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Species Distribution Model and Conservation of *Mentaok* (*Wrightia javanica*) in Indonesia

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Abstract

The Alas Mentaok was a forest dominated by the mentaok tree (Wrightia javanica) that once existed in Yogyakarta, Java Island, Indonesia. This forest has cultural and historical value, as it is believed to be the first location to establish the Mataram Islam Kingdom in Java in 1582 AD. This study utilized species distribution models (SDMs) to investigate the species distribution pattern and assess its latest conservation status in Java and the Lesser Sunda Islands, Indonesia. The methodology used involved collecting occurrence and environmental data of W. javanica, conducting species distribution modeling using the maximum entropy algorithm, evaluating the model's accuracy, and performing an independent assessment of the area of occupancy (AOO) and extensive occurrence (EOO) using the geospatial conservation assessment tool (GeoCAT). Whereas the number of suitable habitat areas for W. javanica in Yogyakarta is projected to decrease by 2100, the islands of Sumba and Timor are anticipated to experience an increase in the suitable habitat areas for the species during the same year. The analysis of BIOCLIM 34 indicates the mean moisture index of the warmest quarter plays a vital role in the current and future projections. AOO calculation in GeoCAT places this species in the endangered (EN) category, particularly within our regions of interest in Java and the Lesser Sunda Islands. Overall, a full assessment combining a habitat suitability model with current conservation status information would provide a more comprehensive understanding of mentaok's habitat preferences and current conservation status in Indonesia.

Keywords: *conservation assessment, endangered species, GeoCAT, habitat suitability, MaxEnt*

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Introduction

The *Alas Mentaok* was a forest dominated by *mentaok*, the local name for the flowering plant *Wrightia javanica* A.DC., from the group Apocynaceae. The *Alas Mentaok* forest once existed in Yogyakarta, Java Island, Indonesia. This forest is believed to be the first location for establishing the Mataram Islam Kingdom in Java in 1582 AD. Therefore, the *mentaok* tree holds cultural and historical value for the people in Yogyakarta. The locals of Kotagede, Yogyakarta City, used *mentaok* trees for shade, decoration, and conservation (Lestari, 2018). In Yogyakarta, *mentaok* wood is used to make *warangka*, a wooden sheath for an Indonesian traditional dagger called *keris* (Syahbudin et al., 2018; Cipta et al., 2022). *Warangka* often showcases intricate carvings and decorations, making them a significant part of the overall aesthetic appeal of a *keris*. The sap from the *mentaok* tree is used by the community of Purwodadi Village, Tepus District, Gunung Kidul Regency, Yogyakarta Province, to treat sore eyes and hematemesis (Faida et al., 2018). *Mentaok* has also been utilized in other parts of Indonesia for various purposes. In Lombok Island, West Nusa Tenggara Province, *mentaok* is known as *jeliti* and used by the Sasak tribe as a traditional medicine to treat rheumatism (Yamin et al., 2018; Hakim et al., 2020), traditional food (local soft cheese) that originated in Taliwang, West Sumbawa (Kisworo, 2022). In Mbeliling Village, Flores Island, East Nusa Tenggara Province, *mentaok* is known as *niti*, and the Manggarai tribe uses the bark as a mixture to treat blood system disorders (Mulu et al., 2020). *Mentaok* leaves produce *wrightiamine A*, the pregnane alkaloid with cytotoxic properties, effectively inhibiting the growth of vincristine-resistant murine leukemia P388 cells (Kawamoto et al., 2003).

W. javanica A.DC. is a heterotypic synonym of *W. pubescens* subsp. *laniti*. The geographical distribution of this subspecies extends from Southern China, Indonesia, Malaysia, and the Philippines (Kew Science, 2023). There is still limited research on this species, and the IUCN Red List has not yet mapped its distribution and conservation status. *Mentaok* seedlings from the Lesser Sunda Islands were once collected from Bali Island and planted in the Bali Botanic Gardens in 1998. Unfortunately, these *mentaok* trees died in 2014 (Bali Botanic Gardens, 2023). Considering the historical value of *mentaok* and its potential uses, added to the limited number of remaining trees, e.g., in Yogyakarta

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and Bali, steps should be taken to facilitate the conservation of this species. Therefore, this study utilized the species distribution model (SDM) to investigate and predict the species distribution pattern of *mentaok* and assess its latest conservation status in Java and the Lesser Sunda Islands, Indonesia.

The distribution and conservation status of native species are key factors for effective conservation decision-making. Understanding species distribution is important because it helps identify areas with high habitat suitability and prioritize conservation efforts (Swan et al., 2021). Delimitation of distribution areas is crucial for determining the risk category of a species and identifying areas of endemism (Mota-Vargas & Rojas-Soto, 2012). Knowing the locations of different species helps assess their conservation status. For this purpose, SDMs or habitat suitability models can be valuable tools to estimate a species' range area and potential locations in various geographical contexts, which can assist in identifying areas suitable for reintroducing lost species or discovering new ones (Rahman et al., 2019). By incorporating relevant predictors such as bioclimatic variables, elevation, land use, and landscape structure, SDMs can provide valuable insights into the factors influencing the distribution of native plant species (Krause & Pennington, 2012).

