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Assessing potential habitat suitability of vulnerable endemic species: a case study of *Diospyros celebica* Bakh and *Rhyticeros cassidix*

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Abstract

Diospyros celebica Bakh and *Rhyticeros cassidix* are known to be associated in several locations in Sulawesi. Both of these species are endemic to Indonesia that live throughout the island of Sulawesi. Species Distribution Modeling using Maximum Entropy (MaxEnt) is considered an alternative way to understand the potential area suitable for a species. Model predictions from MaxEnt for all species have an AUC value of 0.887 and 0.837. Suitable habitat for D. celebica Bakh in Central Sulawesi (Morowali Utara, and The southern coast of Banggai) and South Sulawesi (Luwu Timur, Luwu Utara, Toraja Utara, Barru, Pangkep, Maros, Sidrap, Wajo, Sidenreng Rappang, and Gowa). However, the suitable habitat for *D. celebica* Bakh and *R. cassidix* in the association is much smaller. Environmental variables that are considered important that influence the occurrence of *D. celebica* Bakh are Soil Types, especially soil types Dystric Fluvisols, Eutric Fluvisols, Or-thic Luvisols, Orthic Acrisols, Eutric Cambisols, rainfall, and bio13. While R. cassidix is affected by distance from roads, distance from settlements, and distance from rivers, based on actual data points and habitat predictions. Most of the suitable habitat for *D. celebica* Bakh and *R. cassidix* is estimated to be outside the conservation area, but the suitable habitat is estimated in 8 functional status conservation areas. These results can be used by the Government of the Republic of Indonesia, and the Ministry of Environment and Forestry for determination.
Keywords: *habitat suitability, Diospyros celebica Bakh, Rhyticeros cassidix, maximum entropy*

Introduction

Ebony is a luxurious wood that grows endemic to Sulawesi. Ebony consists of 90-100 species of trees, but only a few species produce heartwood. There are only 7 types of trees belonging to *Diospyros*, including *Diospyrosebenum* Koen, *Diospyrosferrea* Bakh, *Diospyroslolin* Bakh, *Diospyrospilosanthera* Blanco, and *Diospyrosrumphii* Bakh (Najmulmunir, 2003). The ebony tree (*Diospyros celebica* Bakh) is the main type of ebony wood and in trade, it is included in the stracked ebony group (Najmulmunir, 2003). Ebony is easily recognized by the shape of the outer skin which has peeling grooves and is black like charcoal (Allo, 2002). This type of ebony wood is classified as luxurious because of its beautiful pattern and is quite strong, so it is in great demand. The species of Knobbed Hornbill (*Rhyticeros cassidix*) is an endangered endemic Sulawesi bird species that are known to be associated with ebony, especially when the ebony is in fruition and helps in the dispersal of ebony seeds (Mayasari et al. 2012; Mangi et al. 2013; Wulandari et al. 2016). The association is defined as a relationship of mutual dependence between species from the simplest to the most complex as part of the process of ecosystem balance in nature (Heggeness et al. 1978; Tabba et al. 2011). The association is a distinct type of community, found under the same conditions and repeated in several locations (Daubenmire, 1968; Mueller-Dombois & Ellenberg, 1974; Richardson et al. 2000). Associations are characterized by having a similar floristic composition, having a uniform physiognomy, and their distribution has a unique habitat. *R. cassidix* has a high range which helps in the dispersal of ebony seeds to produce new ebony trees in other areas.

D. celebica Bakh and *R. cassidix* are classified as Vulnerable by the IUCN Red List (World Conservation Monitoring Centre, 1998; BirdLife International, 2017) which refers to the risk of extinction in the wild in the future. Not much population information is known from Ebony. However, ebony has been widely exploited to make carvings, inlays, furniture, and musical instruments. It is thought that the number of mature trees has declined and much of the habitat has been converted to other types of plantations (Verhoef, 1938; Djamil, 1987; Whitten et al. 1987; World Conservation Monitoring Centre, 1998). The global population size of R. cassidix has not been quantified, but the species is reported to be declining rapidly due to habitat destruction, hunting, and forest fires (del Hoyo et al. 2001; Kinnaird & O'Brien, 2007).

Sulawesi has experienced deforestation and is in the second largest position after Kalimantan with a deforestation rate of 331,822 ha/year or the equivalent of 2.7% of Sulawesi's forest area (Rijal et al. 2019). This is likely to pose a significant threat to the future of *D. celebica* Bakh and *R. cassidix*. Both species have been included in the IUCN Red List, but the geographic range of *D. celebica* Bakh has not been determined. Time and financial constraints have prevented a comprehensive population survey in Sulawesi. Until recently, a more practical method for assessing the risk status of populations over a wide area was available through the prediction of habitat suitability. This method supports ongoing inventory research by identifying possible new subpopulations in the Sulawesi region that have not been surveyed. To understand predictions of habitat suitability, a Species Distribution Model (SDM) is usually used by combining data on species occurrence and environmental variables (Anderson & Martínez-Meyer, 2004; Elith & Leathwick, 2009; Franklin & Miller, 2009; Thorn et al. 2009). Species distribution modeling (SDM) is the most popular species distribution analysis method for predicting the probability of a species based on environmental variables (Elith & Leathwick, 2009; A. Lee-Yaw et al. 2022). This model has been identified as one of the best global predictive methods when estimating the similarity of environmental conditions to the presence of known species (Elith et al. 2006; Pearson et al. 2007; Elith et al., 2020; Valavi et al., 2022).

