%. In addition, the annual precipitation (Bio12) has a contribution of 1.9% for the distribution of WEFs with the presence the probability of WEFs being higher when the annual precipitation was 3500–4000 mm.

# Threaten status of wild edible fruits

Data from the International Union for Conservation of Nature (IUCN) Red List Index for Plants (2020) was used to determine that of 326 WEFs, 1 (0.3%) species are currently classified as Endangered, 9 (3%) species as Vulnerable, 10 (3%) species as Near Threatened, 138 (42%) species as Least Concern, 2 (0.6%) as Data Deficient, and 166 (51%) have No Available Data (Fig. 7).

Figure 7. [near here]

*Castanopsis argentea* (Blume) A.DC. is the WEFs listed as Engendered, while *Aglaia angustifolia* (Miq.) Miq., *Artocarpus anisophyllus* Miq., *Castanopsis scortechinii* Gamble, *Ctenolophon parvifolius* Oliv., *Durio graveolens* Becc., *Durio lowianus* Scort. ex King, *Horsfieldia polyspherula (*Hook.f.) J.Sinclair, *Mangifera similis* Blume, and *Saurauia bracteosa* DC. were the nine WEFs listed as Vulnerable. Moreover, 10 species were classified as Near Threatened, including *Aglaia crassinervia* Kurz ex Hiern, *Aglaia edulis* (Roxb.) Wall., *Aglaia silvestris* (M.Roem.) Merr., *Artocarpus odoratissimus* Blanco, *Durio carinatus* Mast., *Durio oxleyanus* Griff., *Gonystylus forbesii* Gilg, *Madhuca pallida* (Burck) Baehni, *Mangifera caesia* Jack, *and Palaquium hexandrum* (Griff.) Baill. The IUCN red list, however, has not yet listed the threatened status of more than half of the WEFs found in this study.

# Discussion

The Bukit Barisan Mountains in Sumatra, Indonesia, are well-known for their high species diversity due to their location within the Sundaland biodiversity hotspot. A total of 326 WEFs belonging to 74 botanical families and 170 genera were recorded. The analysis of the WEFs of the study area showed that the Moraceae and Phyllanthacheae are the most dominant botanical families both in the western and eastern Bukit Barisan Mountains. This result was in line with the findings of Rahmah et al. (2016) in the Bukit Dua Belas National Park, Indonesia, Suwardi et al. (2022b) in Aceh province, Indonesia, and Zapanta et al. (2019) in Mt. Apo Natural Park, Mindanao Island, Philippines.

Considering the Shannon diversity index, our study showed that the western Bukit Barisan Mountains have a lower Shannon index (*H'* = 4.076) compared to the eastern (*H'* = 4.841). In the fifteen study areas, the lower biological diversity was noted in Pasaman Barat (*H'* = 1.972). This area is dominated by a single species i.e. *Melastoma malabathricum*, with contributes approximately 60% of the total number of WEFs individuals in the study area. Our findings indicate that land use change activities, particularly the agricultural expansion and monoculture plantations, are the primary causes of the decline in populations of WEFs in this area. Land use changes, particularly agriculture expansion, are one of the most important drivers of species and ecological trait loss in tropical ecosystems (Newbold et al. 2020). Overall, the Shannon diversity index values obtained in the fifteen studied areas are higher than those obtained in other studies in Sumatra, Indonesia. For instance, in the forest of Aceh province, the Shannon diversity index varies from 2.78 to 3.85 (Suwardi et al. 2022b). In the context of this study, we have studied the differences that exist between areas through the coefficient Jaccard similarity index. Moreover, this index gives a very good idea of the presence or absence of species in the different studied areas (Ifo et. al. 2016). Our findings show that the similarity index values are less than 50%, indicating a difference in floristic composition between the study areas. According to Ifo et al. (2016), similarity index values less than 50% indicate a low degree of similarity in terms of species diversity between the two survey sites.

Suitable habitat and geographic distribution potential modeling show that more than 30% of the study area is suitable for supporting the growth of WEFs. WEFs distribution in the study area was more influenced by elevation, temperature, precipitation, and isothermality. The dominant WEFs are found in lowland areas, with the species' elevational optima between 200–300 m a.s.l. and then decreasing at an altitude of 1,600 m a.s.l. Tropical lowland forests are rich in species diversity and typically have higher environmental heterogeneity, which promotes higher biodiversity through the effects on ecological niches and climate refugees (Salvana et al. 2019). In addition, topography is considered the main factor for floral heterogeneity in tropical forests (Basnet 1992). The environmental heterogeneity hypothesis supported our study, which demonstrated that elevational variation has a main factor in the distribution of WEFs in the study area. Our finding shows that there are significant and positive associations between altitudinal range and distributions of WEFs in the study area and emphasizes the crucial role of mountain regions in protecting Sumatra's high biodiversity.

