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Habitat Suitability Modeling of Drummer Rail (*Habroptila wallacii*) on Halmahera Island, Indonesia

*Pemodelan Kesesuaian Habitat Mandar Gendang (*Habroptila wallacii*) di Pulau Halmahera, Indonesia*

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ABSTRACT

Drummer Rail *(Habroptila wallacii)* is a bird species of the Rallidae family with limited ecology and behavior information. The information on the distribution of *H. wallacii* in Halmahera Island is crucial as it is classified as a vulnerable species. Therefore, this research aims to predict the potential distribution of *H. wallacii* on Halmahera Island using the Maximum Entropy (MaxEnt) modeling method, which projects species distributions based on presence data and environmental variables. A total of 47 data points on *H. wallacii* encounters were obtained from open-access data sources and field observation. The variables used were land use land cover (LULC), normalized difference vegetation index (NDVI), elevation, slope, and proximity data (river). The results showed that 33.52% of the area was very suitable for *H. wallacii* habitat, 32.97% was suitable, and 33.50% was unsuitable. Approximately 29.39% of the suitable habitat was located in limited-production forest areas, while conservation areas covered only 5.19%. These results suggested the need to review spatial planning policies to increase protection of the natural habitat of the species. The results could serve as considerations and recommendations for the Ministry of Environment and Forestry regarding the future management of forest areas for these species.

INTISARI

Habroptila wallacii *adalah salah satu spesies burung dari famili Rallidae dengan informasi yang terbatas terkait gaya hidup dan ekologinya. Sebagai salah satu spesies rentan, informasi terkait sebaran* H. wallacii *diperlukan melalui pemodelan kesesuaian habitat di Pulau Halmahera. Penelitian ini menggunakan pemodelan* Maximum Entropy *untuk memproyeksikan distribusi spesies dengan menggunakan data keberadaan dan variabel lingkungan. Empat puluh tujuh data perjumpaan* H. wallacii *diperoleh dari sumber data akses terbuka dan observasi lapangan. Adapun variabel yang digunakan adalah* land use land cover *(LULC),* normalized difference vegetation index *(NDVI),* elevation, slope, *dan* data proximity *(*river*). Penelitian menunjukkan bahwa 33,52% area di wilayah studi sangat sesuai untuk habitat* H. wallacii, *32,97% dinilai sesuai untuk* H. wallacii, *dan 33,50% dinilai tidak sesuai untuk* H. wallacii. *Sekitar 29,39% habitat yang sesuai berada pada kawasan hutan produksi terbatas, sedangkan pada kawasan konservasi hanya mencakup 5,19% dari luas wilayah. Ini mengindikasikan perlunya peninjauan ulang kebijakan tata ruang untuk meningkatkan perlindungan terhadap habitat alami spesies. Hasil penelitian ini dapat menjadi pertimbangan dan rekomendasi bagi Kementerian Lingkungan Hidup dan Kehutanan terkait pengelolaan kawasan hutan bagi spesies ini di masa depan.*

Introduction

Halmahera Island is home to 252 species of birds, 26 of which are endemic to North Maluku, including Drummer Rail (*Habroptila wallacii*). Previous research has shown that *H. wallacii* belongs to the Rallidae family, comprising approximately 155 species with a relatively wide global distribution. Approximately 31 of these species are unable to fly (del Hoyo et al. 2013). Due to the difficulty in accessing the habitat of *H. wallacii* and its naturally shy behavior, it is challenging to observe, with only a few confirmed sightings (Birdbase 2011). Additionally, it is often found in dry swamps within primary or secondary forests, or near small river crossings (Bashari 2012). This species inhabits dense thickets that are difficult to penetrate (Bashari & van Balen 2011).

The International Union for Conservation of Nature (IUCN) categorizes *H. wallacii* as Vulnerable (VU) (BirdLife International 2016). This status signifies a severe risk of extinction in the wild unless effective habitat protection, population monitoring, and targeted conservation efforts are implemented. The population of the species has been declining due to habitat loss and fragmentation from deforestation (Vetter 2009), commercial activities, and predation (BirdLife International 2016). Given the small population and limited knowledge, more information is needed regarding its habitat. The species may be more numerous than the reported population and occurs in a broader range of habitats. Additional research is also necessary to explore remote or under-surveyed areas and to gain a better understanding of the distribution and habitat preferences, providing a clearer picture of its conservation needs and ecological role. Such efforts are specifically important given the increasing threats to tropical forest ecosystems from land conversion and climate change. Without reliable baseline data, conservation measures may fail to capture critical areas of habitat, particularly for cryptic and elusive species (Owens et al. 2024; Thompson et al. 2025), such as *H. wallacii*, whose detectability is inherently low. Therefore, improved habitat assessments through systematic field surveys and modeling approaches are urgently needed.