This study aims to predict the most suitable habitat for *D. celebica* Bakh by considering the potential habitat of *R. cassidix* associated with it and identifying protected areas in Sulawesi that have high suitability for *D. celebica* Bakh. These findings can be used by the government of the Republic of Indonesia to determine protected and conservation-based areas of *D. celebica* Bakh and also provide information that is relevant to the status of the list in the IUCN Red List category.

Methodology

Research Site

Records of the presence of *D. celebica* Bakh and *R. cassidix* were obtained from direct field surveys, GBIF databases, and trusted scientific journals. There are 47 recorded occur-rences of *D. celebica* Bakh (Santoso et al. 2002; Restu, 2007; Mangi et al. 2013; Asdar et al. 2015; Wulandari et al. 2016; GBIF.org, 2023a) and 1,557 recorded occurrences of *R. cassidix* (Mangi et al. 2013; GBIF.org, 2023b). These incident points were recorded in almost all regions of Sulawesi with concentrations in North Sulawesi, Central Sulawesi, and South Sulawesi (Fig. 1).

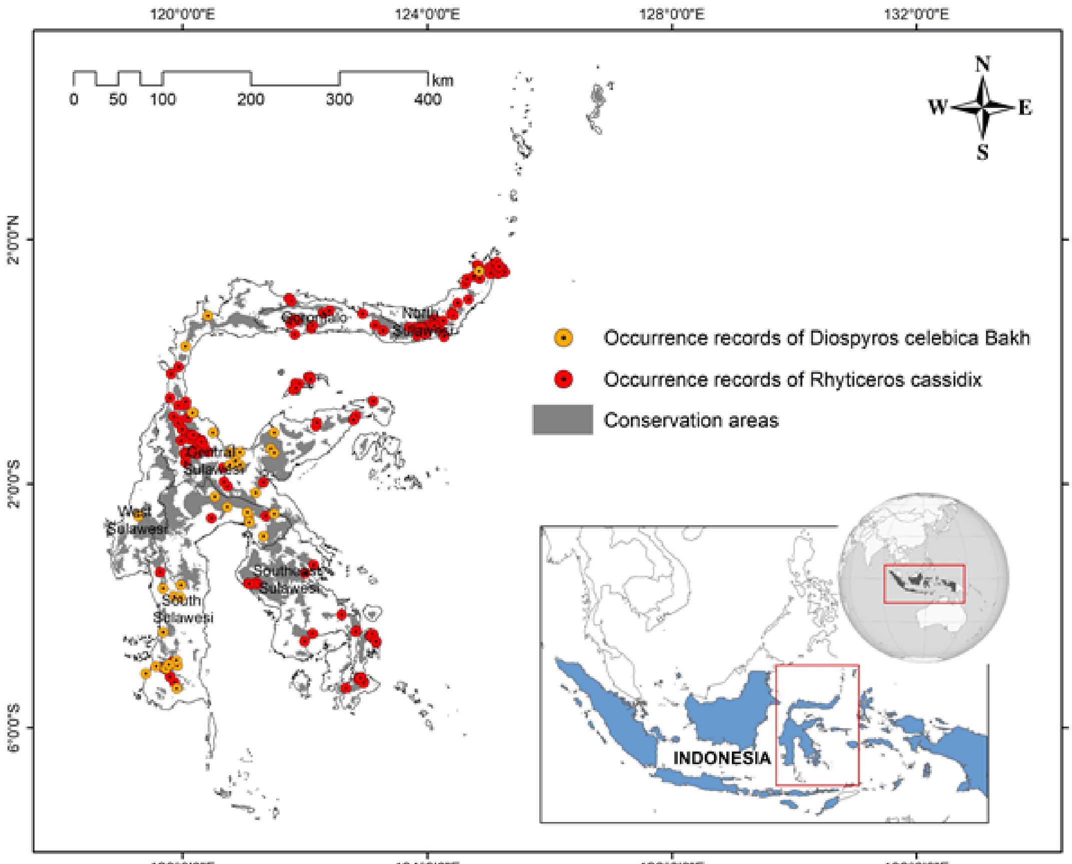

Figure 1. The occurrence records of D. celebica Bakh and R. cassidix in Sulawesi

Species Distribution Modeling

Habitat suitability data for modeling species distribution (SDM) were obtained from previous studies and downloaded from available websites. The data used includes bio1, bio12, bio13, bio14, distance from river, distance from road, distance from settlement, land surface temperature (LST), land use land cover (LULC), normalized difference moisture index (NDMI), normalized difference vegetation index (NDVI), rainfall, slope, soil type, solar radiation, topography, wind speed.