Overall, a full assessment combining a species distribution model with current conservation status information would provide a more comprehensive understanding of *mentaok*'s habitat preferences and current conservation requirements in Yogyakarta and elsewhere in Indonesia. Therefore, the primary objective of this research is to develop a habitat suitability model for *mentaok* using environmental variables and occurrence data. Specifically, we aim to: a) identify the driving environmental factors influencing the distribution of *mentaok*, b) predict the current and future distribution range of *mentaok* in Java and the Lesser Sunda Islands, and c) assess the conservation status of *mentaok* by analyzing various factors, such as population trends, habitat loss and fragmentation, and threats to the species. This combined approach aimed to comprehensively assess conservation needs for this culturally valuable tree species in Indonesia.

Methods

Species description ***Accepted name*** *Wrightia pubescens* subsp. *laniti* (Blanco) Ngan-Ann. Missouri Bot. Gard. 52:153 (1965). ***Synonyms*** *W. ovata* A.DC., *W. javanica* A.DC., *W. laniti* (Blanco) Merr., *W. tomentosa* var. *cochinchinensis* Pierre ex Pit., *W. calycina* A.DC., *W. spanogheana* Miq., *W. multiflora* Zipp. Ex Span. ***Descriptions*** Adapted from the determination key written by Ngan (1965). ***Plants*** of tropical Asia, small trees. ***Leaves*** densely puberulent to glabrescent above. ***Inflorescence*** aggregate dichasial, 4060-flowered leaves exhibiting puberulent texture at least along the veins on the underside, rarely glabrous (hairless). ***Flowers*** fragrant, possessing a subrotate and salverform corolla, with a relatively stout tube shorter than the lobes, approximately 4 mm in length, and glabrous (hairless) on the inner side. ***Corona*** typically as long as the stamens, is puberulent on the inner side, occasionally pubescent; alternipetalous corona segments are present, and corona segments dentate to crenulate. ***Stamens*** are relatively stout and inserted at the orifice (opening) of the corolla tube. ***Anthers*** completely exserted (protruding beyond the corolla), frequently pubescent without, sometimes glabrous, with the basal anther lobes auriculate (ear-shaped) or occasionally attenuate (tapering), as long as or shorter than the filament. ***Antepetalous*** strongly adnate to the blade of the corolla, measuring 37 mm in length; the antepetalous segments medially adnate to the corolla lobes, relatively narrow, with the alternipetaloussegments being 2/3 to about as long as the antepetalous segments. ***The filament*** is relatively short and stout. ***Calycine*** squamellae are ovate, broadly ovate to orbicular, acute, 1/4 to half as long as the corolla tube, measuring about 2.5 m in length. ***Follicles*** are coherent and compressed laterally along the commissure. The *mentaok* herbarium sketch can be seen in Figure 1.

Data collection *Herbarium records W. javanica* was the subject of a herbarium drawing created from a living specimen at the Bali Botanical Garden. The specimen can be found in compartment IV.C of the Apocynaceae family. The accession number is E19940321. Then, the morphological description was observed and noted.

Species occurrence data and environmental predictors We gathered *W. javanica* species occurrence data from desktop studies of government documents/web pages (Akashi, 2023), herbarium records and local databases (I Made Sumerta, personal communication, Bali Botanical Garden), and scholarly publications (Handayani & Priyono, 2016; Hakim & Yuliah, 2018; Lestari, 2018; Syahbudin et al., 2018; Susilo & Asmara, 2020). The information included locations (latitude and longitude) where the species was sighted in Yogyakarta or elsewhere in Indonesia. The dataset (lat, long in decimal degree format) was then saved as a .csv file and uploaded to the Ecocommons platform, which uses the WGS-84 map projection.

Ecocommons is a comprehensive web-based modeling platform that provides a collection of environmental layers, as well as options for importing species occurrence data from third-party sources (Atlas of Living Australia-ALA, Global Biodiversity Information Facility-GBIF, and Ocean Biodiversity Information System-OBIS), and the ability to upload our species occurrence dataset (EcoCommons, 2022). It also offers various modeling algorithms, including geographical, machine learning, statistical regression, and profile models. The platform was previously named the Biodiversity and Climate Change Virtual Laboratory (BCCVL) and has since been used in scholarly publications (Hallgren et al., 2016; 2017; Low Choy & Huijbers, 2017; Sutomo & van Etten, 2017; Booth, 2018; Richmond & Huijbers, 2019; Cravero et al., 2020; Afrianto, 2021; Sutomo et al., 2021a; 2021b; Vaganov et al., 2022; Saputra et al., 2023; Sutomo et al., 2023a; 2023b; 2023c).

