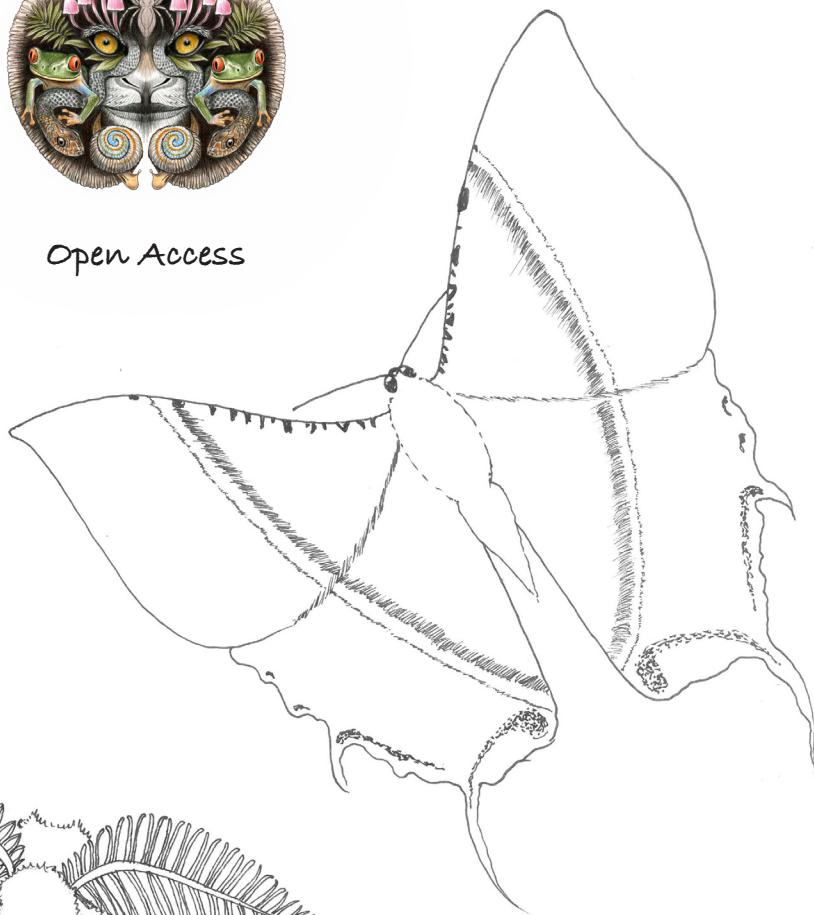
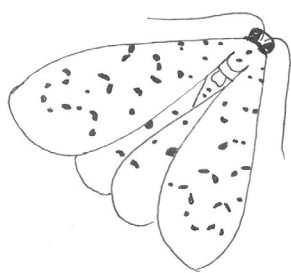


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Cover: Celebrating the unsung heroes—moths, our nocturnal pollinators. © Priyanka Iyer.



Predicting suitable habitat for the endangered Javan Gibbon in a submontane forest in Indonesia

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Abstract: Species distribution modeling is an essential tool for understanding the ecology of species and has many applications in conservation. Using maximum entropy (MaxEnt) modeling, we identify the key factors shaping the potential distribution of the endangered Javan Gibbons *Hylobates moloch* in one of the main remnant habitats, Gunung Halimun Salak National Park (GHSNP), Indonesia, using presence-only data collected between October and November 2015, and in April and May 2016. Maxent results showed that forest canopy density and annual temperature were the principal variables predicting the distribution of Javan Gibbons, with contribution scores of 53.9% and 35.6%, respectively. The predictive distribution map indicated that suitable habitat for Javan Gibbons is not uniformly distributed within GHSNP, i.e., suitable habitat is not located evenly throughout the region, with some areas more suitable than others. Highly suitable habitat comprises the largest proportion of habitat, with 42.1% of GHSNP classified as highly suitable habitat, whereas 24.7% was moderately suitable, and 33.2% of habitat was of low suitability for Javan Gibbons. Priority should be given to increasing habitat quality in degraded areas and law enforcement patrols to reduce degradation in peripheral regions of the park as part of the conservation management strategy.