Annual average temperature and annual precipitation (bio1, bio12, bio13, bio14) and solar radiation extracted from Worldclim version 2.1. These variables are averaged for the years 1970-2000 with a spatial resolution of 30 s (1 km^2) (Fick & Hijmans, 2017). Elevation data was derived from the Data Digital Elevation Model Shuttle (SRTM) (Farr et al. 2007; SRTM NASA, 2013). The slope is calculated from the elevation data. Distance from river and distance from road data obtained from the Geospatial Information Agency (BIG, 2023). Distance from settlement data was obtained from the Open Street Map (OSM) Indonesia (OSM, 2023). Proximity data is calculated using Euclidean Distance. LST, LULC, NDMI, and NDVI data were extracted from Landsat 8 OLI/TIRS satellite imagery with a resolution of 30 m. This data is the median filter data for 2022 (Google Earth Engine, 2023). Rainfall data is extracted from Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) imagery. These variables are for the average year 1981-2023 with a resolution of 0.05° (per pixel) (Funk et al. 2015). Soil data were obtained from the FAO-UNESCO Soil Map of the World (Sanchez et al. 2009). Windspeed data obtained from the Global Wind Atlas in the form of an average wind speed. This data is the average wind speed in 2022 with a resolution of 10 m (Global Wind Atlas, 2023). Each environmental parameter used in the two species is shown in Table 1.

Habitat suitability was modeled using Maxent software version 3.4.4 for both endemic species using a machine learning technique called Maximum Entropy (MaxEnt) (Elith et al. 2020). The default settings are applied to the MaxEnt java program. However, the model assessment procedure is done with little locality and a jackknife (or 'leave-one-out'). The model is built using the remaining n-1 localities. Therefore, for presence data with n observed locations, n separate models were created for testing (Pearson et al. 2007). For the MaxEnt setting: random test percentage 1, regularization multiplier 1, number of background points 104, replicate run type (cross-validation), maximum iteration 500, convergence threshold 10-5, and default prevalence value of 0.5.

Habitat suitability predictions for *D. celebica* Bakh, and *R. cassidix* were made to cross each other to create two intersection areas (*D. celebica* Bakh and *R. cassidix*). The crossing areas between these species are then overlaid with conservation areas to identify the most suitable habitats within the conservation areas. The four potential habitat classes are grouped as follows: unsuitable (≤0.10), low potential (0.11-0.30), moderate potential (0.31-0.70), and high potential (≥0.70) (Choudhury et al. 2016; Qin et al. 2017).

Table 1. Environmental Parameters

Environmental Parameters	*D. celebica* Bakh	*R. cassidix*
bio1	√	
bio12	√	
bio13	√	
bio14	√	
distance from river	√	√
distance from road		√
distance from settle-ment		√
LST	√	√
LULC	√	√
NDMI	√	
NDVI	√	√
rainfall	√	
slope	√	√
soil	√	
solar radiation	√	
topography	√	√
windspeed	√	

Results and discussion

Results

Habitat suitability predictions using MaxEnt from *D. celebica* Bakh and *R. cassidix* were evaluated using the Area Under Curve (AUC) value, which represents the predictive ability of the model on a 0-1 basis. The prediction model for *D. celebica* Bakh has an AUC value of 0.887, and *R. cassidix* has a value of 0.837. The potential habitat suitability prediction models for *D. celebica* Bakh and *R. cassidix* each indicate that both models have good performance. AUC values are grouped into several categories based on model performance, models with AUC in the range of 0.9-1 (very good), 0.8-0.9 (good), 0.7-0.8 (fair), 0.6-0.7 (poor), and 0.5-0.6 (failed) (Krzanowski & Hand, 2009). In addition, a prediction model that has an AUC value in the range of 0.7-0.8 is considered acceptable, and 0.8-0.9 is considered very good (Hosmer & Lemeshow, 2000).

The Jackknife (or 'leave-one-out') procedure was adopted to model the locations of *D. celebica* Bakh, and *R. cassidix*. A high and significant success rate was obtained using the Jackknife test with a large sample size (Pearson et al. 2007). However, in other cases, if the location is < 60, the level of success tends to be poor (Pearson et al. 2007). No critical difficulties were found in this study because the number of locations used was considered sufficient. However, each model still has additional locations added. The outputs from each model are used to map habitat suitability across Sulawesi (Fig. 2).

Habitat suitability for a species is represented by a value ranging from 0 to 1. Areas with a value greater than 0.5 indicate that the area is a suitable habitat for that species. The predicted potential habitat suitability for *D. celebica* Bakh covers an area of 1,161,074 ha, and *R. cassidix* covers an area of 1,726,187 ha throughout Sulawesi. According to the observational records observed on *D. celebica* Bakh and *R. cassidix*. The species *D. celebica* Bakh has a distribution concentration in Central Sulawesi (Morowali Utara, and The southern coast of Banggai) and South Sulawesi (Luwu Timur, Luwu Utara, Toraja Utara, Barru, Pangkep, Maros, Sidrap, Wajo, Sidenreng Rappang, and Gowa). The southernmost distribution is Maros (South Sulawesi) and the northernmost is the border of Central Sulawesi with Gorontalo (Soerianegara, 1967). Natural distribution, especially in the areas of Poso, Donggala, and Parigi (Central Sulawesi), Gowa, Maros, Barru, Sid-rap and Luwu (South Sulawesi), and Mamuju (West Sulawesi), and Gorontalo which borders Central Sulawesi (Santoso, 2007). The distribution of high economic value is only found in the districts of Poso, Donggala, and Parigi (Soenarno, 1996). It is estimated that the remaining stands are only found in protected areas, while outside protected area areas it is estimated that they tend to decrease, especially in West Sulawesi and Central Sulawesi given the high rate of deforestation in these two areas (Rijal et al. 2019). Meanwhile, *R. cassidix* is spread throughout almost the entire landscape of Sulawesi and is most easily found in primary and secondary forest areas that have large trees. Habitat suitability for *R. cassidix* is found in almost all of the Sulawesi islands and surrounding islands including Lembeh Island, Togean Islands, Muna Island, and Buton Island. However, the distribution is very limited at the elevation height of the highlighted model, which is not more than 1,800 meters above sea level.