We found that *mentaok* is not well documented in scholarly publications or global databases during the data collection. While the worldwide database contains only 24 species occurrences for *W. javanica*, we gathered ten local occurrences from literature studies and Indonesian Botanical Garden databases. The smaller dataset of 10 occurrences is

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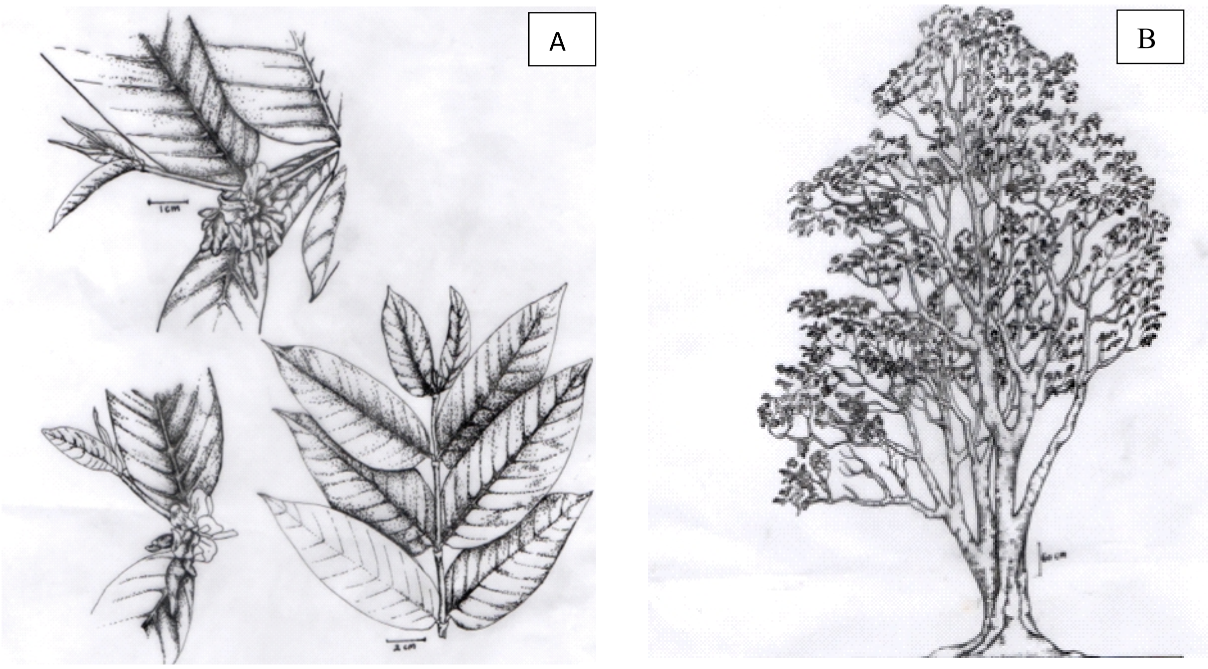

Figure 1 A sketch of *mentaok* (*Wrightia pubescens* subsp. *lanitii*, Apocynaceae) drawn from a type specimen herbarium collection of Kew's Herbarium, Royal Botanic Gardens Kew (A); and a sketch of *W. pubescens* tree drawn from a living collection at Bali Botanic Gardens (B). Both were worked by I Made Sumerta.

used because it is more specific to the local context and likely more accurate in representing the distribution of *W. javanica* in the study area. The dataset was checked for spatial errors and taxonomic inconsistencies before use in modeling.

We collected environmental characteristics that may influence *W. javanica* distribution under climate change. In this case, we used climate data (temperature, precipitation) from Climond Global (www.climond.org) (Kriticos et al., 2012), which is available in the EcoCommons environmental layers dataset (bioclim 01-35), providing past (1990) and future (2100) climate data projections. Future SDM projections utilized Climond global climate data based on CSIRO-MK3.0 at 10-arcmin (~20km) for 2100 under the SRES-A1B emissions scenario. The Intergovernmental Panel on Climate Change issued the SRES (the Special Report on Emissions Scenarios), outlining the baseline of greenhouse gas emission scenarios without considering potential reduction policies (IPCC, 2000). The SRES-A1B scenario used in this study's future climate modeling allows the impacts of any mitigation efforts to be evaluated against baseline reference conditions. This scenario portrays a forthcoming era characterized by swift economic expansion, a worldwide population peak around the middle of the century followed by a decline, and the rapid adoption of advanced and more effective technologies by considering the balanced approach encompassing all energy sources (fossil and non-fossil energy sources) (IPCC, 2000).

Species distribution modeling *Selection of modeling algorithms* MaxEnt modeling technique (Elith et al., 2011) was chosen to analyze the SDM of *W. javanica.* The Maximum Entropy (MaxEnt) modeling approach forecasts species occurrences by determining the distribution pattern that exhibits the most spread out or closest to uniformity while considering the limitations imposed by known environmental factors (Elith et al., 2011; BCCVL, 2021). With over 1,000 documented applications since 2006, MaxEnt has emerged as one of the most widely adopted tools for modeling species distributions and environmental niches (Merow et al., 2013).

MaxEnt is particularly suitable for studies with small sample sizes, such as our dataset of 10 occurrences for *W. javanica*. Wisz et al. (2008) conducted a comprehensive comparison of various modeling methods across different sample sizes and found that MaxEnt consistently performed well, even with sample sizes as low as 10. MaxEnt's superior performance with small sample sizes is due to its adaptive regularization, which adjusts model complexity based on available data, effectively preventing overfitting when occurrence records are limited (Wisz et al., 2008).