Temperature seasonality is the second most important factor influencing the distribution of WEFs, accounting for 12.8% of the total, and has played a larger role in limiting the distribution of WEFs than precipitation. This study is consistent with those reported in South Kalimantan, Indonesia (Gunawan et al. 2021). Temperature is an important climatic factor that determines the phenology of important life cycle events (Ge et al. 2015), such as flowering, fruiting, and withering (Li et al. 2016), and also may have an indirect effect on plant growth (Doughty and Goulden 2008). This study is different from other studies that found that rainfall was the main driver of large-scale distribution patterns of tropical plant and tree species (Maharjan et al. 2011). In the study areas, annual precipitation contributes only 1.9% to determine the distribution of WEFs. Precipitation in the study area is more region-specific rather than showing a strong trend with elevation, which is considered due to the topographic barrier posed by ranging from Bukit Barisan Mountains. This is consistent with several researchers' findings that precipitation is more region-specific due to topographic barriers such as in the Himalayan (Lillesø et al. 2005; Maharjan et al. 2022). In addition, precipitation seasonality contributed only 4% to the distribution of WEFs in the study area. It is comparable to the 5% contribution of precipitation seasonality to plant distribution in Ghana reported by Amissah et al. (2014), but lower than that reported by Gunawan et al. (2021) in South Kalimantan, Indonesia, where precipitation seasonality contributes 7.2% to the distribution of WEFs. Our findings also contradict the report by Borchert (1998) considers that precipitation seasonality has a strong influence on tropical tree distribution.

The majority of the taxa found in the studied area have conservation value and importance. Out of the 326 species recorded, 160 (49.07%) species were threatened status. *Castanopsis argentea* is listed as Engendered, while *Aglaia angustifolia*, *Artocarpus anisophyllus, Castanopsis scortechinii, Ctenolophon parvifolius*, *Durio graveolens*, *Durio lowianus*, *Horsfieldia polyspherula*, *Mangifera similis*, and *Saurauia bracteosa* are listed as vulnerable species according to IUCN (2020). The presence of threatened species in the area may also be due to the area's accidental nature and increased human activities, particularly agricultural expansion to areas that were relatively accessible, letting the inaccessible areas remain relatively undisturbed. Several threatened species, such as *Castanopsis argentea*, have been used as timber, which may be the cause of their population decline in the wild.

WEFs play an important role in not only providing environmental services in the form of regulatory services such as carbon sequestration, erosion prevention, soil fertility maintenance, and water flow regulation, but also as providers of environmental services such as food, raw materials, and medicine, which are essential for human life. Deforestation, which has increased in recent years, particularly in Indonesia, has contributed to the endangered of many wild species, including WEFs. Immediate in-situ and ex-situ conservation efforts are required to prevent the extinction of various WEFs in nature. Plant conservation organizations, such as Botanical Gardens, can contribute to ex-situ conservation by collecting, propagating, and cultivating WEFs. Given the high potential for a suitable habitat of WEFs in the study areas, local people can be involved in actively practicing the cultivation of WEFs by combining these species with crops in their orchards, home gardens or farmland to reduce the overharvesting of WEFs from nature. This concept has also been used in other parts of Indonesia, such as forest management in Banyuasin district, South Sumatra (Undri 2016), and management of Tembawang in Bengkayang district, West Kalimantan (Asmeliati et al. 2020). Wild fruits have implications for the development of agricultural systems as a source of local food (Navia et al. 2020), as well as for traditional medicine (Elfrida et al. 2021; Navia et al. 2021; Suwardi et al. 2021). This activity, in addition to conserving WEFs, has the potential to improve the economy of the local community again through the production and marketing of WEFs and, in the long term, to ensure the availability of WEFs.

# Conclusions

A total of 326 WEFs belonged to 74 botanical families and 170 genera were recorded. Of the 326 species, 125 species are found in the western Bukit Barisan Mountains and 228 species in the eastern Bukit Barisan Mountains. However, a total of 202 species were discovered only in the eastern Bukit Barisan Mountains, while 37 WEFs were discovered only in the western Bukit Barisan Mountains. The elevation is the most important factor influencing the distribution of WEFs in the study areas. More than 30% of the study area is suitable for supporting the growth of WEFs, with the greatest concentration of highly suitable areas primarily predicted in Sumatera Barat province. Of 326 WEFs recorded in Bukit Barisan Mountains, 0.3% species are currently classified as Endangered, 9 3% species as Vulnerable, 3% species as Near Threatened, 42% species as Least Concern, 0.6% as Data Deficient, and 51% species had No Available Data in the IUCN red list. To ensure the future availability of WEFs, in-situ and ex-situ conservation efforts must be carried out in collaboration between the government, communities, and conservation organizations.