Maximum Entropy (MaxEnt) can predict species distributions based on known environmental variables (Phillips et al. 2006). MaxEnt was identified as one of the most effective global prediction methods for estimating the similarity of environmental conditions to the presence of known species (Elith et al. 2020; Renjana et al. 2022; Valavi et al. 2022; Aldiansyah & Risna 2023; Aldiansyah et al. 2024). Despite its strengths, the method has several limitations, including sensitivity to sampling bias, choice of threshold values, and inability to incorporate biotic interactions and dispersal limitations. However, it remains a valuable tool for evaluating potential habitat suitability, specifically for rare or data-deficient species such as *H. wallacii*. The capacity to work with presence-only data makes it particularly suitable for species with few confirmed occurrences (Lissovsky & Dudov 2021), indicating that MaxEnt can serve as a complementary method to guide targeted field validation and support conserva-tion planning in remote and poorly documented landscapes. To date, there is no comprehensive habitat suitability modeling for *H. wallacii* on Halmahera Island. Therefore, this research aimed to predict the potential distribution of *H. wallacii* on Halmahera Island using MaxEnt to inform future spatial planning and conservation strategies for forest and biodiversity management in the region.

Methods

Time and Location

This research was conducted on Halmahera Island, covering a modeled area of 17,952.18 km^2. This research compiled occurrence records of *H. wallacii* from both primary and secondary data sources. The primary data were obtained from field observations of activity trail points, such as footprints and nests on tree stumps. The data was collected using the Garmin 64s Global Positioning System with the random transect technique. In the field, the starting point of each transect was determined randomly, and subsequent transects were set at varying intervals (60 m to 90 m) following the random transect sampling approach (Owusu 2019). This technique ensured that the surveyed area was covered without systematic bias. After the random starting points were established, searches were conducted at locations identified as habitats of the target species, such as on riverbanks or swampy areas, where the target species was more likely to occur. These observations were conducted from 08:10 to 11:50, then continued until 13:00 to 17:30, and the cycle was repeated for five consecutive days from 26 to 30 April 2024. In total, 36 occurrences of *H. wallacii* from secondary data (Birdbase 2011; GBIF 2024) and added 11 points from direct observation around Aketajawe Lolobata National Park, Aketajawe block in Tidore Islands City, East Halmahera Regency. These occurrence points were concentrated in the central region, and no records were found on the northern and southeastern sides of the research area (Figure 1). Secondary data were collected from the Global Biodiversity Information Facility (GBIF) database and scientific reports to enhance the statistical analysis and minimize the need for extensive new data collection.

Species Distribution Modeling

The author used previous research (Collar 2009; Vetter 2009; Bashari & van Balen 2011; Bashari 2012; BirdLife International 2016) from open-access sources as baseline data for habitat suitability in species distribution models (SDM). The data used included land use land cover (LULC), normalized difference vegetation index (NDVI), elevation, slope, and distance from rivers. Previous research indicated that these environmental variables influenced the distribution of *H. wallacii* in its habitat. LULC data were extracted from Sentinel-2 with 10 m resolution and classified into 8 categories, following the classification method described by Aldiansyah and Saputra (2023). NDVI data were obtained from Google Earth Engine processing in 2023 using a one-year median filter (Aldiansyah et al. 2021; Crego et al. 2022). Elevation and slope data were obtained from ASTER DEM with 30 m resolution, and slope values were derived from the elevation dataset. River data were obtained from the Geospatial Information Agency (Badan Informasi Geospasial 2023), and proximity data were calculated using Euclidean distance (de Araujo Barbosa et al. 2025). The encounter points data were stored in Comma-Separated Values (.csv) format, which contains the latitude and longitude coordinates of each species occurrence, with one presence recorded per species point (Phillips et al. 2006).

Habitat suitability modeling was performed using MaxEnt software version 3.4.4. by combining known *H. wallacii* occurrence records and environmental variables that represented the target species' habitat.