There are several advantages to employing MaxEnt, including the requirement of solely presence datacoupled with the ability to incorporate both continuous and categorical predictor variables. Interactions between predictor variables are included. A regularization technique is included to prevent overfitting. It generally has excellent predictive ability (BCCVL, 2021). This technique is already available in the EcoCommons platform (EcoCommons, 2022). We then apply the learned model to the environmental data layers to create a prediction distribution map for *W. javanica*. Based on the environmental criteria evaluated, this map will identify favorable places for the species. The suitable area will be distributed from 0 to 1, where the higher value indicates the suitability of the species to occur and vice versa (Saputra & Lee, 2021).

Model calibration and validation Evaluation metrics such as area under the curve (AUC) are employed to quantify the model's accuracy. This curve serves as a non-parametric, threshold-independent accuracy measure used to evaluate SDM. The ROC plot's x-axis represents the false positive rate (1-specificity), whereas the y-axis represents the true positive rate (sensitivity). Values greater than 0.5 indicate a better forecast than random, whereas values less than 0.5 indicate a random prediction. Crego et al. (2014) categorized the AUC score as follows: value greater than 0.9 is excellent, good 0.9 > AUC > 0.8, fair 0.8 > AUC > 0.7, poor 0.7 > AUC > 0.6, and fail 0.6 > AUC > 0.5.

Conservation status assessment *W. javanica* is not on the IUCN red list, perhaps due to not having had any assessment of this species that has been done and proposed before. We independently assessed the species' Area of Occupancy (AOO) and Extent of Occurrence (EOO) using the Geospatial Conservation Assessment Tool (GeoCAT), a simple and powerful tool for performing quick geographic analysis of species (Bachman et al., 2011; Kew, 2023). GeoCAT, endorsed by Kew Gardens, ViBRANT, and the IUCN, supports the Red Listing process to identify and conserve threatened species (Bachman et al., 2011). AOO refers to the area filled by taxons in the more prevalent EOO (IUCN, 2012). AOO species are among the most commonly used criteria in IUCN Red List evaluations. Adhering to Criterion B, the IUCN Red List assessment utilizes specific geographic range metrics (AOO and EOO) to evaluate species. The AOO for the analysis is calculated based on IUCN guidelines, employing a 2 km grid cell width (IUCN, 2012). The determination of AOO and EOO is facilitated by GeoCAT, a web-based application that leverages primary biological data for semi-automated IUCN Red List assessment and analysis. This open-source tool enables rapid geographic analysis, aiding in the self-assessment process for Red List species (Bachman et al., 2011). The occurrence data we have gathered and used in EcoCommons are also used in the GeoCAT. We imported the .csv data into GeoCAT, and the occurrences of *W. javanica* was mapped to derive information pertaining to the AOO and EOO. To gain insights into these geographic range metrics, the EOO/AOO functionality within the application was activated. GeoCAT automatically generated the polygon and displayed a suggested conservation status.

Results and Discussion

Current distribution and environmental factors The current distribution model of *W. javanica* (Figure 2B) indicates that the species is primarily distributed across three regions: Yogyakarta Province (1,634.7 km^2), several areas in East Java Province (91,893.7 km^2), and several locations in East Nusa Tenggara Province (2,802.5 km^2), including Sumba and Timor Islands. Four environmental factors are responsive to *Wrightia's* current distribution model: mean moisture index of the warmest quarter (27.5%), radiation seasonality (20.5%), precipitation of the coldest quarter (15.4%), and precipitation seasonality (10%) (Figure 3). According to this projection, *W. javanica* shows higher habitat suitability in areas with specific environmental characteristics: a mean moisture index of at least 1 (indicating no water stress), minimal variation in radiation seasonality (preferring consistently sunny areas), lower precipitation during the coldest quarter, and stable precipitation patterns throughout the year.