# Declarations

Competing interests: No potential conflict of interest


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### Authors' contributions

**Conceptualization**: S, EM, ABS. Methodology: EM, S, ABS. **Data collection, formal analysis and investigation**: ABS, N. **Writing — original draft preparation**: ABS. **Writing — review and editing**: EM, S, N, ABS. All authors read and approved the final manuscript.

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### Data availability

The datasets generated during the current study are available from the corresponding author on reasonable request.

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# Figures

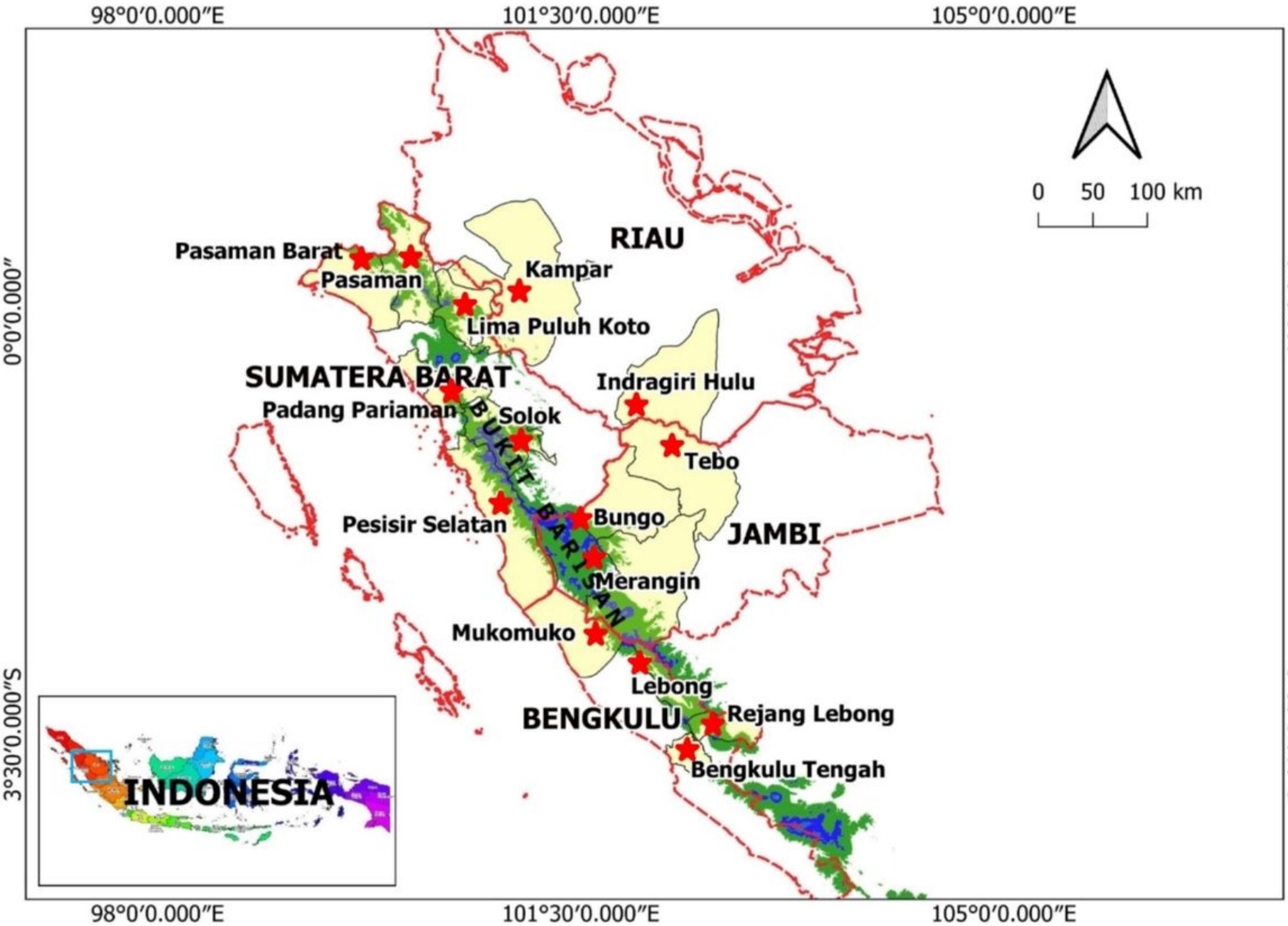
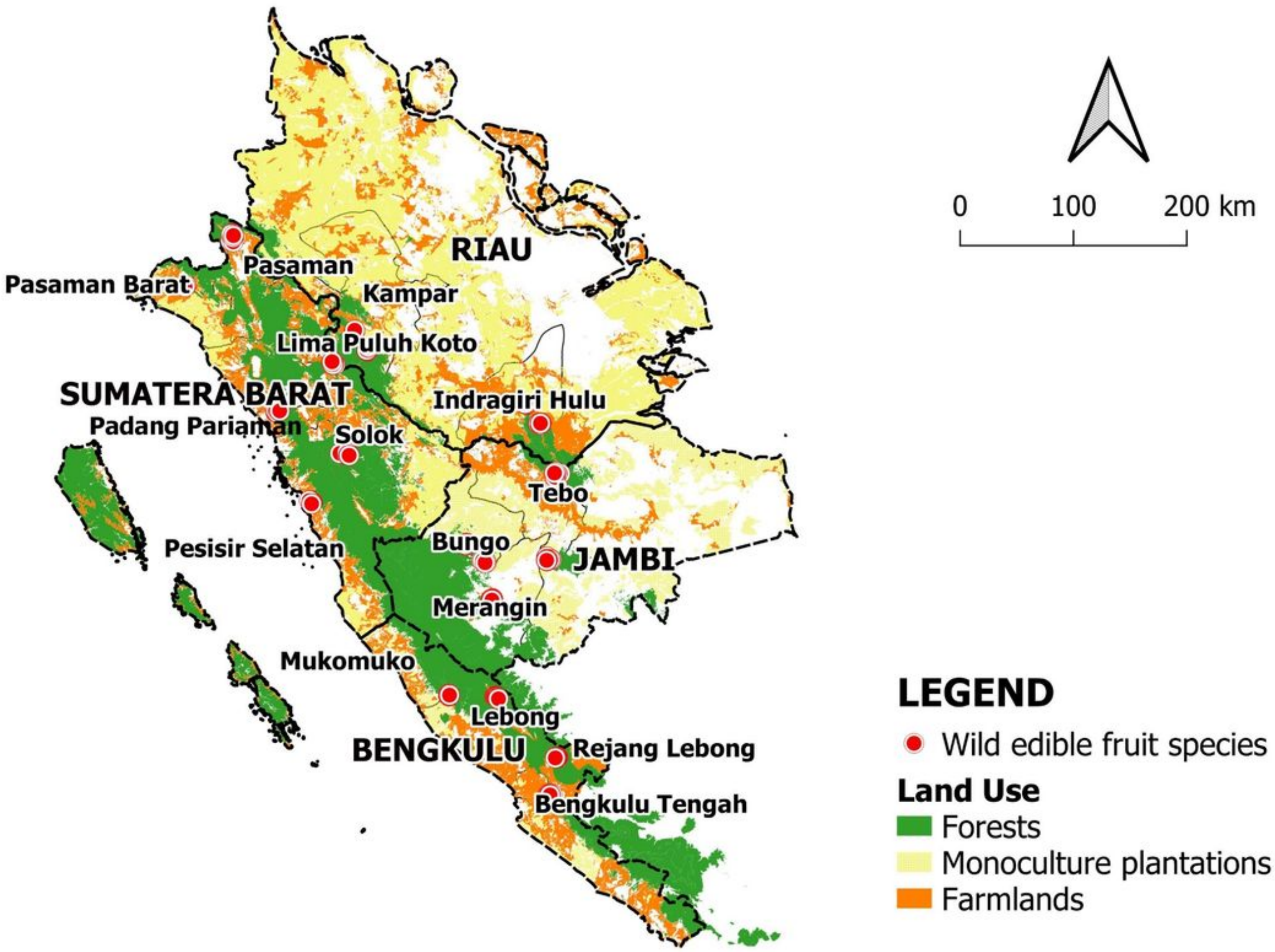