Keywords: Conservation, forest canopy, *Hylobates moloch*, maximum entropy, West Java.

Abbreviations: AUC—Area under the curve | DEM—Digital elevation model | GHSNP—Gunung Halimun Salak National Park | IUCN—International Union for Conservation of Nature and Natural resources. | MaxEnt—Maximum entropy | MoEF—Ministry of Environment and Forestry | SDM—Species distribution models | PCA—Principal components analyses | ROC—Receiver operating characteristic | SRTM—Shuttle radar topography mission.

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INTRODUCTION

Understanding the distribution of animals in space and ecological predictors of abundance are crucially important for designing effective conservation plans (Sarma et al. 2015). However, for most species, resources are not adequate to permit detailed surveys across every area of their potential distribution range. To address this problem, various modeling techniques have been developed to predict species distributions and identify suitable habitats by combining occurrence records with digital layers of environmental variables (Peterson 2001; Guisan & Thuiller 2005; Ortega-Huerta & Peterson 2008). Species distribution models (SDM) have been applied to various conservation problems. For instance, SDM have been used to prioritize areas for conservation (Araújo & Williams 2000), to predict geographical patterns of species occurrence (Peterson 2003), to discover unknown populations (Pearson et al. 2006), to improve the assessment of risk status (Solano & Feria 2006), and to predict species displacement patterns resulting from climate change (Borzeé et al. 2019).

Several algorithms for modeling distributions use evidence of the presence or absence of a species in different locations. However, reliably determining that a species is absent is not often possible, limiting these algorithms' applicability. Alternatively, maximum entropy models (MaxEnt) aim to characterize species probability distributions using presence-only data, and can be applied even in situations with incomplete information from limited datasets (Pearson et al. 2006; Phillips et al. 2006; Guisan et al. 2007). MaxEnt can accurately predict habitat suitability based on relatively few variables (Liu et al. 2001; Dayton & Fitzgerald 2006) and these models can conform to the realized niche of species (Stone et al. 2013). This approach has been used to develop SDM in a wide range of primate species, including Asian Slow Lorises *Nycticebus* spp. (Thorn et al. 2009), Spider Monkey *Ateles geoffroyi* (Vidal-García & Serio-Silva 2011), Ecuadorian Capuchin *Cebus albifrons* (Campos & Jack 2013), Peruvian Night Monkey *Aotus miconax* (Shanee et al. 2015), Eastern Hoolock Gibbon *Hoolock leuconedys* (Sarma et al. 2015), Western Hoolock Gibbon *Hoolock hoolock* (Naher et al. 2021), Southern Yellow-Cheeked Gibbon *Nomascus gabriellae* (Nhung et al. 2021), and Bornean Agile Gibbon *Hylobates albibarbis* (Singh et al. 2018).

Javan Gibbons *H. moloch* are endemic to Java, Indonesia, and are generally restricted to the western and central parts of the island (Nijman 2004). Globally, Javan Gibbons are listed as 'Endangered' on the IUCN

Red List (Nijman 2020). This species is sensitive to habitat alteration because of their dependence on closed-canopy forests for food (Kim et al. 2012), locomotion (Bertram 2004), and sleeping trees (Ario et al. 2018). Deforestation and forest degradation are primary threats as they disrupt the forest canopy and result in habitat fragmentation (Geissmann 2003; Smith et al. 2017).

It is estimated that up to 96% of the original Javan Gibbons habitat has been lost (Supriatna 2006; Nijman 2013; Malone et al. 2014), and most of the remaining habitat is located in protected areas such as Gunung Halimun Salak National Park (GHSNP). GHSNP is the largest remaining forest block in the region and represents the last stronghold for the species, likely harboring 25% and 50% of the global Javan Gibbon population (Nijman 2004). However, estimates of the total population within GHSNP vary dramatically, and populations within GHSNP may be effectively isolated from each other by enclaves of human activity within the park. The probability of persistence for these populations in the long term is likely to be affected by the total carrying capacity and the degree of isolation among subpopulations within GHSNP (Smith et al. 2017). Therefore, a better understanding of the total carrying capacity of GHSNP and the factors affecting habitat suitability is critical for effective conservation planning.