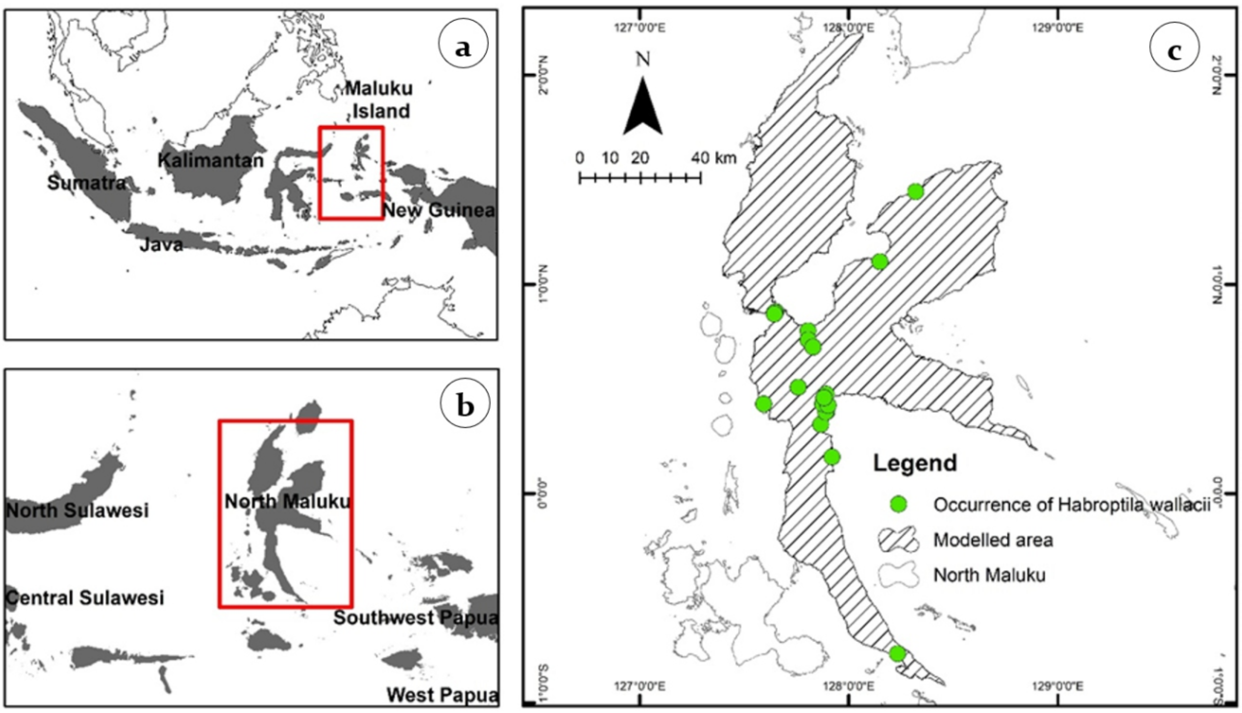

Figure 1. The occurrence records of *H. wallacii* in (a) Maluku Islands, (b) North Maluku, and (c) Modelled area

Preprocessing of the environmental variable layers included adjustments to their projection coordinates and cell dimensions to ensure spatial consistency across datasets. The environmental variable was classified as continuous data, which is numerical data with an infinite range of values, whereas the LULC data was in categorical form. Presence data were refined to ensure that each occurrence point aligned correctly with the corresponding environmental data grid cell. The modeling process applied default settings to the MaxEnt Java program, employed the Jackknife approach to assess the model (also known as leave-one-out cross-validation) as described by (Song & Estes 2023), where models were built using the remaining n-1 localities. For occurrence data with n observed locations, separate models were built for testing each location. The MaxEnt model applied a percentage of random trials of 1, a regularization multiplier of 1, a background points of 121, a replication type (cross-validation), a maximum number of iterations of 500, a convergence threshold of 10^{-5}, and a default prevalence value of 0.5.