**Fig. 1**. The map of the study area and (★) shows the site of the study

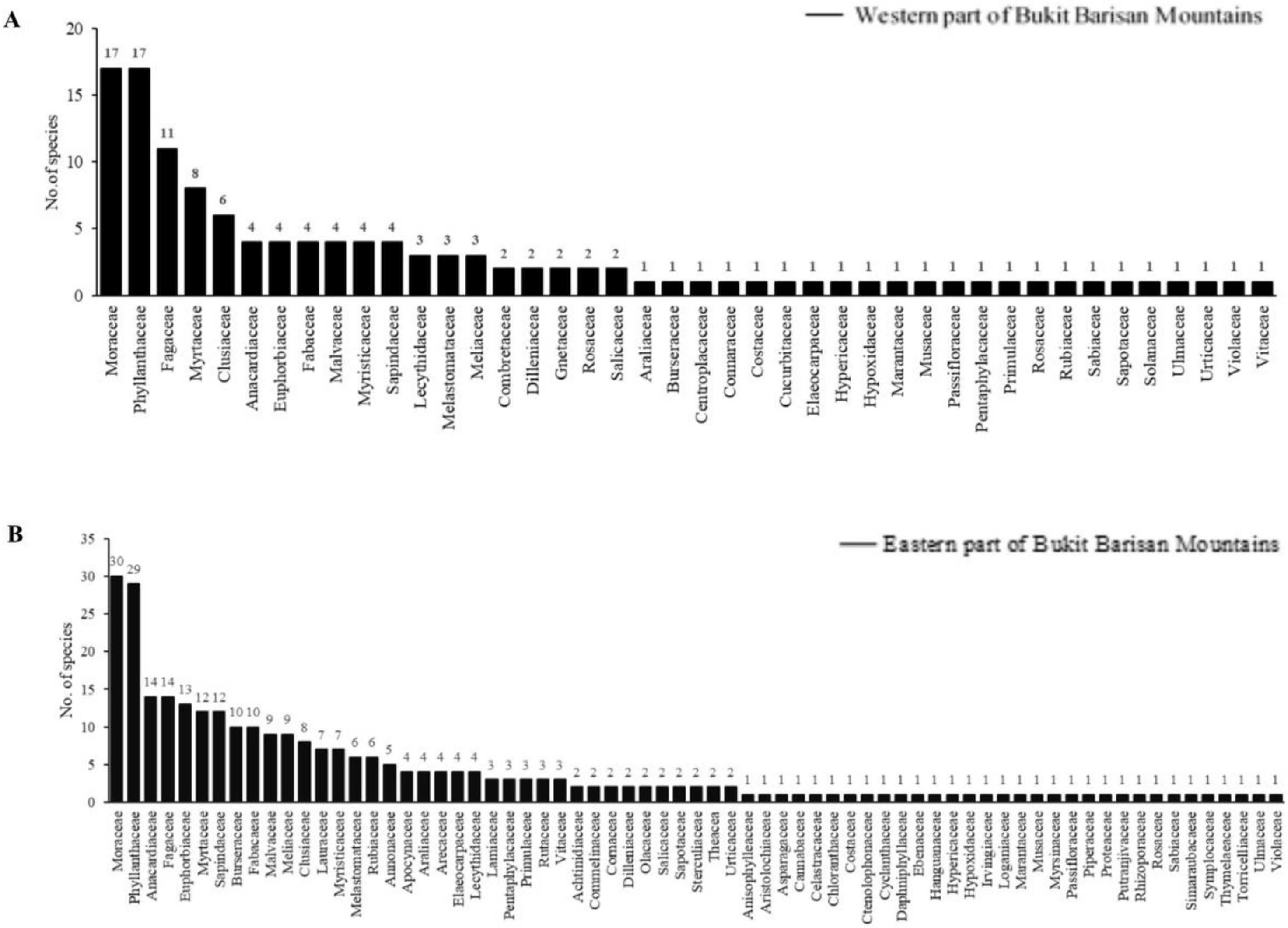
## Figure 1

See image above for figure legend



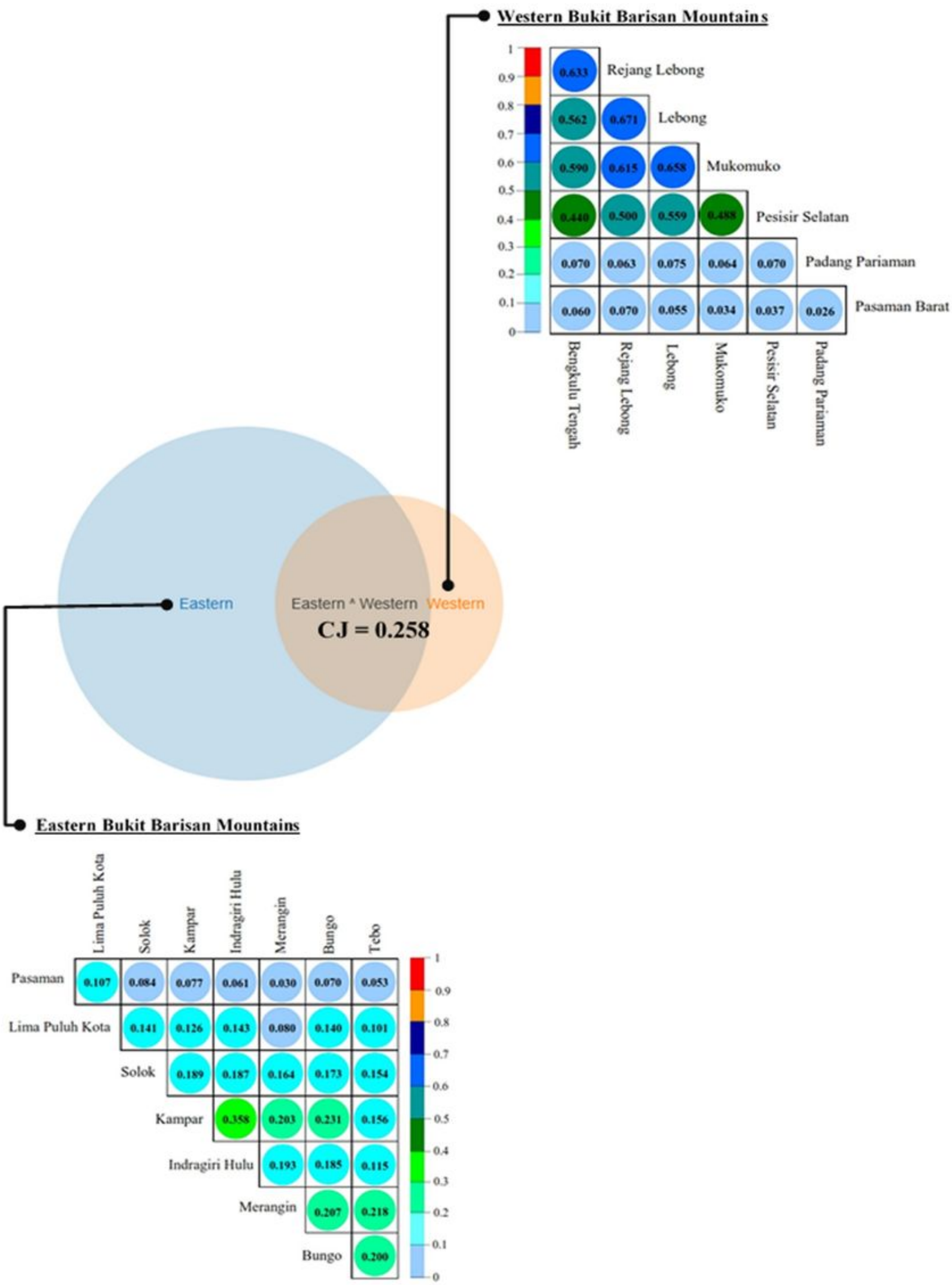

## Figure 2

Distribution point data for wild edible fruit species in the study area




## Figure 3

Botanical families of wild edible fruit species distribution in the western Bukit Barisan Mountains (A) and the eastern Bukit Barisan Mountains (B).