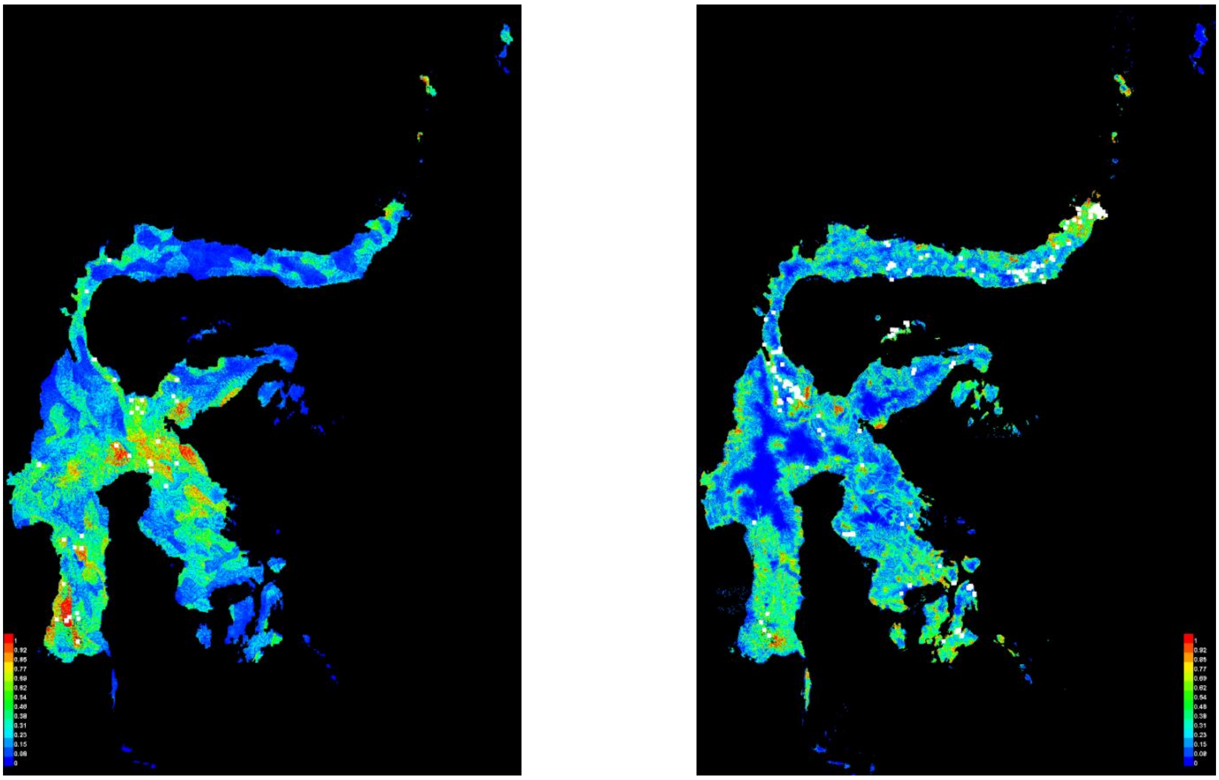

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Figure 2. The predicted suitable habitats provided by MaxEnt Models. (a) *D. celebica* Bakh; (b) *R. cassidix*. The regions with grid cells that have a value > 0.5 indicate more potential, while the regions with the value of grid cells < 0.5 indicate less potential

Species presence records are used to model the habitat suitability of the two species. There are three criteria for selecting actual data points: 1) using actual data point coordinates of target species locations, 2) selecting data points with detailed information on target species locations, and 3) excluding data points located in built-up areas and human cultivation areas. Presence data still allows for bias which can be affected by the accuracy of the data, the method of sampling, and the likelihood of species detection (Barbet-Massin et al. 2010). Observed location data points are sometimes not predicted as a very likely potential distribution due to data limitations. In evaluating the performance of the model, there are two types of errors (commission error and omission error). Commission errors for absences that are incorrectly predicted as attendance (Krzanowski & Hand, 2009), whereas omission errors are attendance observations that incorrectly predict absences (Muschelli III, 2020). Both types of errors can affect the accuracy of the model in predicting the spatial potential distribution of target species and their threats in this study. To better predict the highly suitable habitat of *D. celebica* Bakh its associated species was determined. The highly suitable habitat intersection association area covers an area of 46,301 ha. The areas with the widest intersections are the Rahampu'u Matano Forest, Mountain Klabat, Mountain Lampobang, and Mountain Pompangeo (Fig. 3).