Two habitat suitability analyses for Javan Gibbons in GHSNP have been conducted using principal components analyses (PCA). Helianthi et al. (2007) estimated that 71.43% of the total area of GHSNP is highly suitable for Javan Gibbons, while Ikbali et al. (2008), in an analysis restricted to the Mount Salak region within GHSNP, estimated that only 13.20% of the habitat was highly suitable. Given changes in forest management and ongoing habitat alteration, habitat quality for Javan Gibbons in GHSNP may have changed in recent years; thus, a new approach and update are needed. We used MaxEnt modeling to identify environmental factors that contribute to the Javan Gibbon presence and to identify areas in GHSNP where habitat characteristics best align with the ecological niche of the species. The results of this study may help identify priority areas for conservation efforts and may lead to improved management practices within the park to ensure the continued survival of Javan Gibbons as one of the key species in GHSNP.

MATERIALS AND METHODS

Study Area

This study was conducted at GHSNP, Indonesia (6.739° S, 106.530° E), located within three administrative districts: Bogor and Sukabumi in West Java Province and Lebak in Banten Province. The Halimun area was established as a national park in 1992. To reduce forest loss, the Indonesian government increased the size of the protected area in 2003 by merging Halimun National Park and Salak Reservation Area, including the production forest. Currently, GHSNP covers an area of approximately 87,699 ha. Besides protecting water catchment areas for several big cities near the national park, it also protects essential habitat for endangered species such as Javan Gibbons, Javan Leopards *Panthera pardus melas*, and Javan Hawk-Eagles *Nisaetus bartelsii*. The park includes forests ranging from 500–2,200 m, a tropical climate with annual temperatures between 19° C and 31° C, and average precipitation of 4,000–6,000 mm. This national park experiences various pressures, including illegal gold mining, poaching, and forest encroachment for agricultural land & settlements, which cause fragmentation and degradation. Forest encroachment for agriculture is the biggest threat to GHSNP, driving fragmentation that may threaten the persistence of protected species in the area (Iwanda et al. 2019). Moreover, social conflicts related to land ownership, intensive land use, and ongoing timber exploitation by the rural community are significant problems in managing this national park (Rosleine et al. 2014).

METHOD

Field Survey

We conducted field surveys to determine the occurrence of Javan Gibbons at 10 locations across the GHSNP (Figure 1). We selected survey areas by combining historical information from Ikbali et al. (2008) and information obtained during a meeting in October 2015 with two GHSNP officers: Mr. Wardi Septiana from Conservation Area Affairs and Mr. Momo Suparmo from Biodiversity Conservation Affairs. In total, we obtained 73 occurrence records of Javan Gibbons across 10 survey sites representing ten resorts (the smallest administrative unit of the national park); 80.8% of occurrence records were based on direct observation, and 19.2% were based on indirect observation.

Field surveys were conducted in both rainy and dry seasons. The survey for the rainy season was undertaken between October and November 2015, while the dry season survey took place between April and May 2016

along the transect lines. To minimize negative impacts on the survey area, the survey team (2–3 people for each site, including at least one of the authors) walked along existing trails in the forest for 1–2 km depending on the difficulty of the terrain. Surveys were conducted for four hours in the morning (0700–1100 h) and three hours in the afternoon (1400–1700 h) each day of a four-day survey. This schedule was followed during both seasons except on heavy rainy days when we stopped the observation and repeated it the next day. The survey times were chosen based on the activity patterns of the species. During the walks, we recorded the time and location for all direct (visual) and indirect (auditory) encounters using a GPS Garmin 64s (Kansas, United States), by estimating the distance from the observers the individuals sighted by using Bushnell Digital Laser Rangefinder 850 (Utah, United States), and sighting angle between the transect line and the observers to species line.