## Figure 4

Coefficient Jaccards similarity index

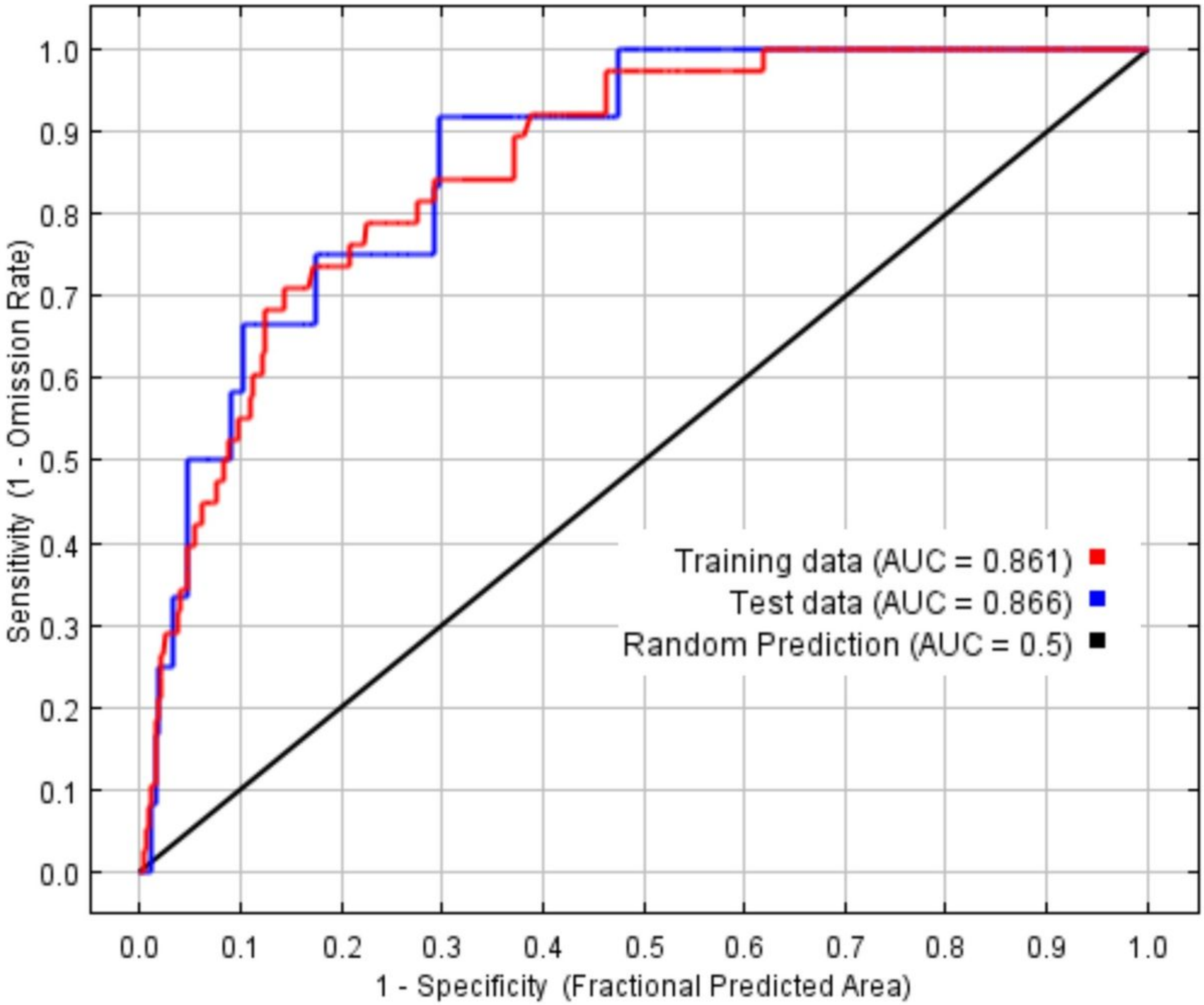
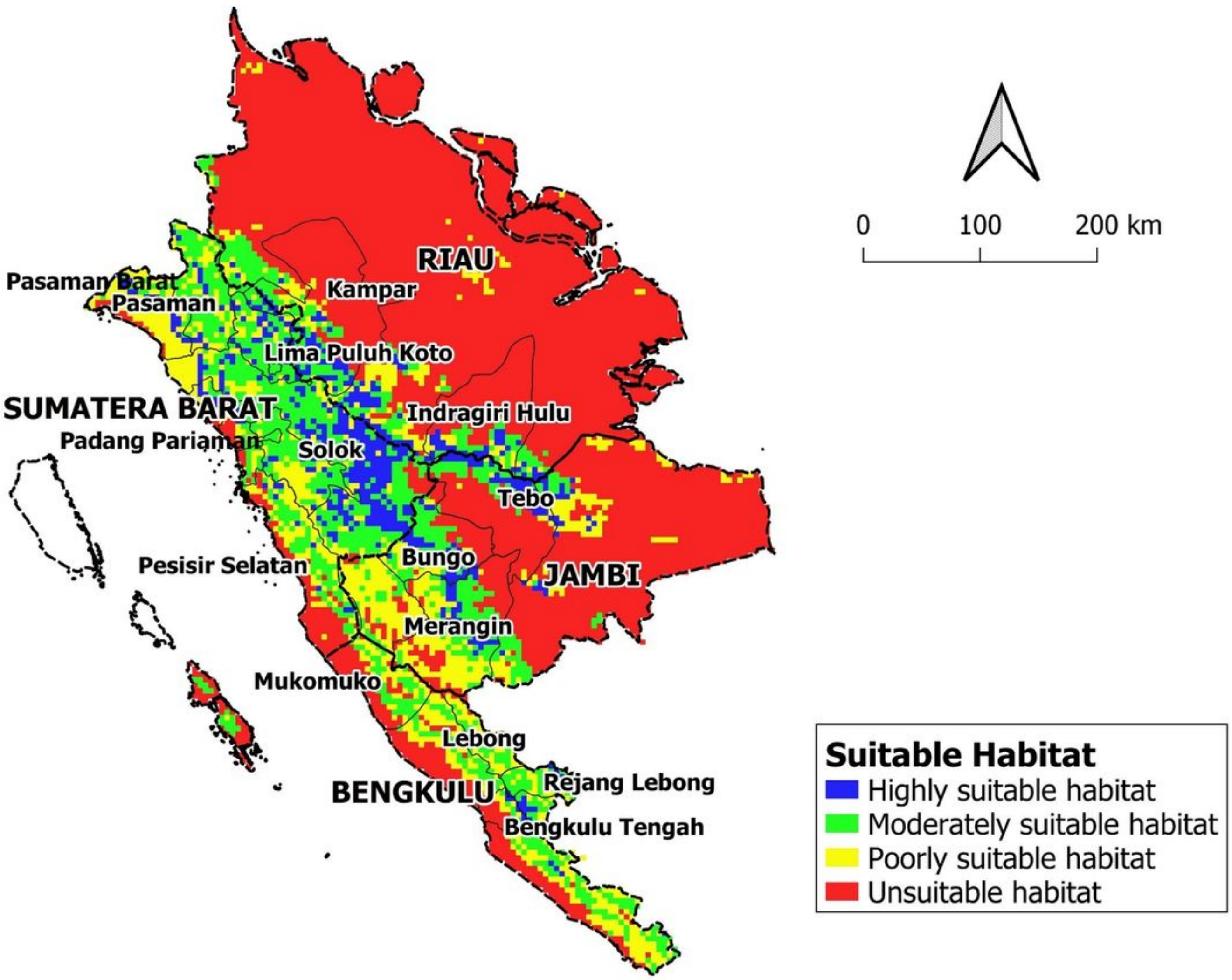