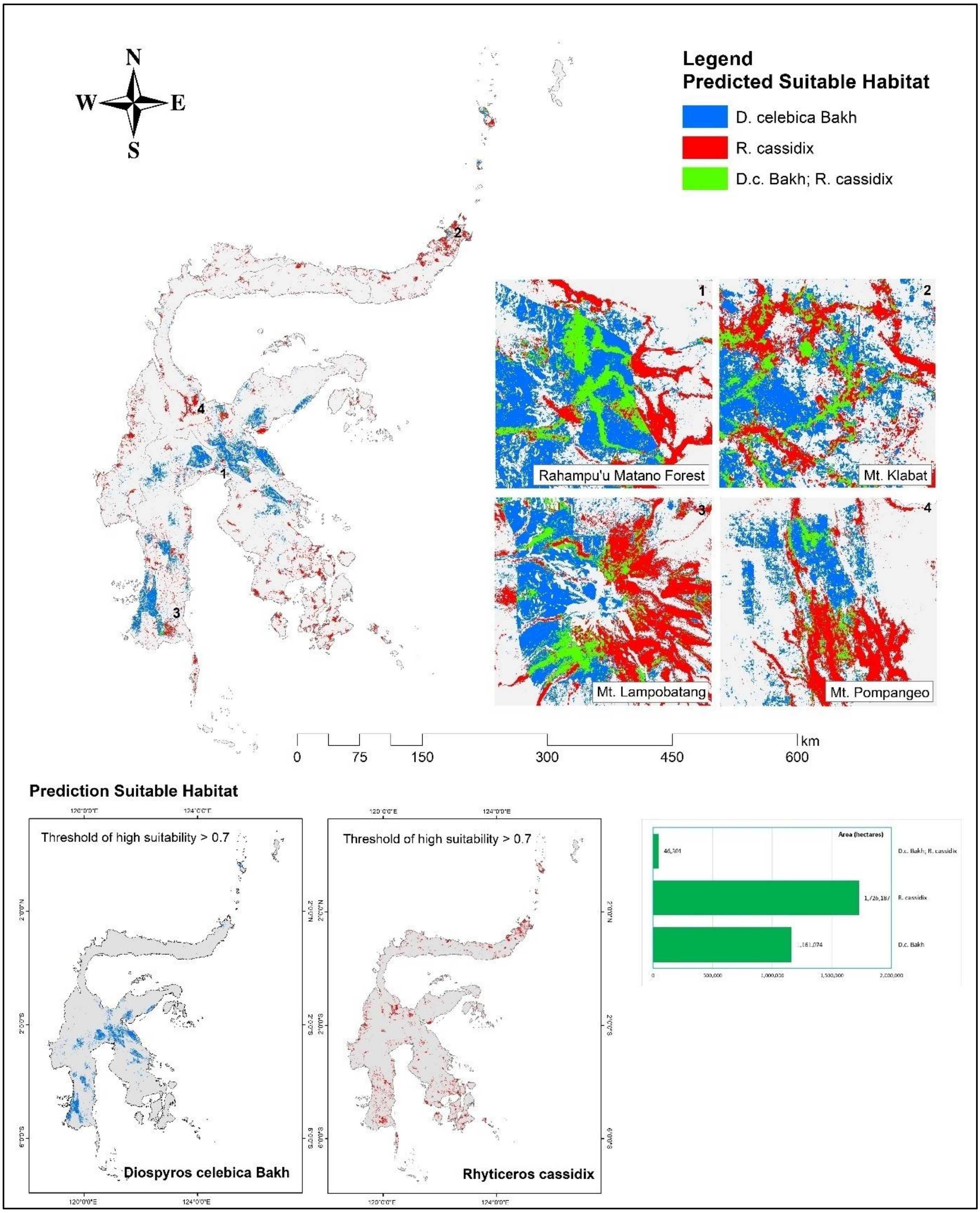

Figure 3. The predicted intersection areas of *D. celebica* Bakh and *R. cassidix*

Habitats that are considered highly suitable based on the species crossing areas are mostly located outside conservation areas. The total prediction is very suitable outside the conservation area covering 36,088 ha (77.94%). Meanwhile, the total suitable and associated habitat in conservation areas throughout Sulawesi covers approximately 10,213 ha (22.06%) (Fig. 4).

There are 9 functional conservation areas in Sulawesi that have been identified as potential habitat areas for *D. celebica* Bakh and *R. cassidix*. There are 8 conservation area functions for *D. celebica* Bakh and *R. cassidix* in association (Table 2).