Data Analysis

We included seven environmental variables in our models that were also used in previous modeling for the same species (Helianthi et al. 2007; Suheri et al. 2014; Widyastuti et al. 2020), and as they were found to be likely to influence habitat use by Javan Gibbons (Table 1).

We used MaxEnt v3.3.3 (Phillips et al. 2006) to produce a map of suitable habitats for Javan Gibbons in GHSNP. Of the 73 occurrence data points, 75% of points were used as a training sample and 25% of points as references for model validation. Environmental variables that predicted >10% of the variance in gibbon presence in the models were identified as important, following Norris et al. (2011).

We classified habitat with values < 0.25 as having low suitability, values between 0.25–0.75 as having moderate suitability, and values > 0.75 as having high habitat suitability for Javan Gibbons. In most cases, values greater than 0.5 indicate suitable habitat (Yang et al. 2013). The default value of 1 has been identified as the most suitable to prevent overfitting (Merow et al. 2013).

Model accuracy should be tested in a modeling approach to evaluate model performance. We used a receiver operating characteristic (ROC) value closer to 1 to assess the model. This method does not require arbitrary threshold selection and has been widely used. The ROC generates a single measure of model performance called area under the curve (AUC) with AUC values > 0.9 indicating high accuracy of the model (Elith et al. 2006; Phillips et al. 2006).

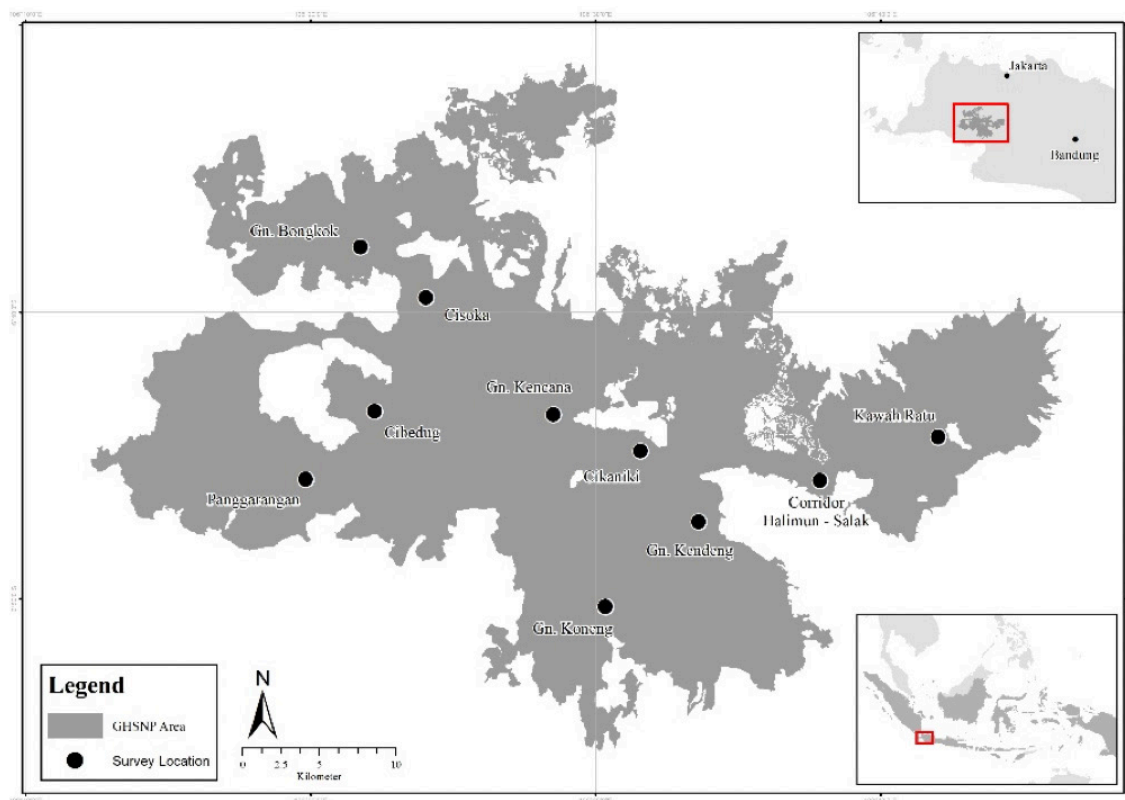


Figure 1. Locations in GHSNP, Indonesia, surveyed for the presence of Javan Gibbons in October–November 2015 and April–May 2016.