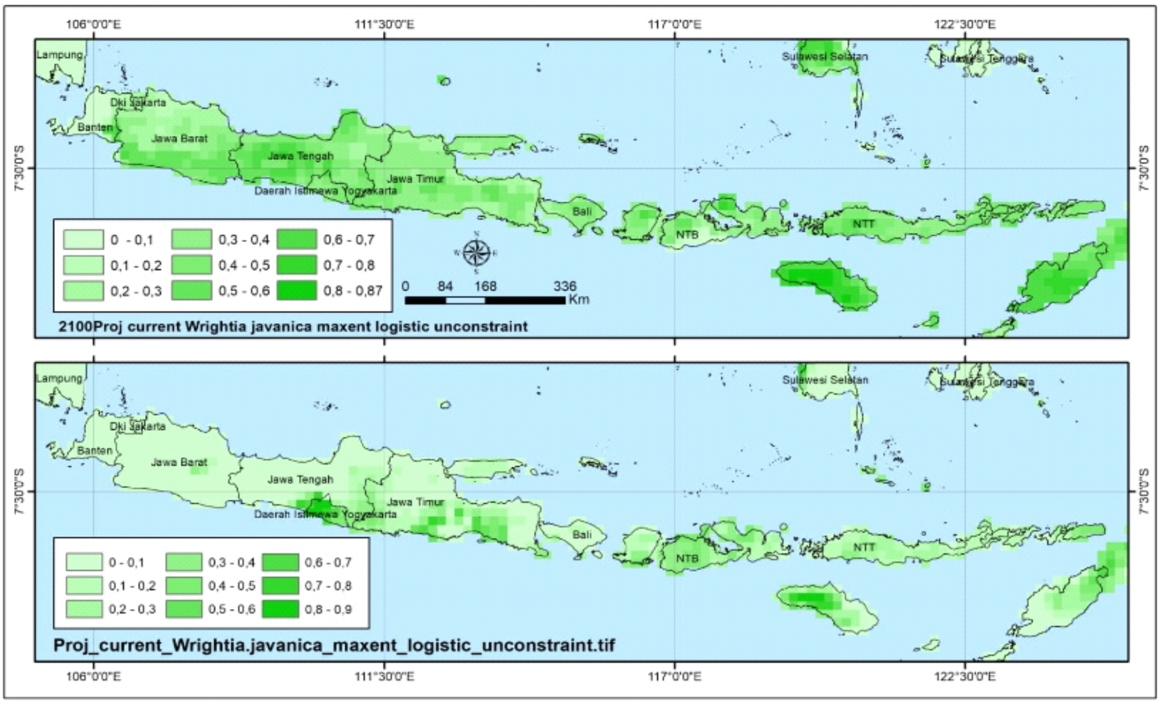

Figure 2 *Wrightia javanica* distribution model across Java and Lesser Sunda Islands; future/year 2100 (A) and current (B) projections. Darker areas indicate a more likely *Wrightia javanica* attribute.

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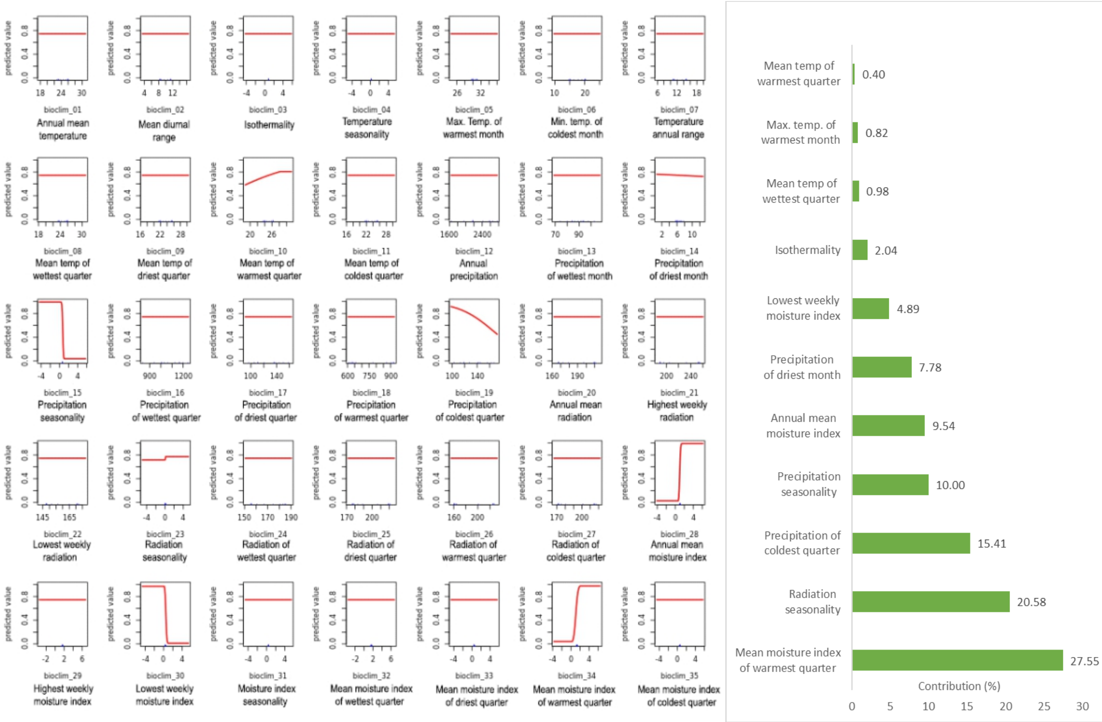

Figure 3 The response curve for *Wrightia javanica* current species distribution model (left) and percentage of environmental factors contribution in the resulting model (right).

In its actual habitat, *W. javanica* thrives in environments typical of tropical Indonesian climates, characterized by warm temperatures, high moisture indices, consistent sunlight exposure, and distinct wet and dry seasons (Kew Science, 2023). These conditions align with the current climate in Yogyakarta, which has a monthly average temperature of 26.02 °C and monthly average precipitation of 268.48 mm (BPS Yogyakarta, 2023). In contrast, East Sumba experiences slightly warmer conditions, with a monthly average temperature of 27.58 °C, monthly air humidity of 76.83%, and monthly precipitation of 75.33 mm (BPS Sumba Timur, 2023). Our distribution model demonstrates excellent predictive performance, as evidenced by the ROC plot with an AUC value of 0.95 (Figure 4).