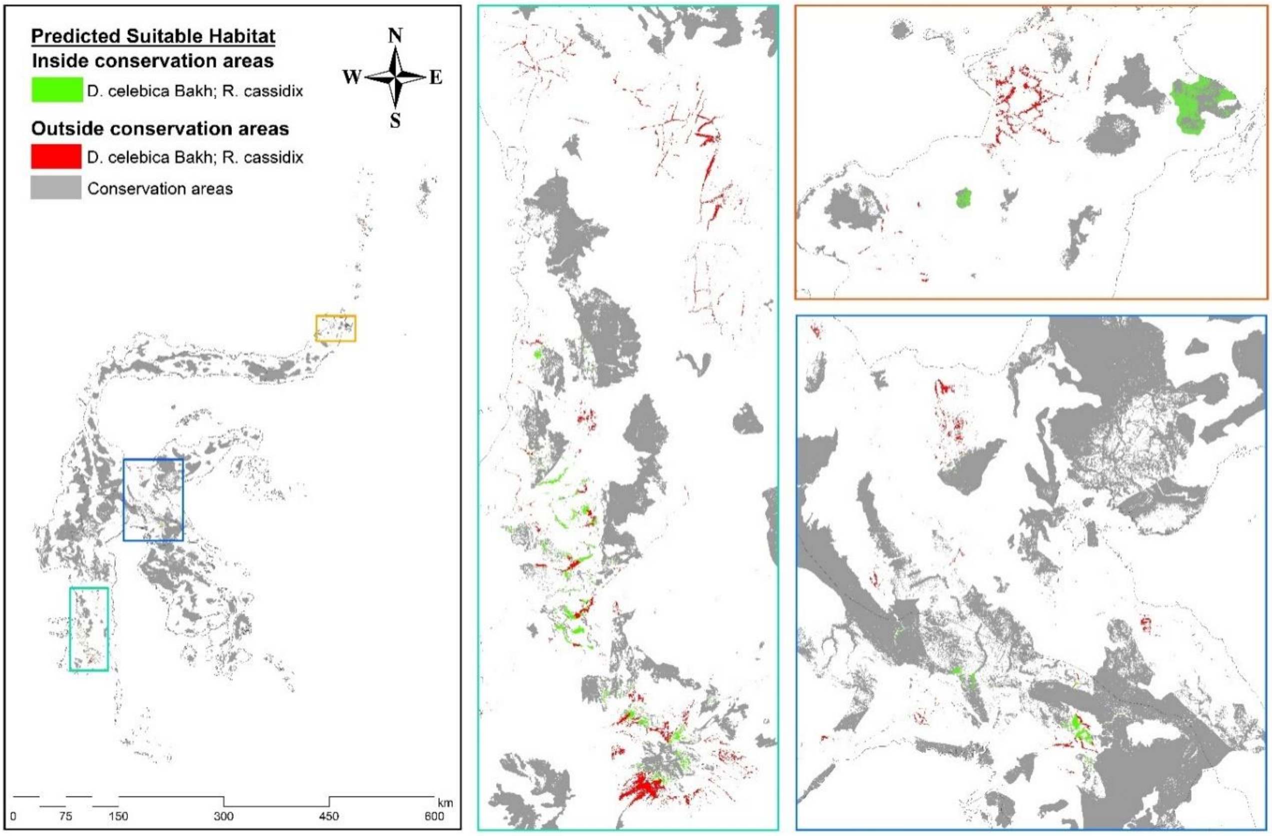

Figure 4. The predicted intersection areas of *D. celebica* Bakh and *R. cassidix* that are located inside and outside conservation areas

Table 2. Identified conservation areas that are suitable habitats for *D. celebica* Bakh and *R. cassidix*

Areas Status	**Intersection (hectare)**
	D. celebica* Bakh; *R. cassidix
Nature Reserve	303
Protected Forest	7,098
Nature Reserve Forest	3
Nature Reserve Areas/Nature Conservation Areas	36
Wildlife Reserve	5
Grand Forest Park	23
Hunting Park	0
National Park	2,117
Nature Recreation Park	627

MaxEnt modeling also makes it possible to identify the relative effect of environmental variables on habitat suitability. The selection of environmental variables is also important in the modeling process. The process of selecting the right environmental variables in determining attendance is still a challenge (Araújo et al. 2019). The use of meaningful predictors is very important in determining the suitability of potential habitats for these endemic species (Petitpierre et al. 2017; Low et al., 2021). In the prediction of this model, there are four predictor groups (topography, climate, environment, and land cover) for endemic plant species, and four predictor groups (topography, environment, land cover, and human disturbance) for endemic bird species used as input. The three most important variables that affect the suitability of *D. celebica* Bakh's habitat are soil type, rainfall, and bio13. Meanwhile, *R. cassidix* was most affected by distance from roads, distance from settlements, and distance from rivers (Fig. 5). Ebony can thrive in soils that are shallow, and rocky, and in conditions with moderate to high levels of organic matter. Ebony can grow in C-D climates (rainfall 1500 mm/year), on calcareous, sand, clay, and rocky soils at an altitude of 400 meters above sea level (Soerianegara, 1967; Gintings, 1990). Conditions of sufficient humidity and sunlight can make ebony seeds germinate quickly (Sidiyasa, 1988). One of the environmental factors supporting plant growth is rainfall and soil type (Yovita, 1993). Ebony can thrive in soils that are shallow, and rocky, and in conditions with moderate to high levels of organic matter. Ebony can grow in C-D climates (rainfall 1500 mm/year), on calcareous, sand, clay, and rocky soils at an altitude of 400 meters above sea level (Soerianegara, 1967; Gintings, 1990). Conditions of sufficient humidity and sunlight can make ebony seeds germinate quickly (Sidiyasa, 1988). One of the environmental factors supporting plant growth is rainfall and soil type (Yovita, 1993). We consider these variables to be significant in determining the habitat suitability of the two endemic species. The inclusion of land cover significantly increases the power of the explanatory variables of the bioclimatic model and the most relevant variables across groups are those that are not explained or poorly explained by climate (Randin et al. 2020). The environmental (soil) and climate variables are variables that have a higher level of importance than other variables. The endemic bird species model shows that the human disturbance variable is one of the variables that cannot be ignored and is the most relevant for the entire group.