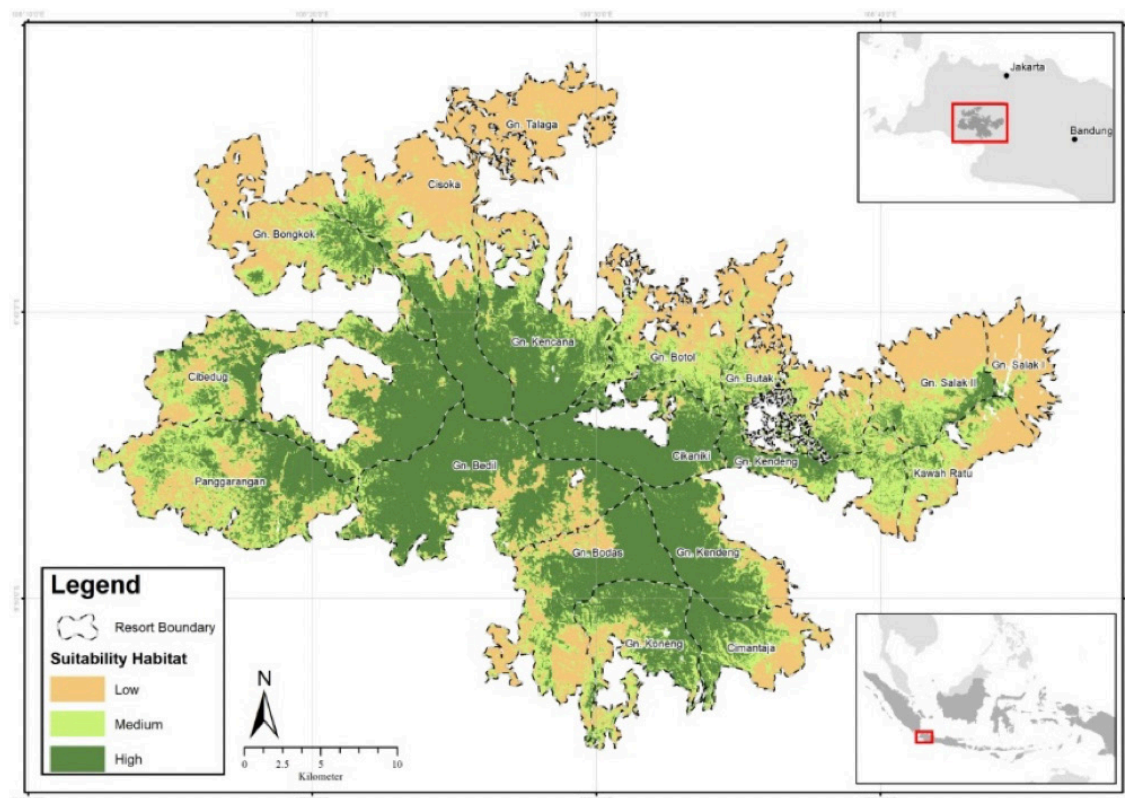


Figure 2. The habitat suitability map for GHSNP indicated that the central part of the park had high suitability while peripheral areas had low suitability for Javan Gibbons.

RESULTS

The final ecological niche model for Javan Gibbons provided a ROC with an AUC of 0.936 for the training data, indicating good performance and suggesting that the model can be used to predict species occurrence. Among the seven environmental variables investigated, forest canopy density and mean annual temperature contributed the most to the model and to predicting Javan gibbon distribution, accounting for 53.9% and 35.6% of the variation in habitat suitability, respectively (Table 2). No other variables in the model were identified as important predictors of habitat suitability for Javan Gibbons.