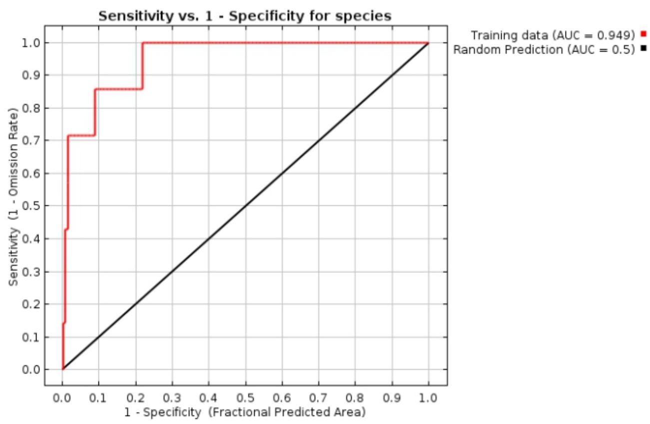

Figure 4 The area under the curve (AUC) to measure the current projection model's accuracy.

Future distribution projections Climate change will most likely increase the areas where *W. javanica* will be suitable for distribution (Figure 2A). Thus, there will be a shift in the distribution of species. Yogyakarta Province will have a decrease in the suitable habitat for the species (107.1 km^2). In contrast, the species would spread to Central Java (5,087.8 km^2) and West Java, including Banten (1,019.7 km^2). There will be an increase in the suitable habitat in East Nusa Tenggara Province in the year 2100 (17,430.6 km^2). The islands of Sumba and Timor will be the locations where the species will be evenly distributed. As for the future projection (Figure 5), environmental factors that are responsive are namely radiation of the driest quarter (37%), precipitation of the warmest quarter (18.7%), mean moisture index of the driest quarter (17.2%), and highest weekly moisture index (11.6%). The ROC plots perform well with an AUC value of 0.85 (Figure 6).

However, this study predicts that the number of suitable habitat areas for *W. javanica* in Yogyakarta in 2100 will decrease. Meanwhile, the number of suitable habitat areas on the islands of Sumba and Timor is projected to increase in 2100. Previous studies estimate only a few *mentaok* trees in Yogyakarta (Sudrajat, 2012; Hakim & Yuliah, 2018; Lestari, 2018; Faida & Marhaento, 2019; Akashi, 2023). Kotagede market and Imogiri royal cemetery are those locations where *mentaok* can still be found in Yogyakarta, with only a few individuals.

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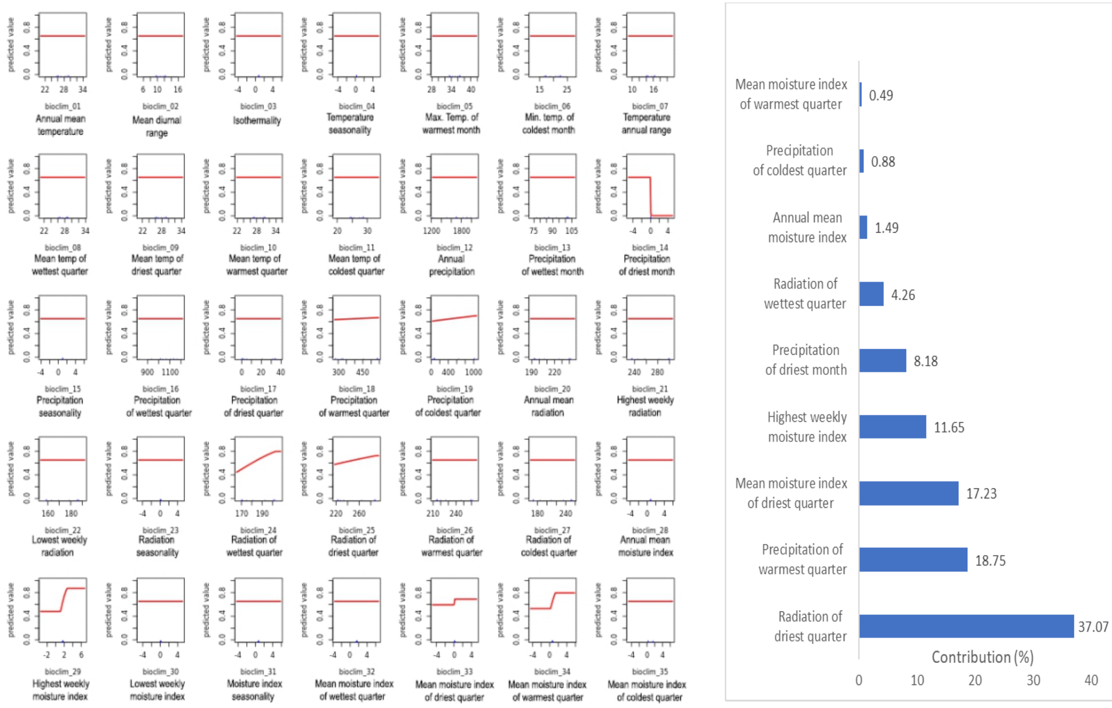

Figure 5 The response curve for *Wrightia javanica* future species distribution model (left) and percentage of environmental factors contribution in the resulting model (right).