The Jackknife test determined the importance of environmental variables based on the highest percentage contribution. The model development utilized 75% (35 points) of the total encounter records (Zhang et al. 2019; Aldiansyah et al. 2024), while the validation used 25% (12 points) of the remaining records. The model validation employed the Area Under the Curve (AUC), which measures the degree of separation between classes of the prediction model (Konowalik & Nosol 2021; Aldiansyah & Risna 2023). Lazagabaster et al. (2024) suggested that an AUC value of less than 0.5 indicates an unacceptable model, while a value between 0.5 and 0.7 suggests low accuracy. Values from 0.7 to 0.9 indicate moderate accuracy, and values greater than 0.9 reflect high accuracy. The Lazagabaster' framework was widely used as a standard for evaluating model performance in species distribution modeling. MaxEnt modeling results were classified into three categories: unsuitable, suitable, and very suitable, using the quantile method, which was chosen for its effectiveness in classifying pixel values based on their similarities. Further analysis was conducted to examine the distribution of the habitat within various forest functions. The entire series of research methods is illustrated in Figure 2.

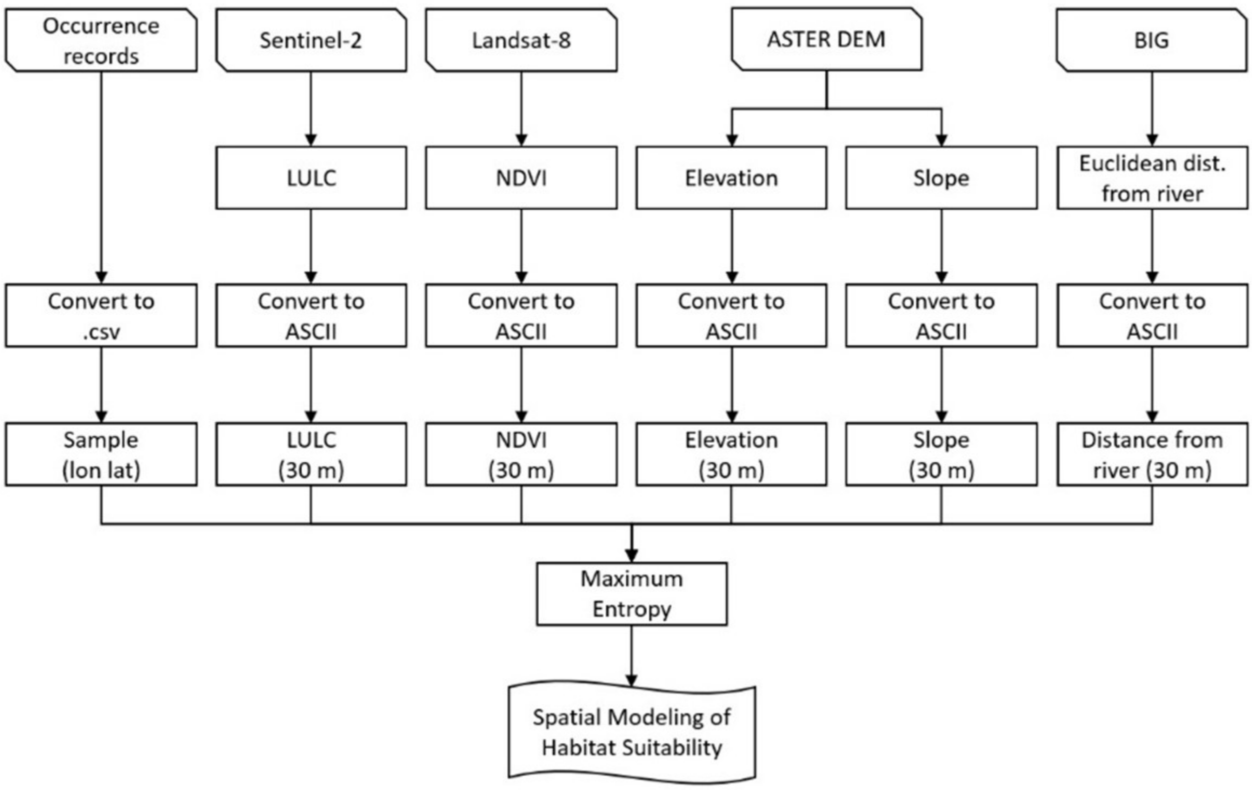

Figure 2. Workflow of the research

Result and Discussion

Modeling the habitat suitability of *H. wallacii* on Halmahera Island, based on species occurrences and seven environmental variables, yielded an AUC value of 0.842, indicating moderate accuracy. When the resulting AUC value was close to 1, it indicated that the model had excellent predictive performance (Konowalik & Nosol 2021). The authors applied a 10th percentile training logistic presence threshold of 0.3214, below which areas were considered uninhabitable by *H. wallacii*. The model classified the habitat into not suitable (6,014.31 km^2), suitable (5,919.67 km^2), and very suitable (6,018.25 km^2), as illustrated in Figure 3. The largest suitable habitat, covering 2,391.97 km^2, was located in the limited production forest, while the smallest, at 422.59 km^2, was found in the national park (Figure 4). This small area was considered insufficient (Hanski 2015) for *H. wallacii,* as it typically requires extensive, continuous habitats. A habitat size that is too small unequivocally cannot sustain species diversity in the long term (Ylisirniö et al. 2016). Maintaining sufficient habitat size was particularly critical, as these species constantly encounter challenges in adapting to managed landscapes (Moore et al. 2022). The variation in habitat areas might have resulted from intensive land conversion over recent decades (Vetter 2009, Sabaruddin et al. 2024). Shrinking habitat conditions could cause individuals of this species to occupy smaller areas, potentially increasing competition for resources. However, current observation data were insufficient to confirm the extent of such interactions, while zoning planning seems necessary to separate areas that were focused on production.

The jackknife test was used to evaluate environmental variables in modeling results (Phillips et al. 2006; Aldiansyah et al. 2024; Maarif et al. 2024). Jackknife analysis for habitat suitability modeling *H. wallacii* showed that each variable had varying levels of importance (Figure 5). Each environmental variable yielded an AUC value greater than 0.70,