Most of the area within GHSNP was classified as highly suitable or moderately suitable, with highly suitable habitat comprising the largest proportion of habitat. A total of 36,921 ha (42.1%) of GHSNP was classified as highly suitable habitat, whereas 21,662 ha (24.7%) was classified as moderately suitable, and 29,116 ha (33.2%) was considered to be habitat of low suitability for Javan Gibbons (Figure 2).

DISCUSSION

The MaxEnt analysis confirmed that forest canopy density was the most critical predictor of Javan gibbon distribution in GHSNP and suggested that habitat with dense tree cover is associated with a greater probability of occurrence for this species. Widyastuti et al. (2020) reported similar results for Javan Gibbons in the Dieng Highland in Central Java, where the presence of natural forest with a connected canopy was the most crucial variable predicting habitat suitability in their MaxEnt analysis. Gibbons preferentially use high canopy layers for many activities, including travel, feeding, resting, and singing (Fan et al. 2009; Hamard et al. 2010; Cheyne et al. 2016; Jang et al. 2021). Because Javan Gibbons,

like all small apes, primarily travel through brachiation (arm-swinging locomotion that can only be performed across a relatively intact forest canopy), they require high canopy connectivity to travel efficiently and are particularly susceptible to habitat disturbance. High forest connectivity may also indicate high tree density or the presence of large trees, which are associated with the increased availability of plant foods (Zhang et al. 2022) and protection against predators. Our observations suggest that avian predators represent a real threat to gibbons, as we observed the predation attempts from above to the immature individuals by *Spilornis cheela* (Rahayu Oktaviani pers. obs. September 27th, 2019 & February 26th, 2020).

Canopy cover and tree height have also been found to influence the spatial distribution and density of other gibbon species, i.e., Agile Gibbons *Hylobates agilis* (Pang et al. 2022), Bornean White-Bearded Gibbons *Hylobates albibarbis* (Singh et al. 2018), Hoolock Gibbons *Hoolock hoolock* (Alamgir et al. 2015), Yellow Cheeked-Gibbons *Nomascus gabriellae* (Gray et al. 2010), and other arboreal primates, i.e., Bornean Orangutans *Pongo pygmaeus* (Felton et al. 2003), Pied Tamarins *Saguinus bicolor* (Vidal & Cintra 2006), Thomas's Langurs *Presbytis thomasi* (Slater 2015), and Red-Crested Tamarins *Saguinus geoffroyi* (Kim & Riondato 2016).

Climatic conditions have long been observed to play a primary role in limiting species distributions (Gaston 2003; Franklin 2009; Kamilar 2009), either directly or indirectly, through their effects on vegetation (Guisan & Thuiller 2005). Climatic variables may affect the productivity of food plant species that animals consume and, therefore, affect animal behavior, abundance, and distribution (Vidal-García & Serio-Silva 2011). For example, temperature and precipitation affect the distribution of Hoolock Gibbons, likely because of the influence of climate variables on the phenology of fruiting trees (Alamgir et al. 2015; Sarma et al. 2021).

Accordingly, our results showed that mean annual

Table 1. Predictor variables of habitat suitability for Javan Gibbons in GHSNP.

	Environmental variable	Unit	Data source
1	Annual precipitation	Millimeters	Bioclimatic map (http://www.worldclim.org/)
2	Mean annual temperature	°C	Bioclimatic map (http://www.worldclim.org/)
3	Aspect	Degrees	Digital Elevation Model (DEM) SRTM with a 30-meter spatial resolution (http://earthexplorer.usgs.gov/)
4	Distance from river	Meters	The Euclidean distance at software QGIS 2.10
5	Elevation	Meters	Digital Elevation Model (DEM) SRTM with a 30-meter spatial resolution (http://earthexplorer.usgs.gov/)
6	Forest canopy density	%	Imagery 8 2013 using the software Forest Canopy Density Mapper V2
7	Slope	%	Digital Elevation Model (DEM) SRTM with a 30-meter spatial resolution (http://earthexplorer.usgs.gov/)