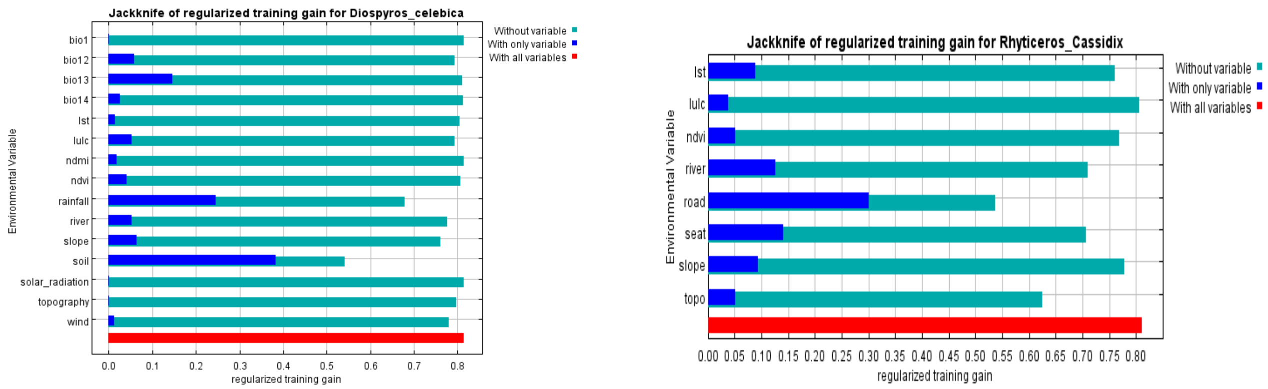

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Figure 5. The important variables that affecting of *D. celebica* Bakh and *R. cassidix*

Habitat suitability maps of *D. celebica* Bakh and *R. cassidix* produced from this study may not accurately predict the location of the species because they only depend on the variables used. Other factors such as the history of the site can also be important. Although the prediction of habitat suitability for a site may be high, there are many reasons why the species may not be found in that location. There is a possibility that the species could not have spread to that location. Unidentified biotic interactions may inhibit recruitment or survival at some sites. It is possible that the species was once found in the area in question, but has since disappeared from that area. Failure to find species even when present may be due to dormancy. Conversely, the model can predict that a certain area is a potential distribution, but that species may occur in that location. Some species can spread to a location and adapt physiologically to less suitable areas (Peterson et al. 2011). Given the difficulty in taking full samples to pinpoint the location of endangered species, it is important. MaxEnt modeling is useful for assessing the potential habitat suitability of *D. celebica* Bakh, and *R. cassidix*, as well as other species around the world.

The findings in this study can be used by the Government of the Republic of Indonesia in particular the Ministry of Environment and Forestry to establish monitoring of protected areas and improve conservation-based management and can help inform and update the distribution of *D. celebica* Bakh and *R. cassidix* on the IUCN Red List in the future. future. Further studies incorporating biophysical variables, aspects of dispersal, human activities, and the habitat history of the site can provide important tools for management and conservation.

Discussion

According to the observational records observed on *D. celebica* Bakh and *R. cassidix*. The species *D. celebica* Bakh has a distribution concentration in Central Sulawesi (Morowali Utara, and The southern coast of Banggai) and South Sulawesi (Luwu Timur, Luwu Utara, Toraja Utara, Barru, Pangkep, Maros, Sidrap, Wajo, Sidenreng Rappang, and Gowa). It is estimated that the remaining stands are only found in protected areas, while outside protected area areas it is estimated that they tend to decrease, especially in West Sulawesi and Central Sulawesi given the high rate of deforestation in these two areas (Rijal et al. 2019). Meanwhile, *R. cassidix* is spread throughout almost the entire landscape of Sulawesi and is most easily found in primary and secondary forest areas that have large trees. Species presence records are used to model the habitat suitability of the two species. There are three criteria for selecting actual data points: 1) using actual data point coordinates of target species locations, 2) selecting data points with detailed information on target species locations, and 3) excluding data points located in built-up areas and human cultivation areas. Presence data still allows for bias which can be affected by the accuracy of the data, the method of sampling, and the likelihood of species detection (Barbet-Massin et al. 2010).

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The potential habitat suitability prediction models for *D. celebica* Bakh and *R. cassidix* each has an AUC value > 0.80 which indicates that both models have good performance. AUC values are grouped into several categories based on model performance, models with AUC in the range of 0.9-1 (very good), 0.8-0.9 (good), 0.7-0.8 (fair), 0.6-0.7 (poor), and 0.5-0.6 (failed) (Krzanowski & Hand, 2009). In addition, a prediction model that has an AUC value in the range of 0.7-0.8 is considered acceptable, and 0.8-0.9 is considered very good (Hosmer & Lemeshow, 2000).