**Figure 5**

ROC curve of the Maxent model of wild edible fruit species




## Figure 6

Potential suitable habitat for wild edible fruit species under current climate condition

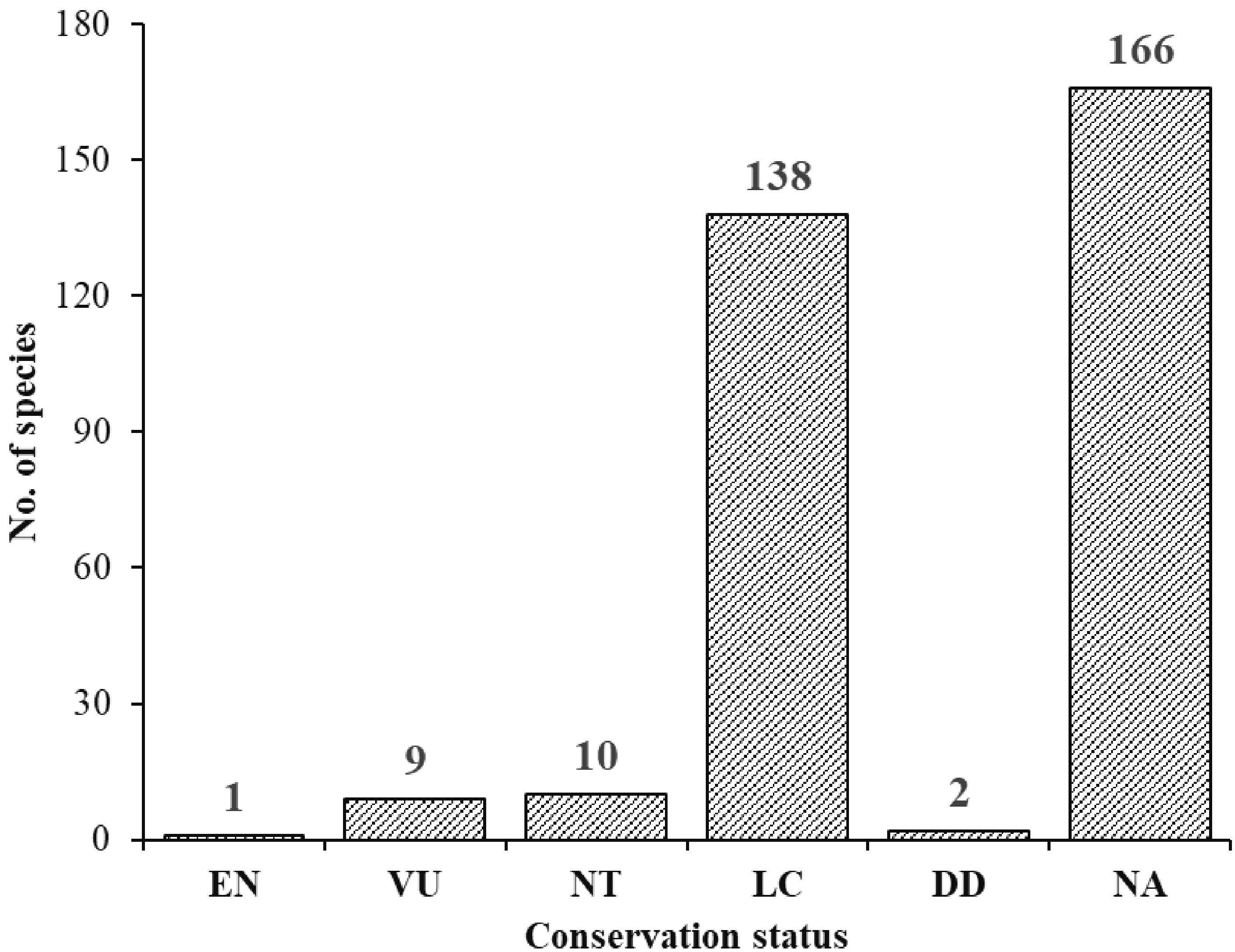



**Figure 7**

The number of wild edible fruit species on the IUCN Red List of Threatened Species (2020) is classified by class and risk category. NA: Not Available; DD: Data Deficient; LC: Least Concern; NT: Near Threatened; VU: Vulnerable; EN: Endangered

## Supplementary Files

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