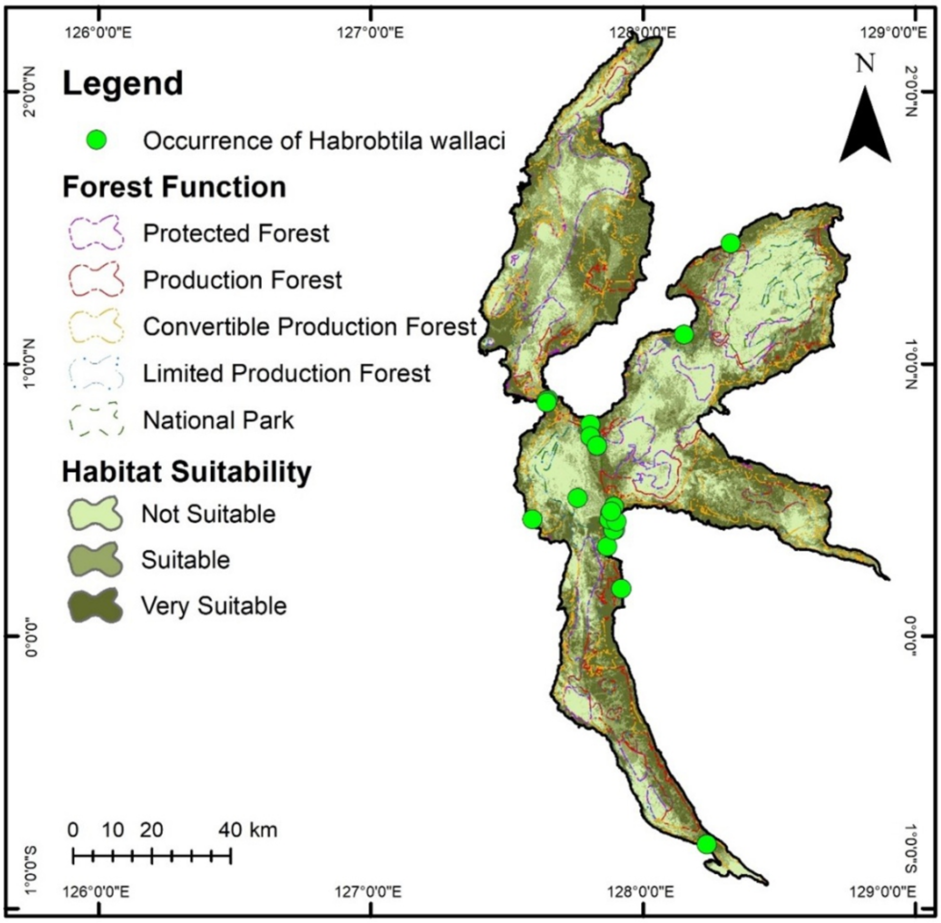

Figure 3. Map of the habitat suitability distribution of *H. wallacii*

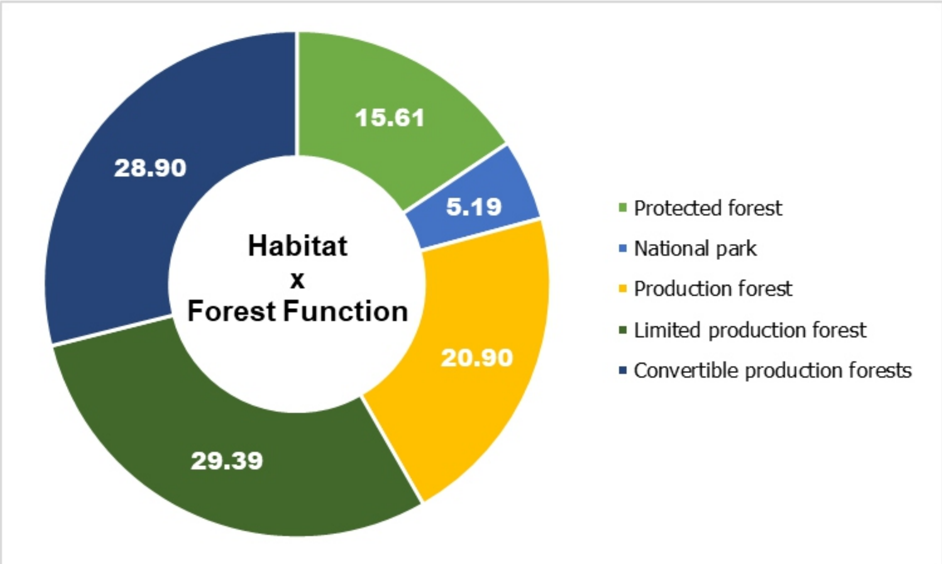

Figure 4. The extent of habitat suitability within various forest functions (%)

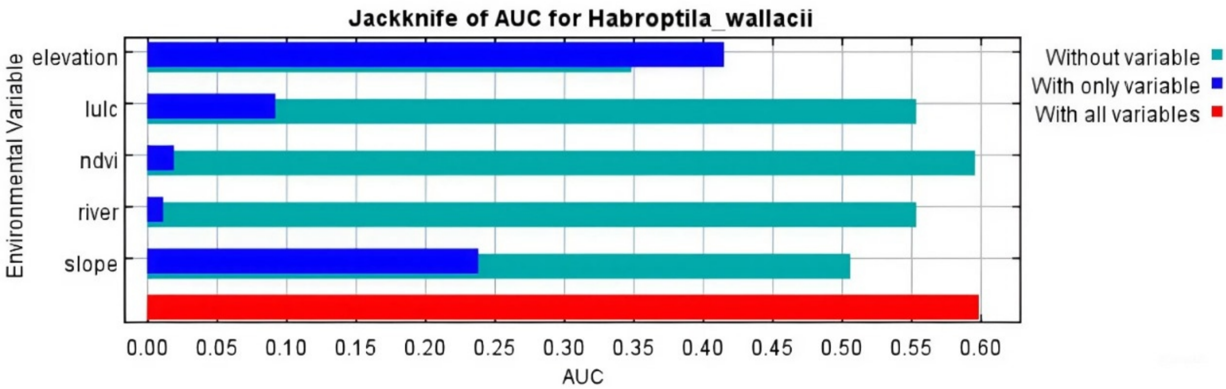

Figure 5. AUC value for the environment variables

indicating that the assumed predictor variable adequately explained the species' habitat (Aldiansyah & Risna 2023; Maarif et al. 2024). However, none of the environmental variables reached this threshold. Although no single predictor variable strongly explained the species' habitat, the combination of several variables in the model still contributed to explaining habitat suitability, indicating that the species' distribution is influenced by the complex interaction of multiple environmental factors rather than by a single dominant factor. Elevation was the variable with the most considerable AUC value contribution in building the model, while distance from the river showed the smallest contribution. A variable was considered to have contributed to a model when its contribution percentage exceeded 10% (Aryanti et al. 2021). The significance of an environmental variable in estimating a species' appropriateness increased with its contribution percentage value (Giri et al. 2023). The analysis of the environmental factors' contributions revealed that elevation had the most significant influence, accounting for 69.4% of the total contribution (Table 1). Other environmental variables that influenced the model were slope (14.3%), followed by LULC (8.1%), distance from river (7.8%), and NDVI (0.3%), as summarized in Table 1. The model revealed that elevation and slope were key determinants of *H. wallacii* habitat suitability, and the presence of *H.*