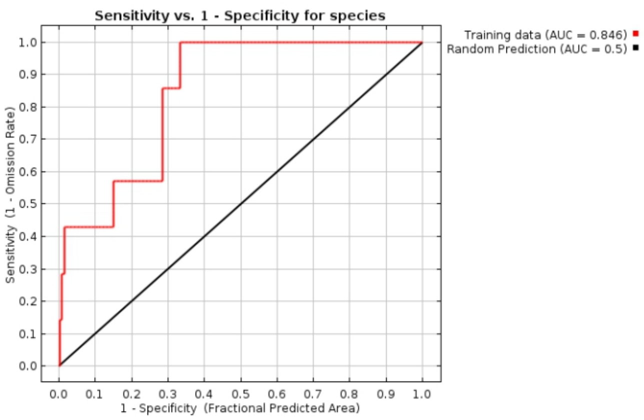

Figure 6 The area under the curve (AUC) to measure the future projection model's accuracy.

Based on the results, the mean moisture index plays a vital role in the current and future projections. The mean moisture index of the warmest quarter measures the average moisture conditions in a specific region or place during the hottest three months of the year. The index considers the amount of rainfall or precipitation received and evapotranspiration. The resulting mean moisture index indicates the moisture availability during the hottest part of the year. It can be used to assess the suitability of an area for certain types of vegetation and agricultural practices or even for understanding the potential impacts of climate change on water resources in a specific region. From the observation of the bioclim_34 climate data, both in the current and future 2100, it is seen that there will be changes. The value or bioclim_34 index will decrease from the current projection to future projection, especially in Java, Bali, Lombok, Sumbawa, Flores, and Sumba Islands, where these areas will likely become drier in the future in the 2100 projection.

Aside from the mean moisture index, precipitation, and radiation are major predictors of species distribution in the present and future. The graph for precipitation in the coldest quarter (Figure 3) shows that the expected value decreases as the number of precipitation increases. This result is similar to several research for tree species such as *Mentha pulegium L.* in Tunisia (Soilhi et al., 2022), and *Daphne mucronata* in central Iran (Abolmaali et al., 2018). Both explain that the precipitation of the coldest quarter affected the distribution of species by shifting in future predictions. On the other hand, the expected value of precipitation in the warmest quarter in the future (Figure 5) increases as precipitation increases. This result indicates that *W. javanica* tolerates a large amount of precipitation. Thus, the warmest conditions in the future must balance with a large amount of precipitation to survive.

Meanwhile, the larger the radiation, the higher the estimated value of *W. javanica*, indicating that the largest region of sunshine is significant in *W. javanica* dispersion requirements. As *W. javanica* is known to have a wide variety of forest habitats (Middleton, 2005), this result describes the shift of *W. javanica* distribution that tends to favor the drier environment of Sumba and Timor Island. The future projections show that *W. javanica* prefers and adapts to disturbed open areas due to its drought-tolerant and light-demanding nature (van Sam et al., 2004).

Conservation status assessment *GeoCAT analysis* In order to assess its conservation status, according to the GeoCAT

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analysis (Figure 7), the estimated Extent of Occurrence (EOO) was 286,078.2 km^2, which exceeded the extent required for the endangered category. *Wrightia javanica* is classified as Least Concern (LC) by the EOO; nonetheless, the EOO spans a considerable ocean area, as indicated in Figure 7. As a result, *W. javanica* AOO (40,000 km^2) is preferable because it fits criterion B (estimated AOO of less than 500 km^2) (IUCN, 2012) and places this species in the endangered (EN) category, particularly within our study regions or regions of interest in Java and the Lesser Sunda Islands. In other words, the value of AOO is considered more reliable. As a result, the category of AOO calculation can be used as a parameter to decide the conservation status of *W. javanica*.

Ex-situ conservation efforts A botanical garden is an ex-situ conservation institution to conserve rare, endangered, and potential (medicinal, ornamental, others) plant species as a saving of germplasm to safeguard plant biodiversity's sustainability. In Indonesia, under the National Research and Innovation Agency (BRIN), there are four botanical gardens: the Cibodas, Bogor, Purwodadi, and Bali Botanical Gardens (BBG), with the Bogor Botanical Garden being the oldest (since 1817). Private sectors, local or provincial governments, and universities in Indonesia also run several newly established botanic gardens. Every year until 2019, BBG routinely conducted field exploration to eastern parts of Indonesia to carry out plant collection and exploration, especially the rare, endangered, and potential plant species. Bali Botanical Garden records the origin of several *W. javanica* collections that were once planted in the garden from Sumba and Bali Island. *W. javanica* records from the BBG data show it grows at an altitude from 400, 600, 750 up to 850 m asl. *Mentaok* was planted in Bali Botanic Gardens in 1998. Unfortunately, this *mentaok* tree died in 2014 (Bali Botanic Gardens, 2023) and no longer exists a *mentaok* specimen in the garden's collection in the Apocynaceae compartment.

Cultural significance and historical distribution Mentaok holds significant cultural value in Yogyakarta, a province in Central Java, Indonesia's most populous island. Before urbanization, this region was covered by dense forest. The initial forest clearing occurred in the early 16th century A.D. by *Ki Ageng Giring, Ki Ageng Pamanahan,* and *Ki Juru Martani*, who received the land as a reward from *Sultan Adiwijaya*, the ruler of the Pajang Kingdom. This area later developed into the Mataram Islam Kingdom (Susilo & Asmara, 2020; Akashi, 2023) and eventually became the Province of Yogyakarta during Indonesia's state formation. The ancient forest was known as *Alas Mentaok*, where *'alas'* means forest and *'mentaok'* refers to *W. javanica*, an indigenous species that dominated this dry woodland ecosystem.