The Jackknife (or 'leave-one-out') procedure was adopted to model the locations of *D. celebica* Bakh, and *R. cassidix*. A high and significant success rate was obtained using the Jackknife test with a large sample size (Pearson et al. 2007). However, in other cases, if the location is < 60, the level of success tends to be poor (Pearson et al. 2007). No critical difficulties were found in this study because the number of locations used was considered sufficient. However, each model still has additional locations added.

Habitat suitability for a species is represented by a value ranging from 0 to 1. Areas with a value greater than 0.5 indicate that the area is a suitable habitat for that species. The main distribution area of *D. celebica* Bakh is found in Central Sulawesi. The southernmost distribution is Maros (South Sulawesi) and the northernmost is the border of Central Sulawesi with Gorontalo (Soerianegara, 1967). Natural distribution, especially in the areas of Poso, Donggala, and Parigi (Central Sulawesi), Gowa, Maros, Barru, Sid-rap and Luwu (South Sulawesi), and Mamuju (West Sulawesi), and Gorontalo which borders Central Sulawesi (Santoso, 2007). The distribution of high economic value is only found in the districts of Poso, Donggala, and Parigi (Soenarno, 1996). Habitat suitability for *R. cassidix* is found in almost all of the Sulawesi islands and surrounding islands including Lembeh Island, Togean Islands, Muna Island, and Buton Island. However, the distribution is very limited at the elevation height of the highlighted model, which is not more than 1,800 meters above sea level. Observed location data points are sometimes not predicted as a very likely potential distribution due to data limitations. In evaluating the performance of the model, there are two types of errors (commission error and omission error). Commission errors for absences that are incorrectly predicted as attendance (Krzanowski & Hand, 2009), whereas omission errors are attendance observations that incorrectly predict absences (Muschelli III, 2020). Both types of errors can affect the accuracy of the model in predicting the spatial potential distribution of target species and their threats in this study.

The most important variables that contribute to the suitability of *D. celebica* Bakh's habitat are soil type, rainfall, and bio13. Ebony can thrive in soils that are shallow, and rocky, and in conditions with moderate to high levels of organic matter. Ebony can grow in C-D climates (rainfall 1500 mm/year), on calcareous, sand, clay, and rocky soils at an altitude of 400 meters above sea level (Soerianegara, 1967; Gintings, 1990). Conditions of sufficient humidity and sunlight can make ebony seeds germinate quickly (Sidiyasa, 1988). One of the environmental factors supporting plant growth is rainfall and soil type (Yovita, 1993). The most important variables contributing to the distribution of *R. cassidix* are proximity to human disturbance (distance from roads and distance from settlements) and distance from rivers. The species *R. cassidix* is threatened by habitat destruction with forest loss and land degradation in Sulawesi (Kinnaird & O'Brein, 1999, Winarni & Jones, 2012). *R. cassidix* is known to take advantage of forests that provide large and tall trees to make nests, usually in the middle of a forest far from human activity. There is an association between *R. cassidix* and *D. celebica* Bakh in the fruiting season (Mangi et al. 2013). The existence of ebony trees is often associated with the supply of springs because ebony can absorb water in a large enough size (Mayasari et al. 2012).

Habitat suitability maps of *D. celebica* Bakh and *R. cassidix* produced from this study may not accurately predict the location of the species because they only depend on the variables used. Other factors such as the history of the site can also be important. Although the prediction of habitat suitability for a site may be high, there are many reasons why the species may not be found in that location. There is a possibility that the species could not have spread to that location. Unidentified biotic interactions may inhibit recruitment or survival at some sites. It is possible that the species was once found in the area in question, but has since disappeared from that area. Failure to find species even when present may be due to dormancy. Conversely, the model can predict that a certain area is a potential distribution, but that species may occur in that location. Some species can spread to a location and adapt physiologically to less suitable areas (Peterson et al. 2011). Given the difficulty in taking full samples to pinpoint the location of endangered species, it is important. MaxEnt modeling is useful for assessing the potential habitat suitability of *D. celebica* Bakh, and *R. cassidix*, as well as other species around the world.

The findings in this study can be used by the Government of the Republic of Indonesia in particular the Ministry of Environment and Forestry to establish monitoring of protected areas and improve conservation-based management and can help inform and update the distribution of *D. celebica* Bakh and *R. cassidix* on the IUCN Red List in the future. future. Further studies incorporating biophysical variables, aspects of dispersal, human activities, and the habitat history of the site can provide important tools for management and conservation.

Conclusions

The best-estimated habitat suitability of *D. celebica* Bakh in Central Sulawesi and South Sulawesi. Meanwhile, *R. cassidix* covers a much wider landscape. However, suitable habitat covers a much smaller area. The most suitable habitat for *D. celebica* Bakh and *R. cassidix* is mostly thought to be outside the conservation area. These results can be used by the Government of the Republic of Indonesia, and the Ministry of Environment and Forestry for determination.

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Author contribution

Conceptualization, Septianto Aldiansyah and Risna.; methodology, Septianto Aldiansyah.; formal analysis, Septianto Aldiansyah and Risna; writing—original draft preparation, Septianto Aldiansyah.; writing—review and editing, Septianto Aldiansyah and Risna. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors declare no conflict of interest.

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