Table 1. Contribution of environmental variables to habitat suitability modeling

Variable	Contribution (%)
Elevation	69.4
Slope	14.3
LULC	8.1
Distance from the River	7.8
NDVI	0.3

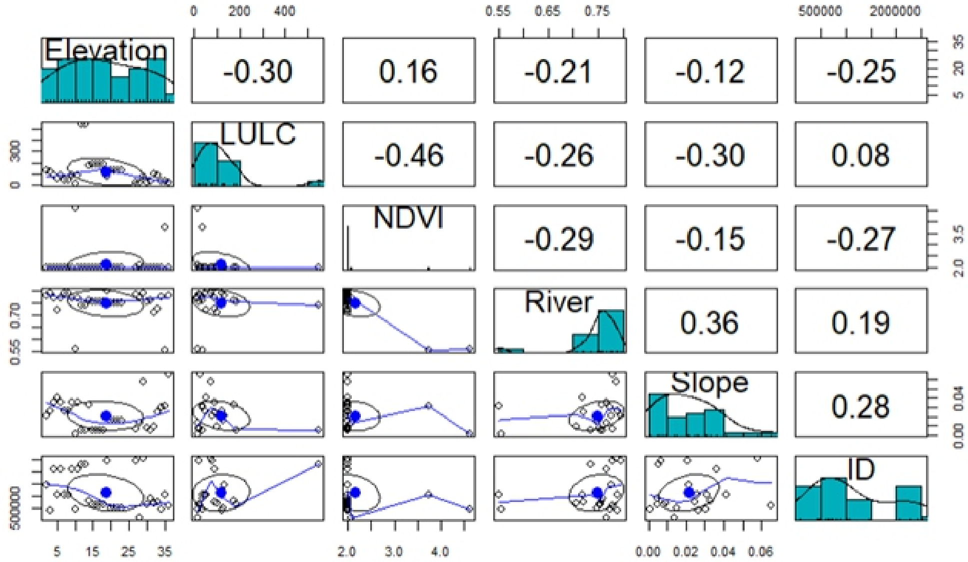

Figure 6. Pearson correlation between environmental variables

wallacii decreased with increasing elevation. This result aligned with previous research, which shows that the species is predominantly found in muddy swamp areas close to forest edges (Heinrich 1956) in lower-altitude regions, with a distinct boundary separating it from the ocean.

Figure 6 summarizes the results of the Pearson correlation (Ongky et al. 2025) between the environmental variables. The elevation and slope had a negative correlation (r = -0.12). This species has a greater chance of thriving and successful breeding in areas with low elevation and gentle slopes. However, in areas with high elevation or steep slopes, bird species could be more isolated, with limited resources and restricted movement. This flightless bird species often had a limited distribution and was highly dependent on geographic conditions and its surrounding environment (Garcia-R & Matzke 2021). Elevation and slope influenced many aspects of the species' ecology, including food availability (sago shoots, insects, and freshwater mussels), shelter, and protection from predators such as humans and domestic dogs (Dimara et al. 2021; Roberts et al. 2022; Zhao et al. 2023).

The *H. wallacii* encounters were more frequent in lowland areas with dense vegetation within Halmahera Island (Figure 3). This result suggested a potential association between species occurrence and the vegetation community, consistent with its documented preference for lower-elevation habitats. The model also suggested a higher likelihood of occurrence in the southwest and north, as well as on the edges of the island, where suitable habitat and environmental conditions prevail. Tree conditions, such as those of the sago palm, were more favorable to survival than the more variable conditions in the central region of the island. The lowland-dominated environmental conditions in the fringes of the island were suitable for *H. wallacii* to thrive. Additionally, the gentler slopes had a significant positive correlation with proximity to the river (r = 0.36). However, the interpretation of this value should be with caution as ecological systems often reflect only a portion of the variance explained, and moderate values could still be meaningful when accounting for natural variability and noise in ecological data (Yates et al. 2018). While the correlation shows statistical significance, it should be interpreted as indicative rather than definitive.

Although their overall contributions to the model were low, land cover types, distance from the river, and NDVI still played a significant role in shaping the species' habitat preferences, significantly affecting model accuracy. Other elements, including the site's history, could also be significant. Previous research has suggested that *H. wallacii* was found in reed grass or nettle bushes (Collar 2009). Bashari and van Balen (2011) found nests in secondary dry swamp forests dominated by Pigafetta palms. Commercial sago extraction, irrigation schemes, the conversion of wetlands to agricultural areas, and the development of shrimp ponds have significantly damaged the sago swamps in Halmahera, thereby reducing the habitat (Vetter 2009; BirdLife International 2016).