Mentaok offers diverse applications, ranging from creative productions to traditional medicine. The tree produces solid, white wood (Syahbudin et al., 2018) that is particularly valued in craftsmanship due to its workability. It plays a crucial role in creating various cultural artifacts, including wayang puppets, keris sheaths, and statues. Beyond its cultural applications, *mentaok* possesses notable medicinal properties: its sap is traditionally used to treat diarrhea, while its leaves serve as an anti-inflammatory agent for eye conditions.

Given *mentaok*'s historical significance and multiple benefits, conservation efforts are essential, particularly considering the challenges in propagation and gaps in understanding its biological cycle. Collaborative research with local government can help identify existing species distribution, develop propagation protocols, and determine suitable planting locations using SDM technology. Additional conservation strategies should focus on: a) maintaining market demand for *mentaok* wood products, b) facilitating skill transfer to new artisans in potential development areas, and c) establishing comprehensive production-marketing networks for *mentaok* wood products. These efforts would help preserve both the species' cultural heritage in its original location and ensure its sustainable utilization in newly identified suitable habitats.

Methodological strengths and limitations Biodiversity conservation requires comprehensive methods to protect and

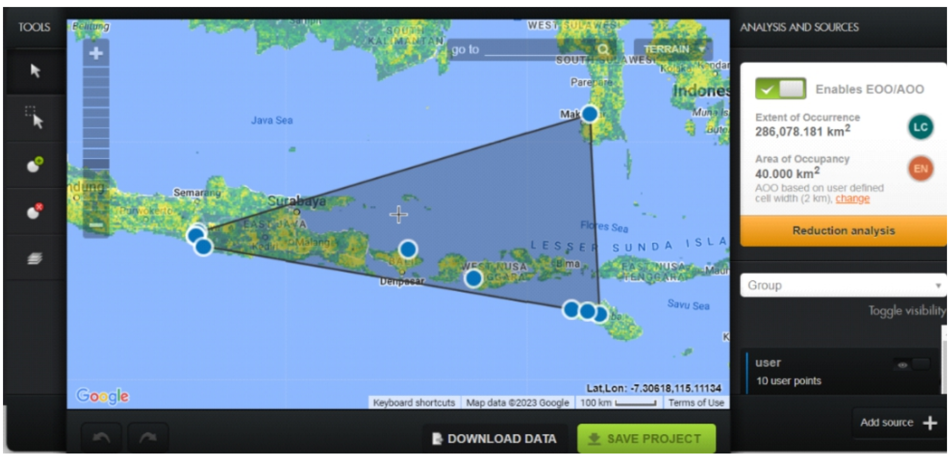

Figure 7 A screenshot of the results from the GeoCAT application website to measure *Wrightia javanica* EOO/AOO and its conservation status.

restore fragile species and ecosystems. SDM has emerged as a valuable tool for conservation efforts, forecasting species' distributions and identifying suitable sites for reintroduction programs. In this study, SDM provided critical insights into the distribution of *W. javanica*, assessing habitat and climate change effects, and identifying potential restoration areas.

Our approach combined multiple sophisticated techniques to maximize the utility of limited data. We utilized MaxEnt, which is robust for small sample sizes and incorporated a wide range of bioclimatic variables to capture complex environmental interactions. By projecting future distributions under climate change scenarios, we provided valuable foresight for long-term conservation planning. Additionally, we complemented SDM with GeoCAT analysis for a comprehensive assessment of conservation status.

These methods allowed us to gain meaningful insights despite data limitations. However, it's important to acknowledge some constraints. The small sample size of 10 occurrence points may limit the model's ability to capture the full range of suitable conditions for *W. javanica*. Additionally, the model doesn't account for biotic interactions or dispersal limitations.

Future research could enhance this work by increasing sample sizes through extensive field surveys, incorporating biotic interactions, and validating projections with long-term monitoring data. Despite these limitations, this study provides valuable guidance for *W. javanica* conservation. As modeling techniques and data availability improve, SDM will continue to play a crucial role in protecting rare and endangered plant species.

Conclusion

Habitat suitability modeling provided valuable insights into environmental factors influencing the current and potential future distribution of *mentaok*. This paper highlights habitat suitability modeling for *mentaok* using the MaxEnt algorithm and environmental variables. Our model of *mentaok* habitat identifies four main environmental factors influencing current distribution, i.e., mean moisture index of the warmest quarter, radiation seasonality, precipitation of the coldest quarter, and precipitation seasonality. Yogyakarta has high cultural value for *mentaok* but may become less suitable by 2100, while Sumba and Timor emerge as future strongholds. Projections for 2100 suggest a decrease in suitable habitat in Yogyakarta but an increase in Central Java, West Java, Sumba, and Timor Islands. Radiation and precipitation variables were most influential for future projections. Drier conditions are expected in future climates. Full assessment combining modeling with GeoCAT conservation status categorization gives a comprehensive understanding of the distribution, environmental preferences, and endangered status of *mentaok* in Indonesia. Climate change is projected to alter moisture availability and suitability for *mentaok*, with implications for conservation planning. Further field studies, population monitoring, and protective measures are recommended to conserve this culturally and ecologically important species in Indonesia.

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