However, even when a site's habitat suitability can be well predicted, the species may still be absent due to various limiting factors and not have dispersed to that area. Unknown biotic interactions may impede recruitment or survival. Similar species showed that biotic factors significantly influenced these rates. For example, dung beetle communities influenced seed burial and seedling recruitment Griffiths et al. (2016), revealed that dung beetle communities play a significant role in seed burial and the recruitment of seedlings in tropical forests. Additionally, previous research on *Margaritifera laevis* revealed a close relationship between recruitment success and the density of host fish. These findings highlighted the importance of biotic interactions between mussels and their host fish for successful recruitment (Kawajiri et al. 2021). Additionally, predation and habitat changes can control bivalve recruitment (Tamario et al. 2022). It is also possible that the species was once present but has since disappeared, or that its cryptic behavior or seasonal inactivity makes it difficult to detect. Moreover, this flightless species, confined to a single island, faced severe population declines due to predation by introduced species and was sometimes caught by dogs during local hunts for deer and pigs (BirdLife International 2016).

The MaxEnt modeling could evaluate the potential habitat suitability of *H. wallacii* and other species worldwide. The model could indicate the extent of potential habitat distribution beyond the study area, predict the existence of the species in a particular region, and the species' capability for dispersal and physiological adaptation to suboptimal habitats (Chen et al. 2024). Accurate habitat modeling posed significant challenges because endangered species were often rare and elusive, making it difficult to obtain comprehensive field samples (Worku et al. 2024). Therefore, the MaxEnt model has been widely applied in species distribution modeling as it utilizes presence-only data.

However, the model had several limitations, including sampling bias, threshold selection, and inherent uncertainty associated with presence-only data. Sampling bias could arise when presence data were collected non-randomly or focused on spatially clustered areas, which may result in inaccurate representations of actual habitat suitability (Baker et al. 2024). Incorporating bias grids or selecting more representative background points could mitigate sampling bias (Støa et al. 2018). The MaxEnt produced continuous probability outputs, and it required thresholding to generate binary presence–absence maps. Various methods existed for determining an optimal threshold, such as Maximum Training Sensitivity Plus Specificity (maxSSS) and Equal Sensitivity and Specificity. However, the choice depended on the characteristics of the dataset (Hooftman et al. 2016). As presence-only data accounted for only the area surveyed and species detected, MaxEnt estimated relative habitat suitability rather than the true occurrence probabilities, which could limit cross-species or cross-regional comparisons (Schartel & Cao 2024). The reliability of presence data could be affected by species misidentification or spatial inaccuracies, particularly when sourced from unverified records or public databases (Støa et al. 2018). Despite these limitations, such as its reliance on presence-only data, potential sampling bias, and limited capacity to capture biotic interactions, MaxEnt remained a valuable tool for evaluating potential habitat suitability for *H. wallacii*.

The conservation of *H. wallacii* should include designating High Conservation Value (HCV) zones, restoring habitat corridors, and integrating habitat data into spatial planning (Montes-Rojas et al. 2024). HCV zones protect key ecosystems in production forests without conflicting with economic policies. This strategy should complement the integration of habitat suitability data into spatial planning to ensure that HCV zones encompass high-priority areas (Montes-Rojas et al. 2024). The coordinated implementation of fragmented forest restoration was crucial for promoting habitat connectivity, identifying priority habitats, and enhancing long-term conservation programs. Indonesia's Ministry of Forestry could use the research results to update the IUCN Red List of *H. wallacii* distribution. Future research should integrate species distribution, biophysical factors, human activities, and habitat history to inform the development of effective management and conservation strategies.

Conclusion

Habitat suitability modeling results indicated that Halmahera Island encompassed approximately 66.50% of the total suitable habitat for *H. wallacii*. However, the majority of this suitable habitat was confined to small, fragmented forest areas. This species thrives in similar environmental conditions across much of its potential range. Conditioning factors that contributed to the suitability of *H. wallacii* habitat included elevation, slope, LULC, distance from river, and NDVI. The findings from this research served as a reference for Aketajawe National Park in assessing forest areas in Halmahera, including informing the development of zoning plans for various conservation areas, such as protection, production, and conservation forests.

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