temperature is the second-most important predictor of Javan Gibbons distribution in GHSNP. This variable is also correlated with elevation, and the relationship with Javan Gibbon distribution may result from an indirect influence of temperature on plant productivity. From an activity budget and behavior perspective, temperature variation may also influence resting time, an essential determinant of primate distribution (Stone et al. 2013; Fei et al. 2019). As a result, feeding and traveling time are generally positively affected by temperature in frugivorous primates (Korstjens et al. 2010; Fan et al. 2012). In future studies, the inclusion of animals experiencing a broader range of ecological conditions could shed more light on Javan Gibbons responses to temperature variation.

The model showed that most of the highly suitable habitat for Javan Gibbons is in the central part of the park, where substantial areas of sub-montane forest have the optimal physical and biotic resources to support Javan Gibbons. However, the area of highly suitable habitat is discontinuous, with some areas fragmented or isolated by areas with lower suitability for Javan Gibbons, especially in the western and eastern parts of the park.

Isolation in habitat fragments could severely threaten Javan Gibbons' long-term survival in these areas. For example, a recent Population and Habitat Viability Analysis for Javan Gibbons in GHSNP by Smith et al. (2017) showed that if the population is fragmented under current pressures, all subpopulations are likely to decline substantially in the next 100 years, and local extinction is very likely for the smallest subpopulations. Thus, maintaining or reestablishing connectivity of fragmented habitats and restoring habitat quality in habitat corridors is critical to facilitating the dispersal of arboreal species like Javan Gibbons across areas of high-quality habitat in GHSNP. Low suitability habitat mainly occurs in the peripheral areas of the park, which may limit Javan Gibbons to more central areas with higher food abundance in GHSNP.

Our species distribution modeling has limitations because it is based on the current realized niche (i.e., it considers where Javan Gibbons occur in the present day) rather than the fundamental niche (the range of places Javan Gibbons could occupy). Other studies have shown that some areas fall under environmental conditions matching the species' ecological environments, although the species does not occur in these areas (Raxworthy et al. 2003; Pearson et al. 2006; Thorn et al. 2009; Abolmaali et al. 2018). The model is also based on surveys at only a limited set of sites within the GHSNP landscape. A more detailed analysis based on a more extensive data set



Image 1. A mountainous survey area in Gunung Halimun Salak National Park.



Image 2. A Javan Gibbon *Hylobates moloch* found during the survey period.

Table 2. Environmental variables and their contribution to habitat suitability in a Maxent model for Javan Gibbons in GHSNP.

	Environmental variable	Predictive value and % contribution
1	Forest canopy density	53.9
2	Annual temperature	35.6
3	Annual precipitation	6.3
4	Slope	2.5
5	Distance from river	1.7
6	Elevation	0.1
7	Aspect	0

would allow the inclusion of more explanatory variables, which might improve our ability to model the Javan Gibbons ecological niche accurately.

The results of this study add to a growing body of information about Javan Gibbons distribution and habitat suitability in GHSNP, one of the most significant

remaining habitats for this endangered species (Nijman 2020). The predictive distribution map indicates that suitable habitats for Javan Gibbons are not uniformly distributed across GHSNP; some areas in GHSNP are more suitable than others for the species. Most of the suitable area is in the central part of the park, which must be protected to optimize the habitat and ensure the long-term persistence of the species. In addition, some high-quality habitat is located in peripheral areas of GHSNP. To prevent further degradation of these areas and to maintain and improve connectivity between fragments of high-quality habitat, buffer areas surrounding areas of high-quality habitat should be protected and, where possible, restored.

To ensure the long-term persistence of Javan Gibbons, an endangered species endemic to Indonesia, we recommend that the Indonesian Ministry of Environment and Forestry (MoEF) and the GHSNP authorities prioritize habitat protection to prevent erosion and degradation of high-quality habitats, including the area of Resort Cikaniki, Gunung Kendeng, and Gunung Bedil. Habitat restoration to increase habitat quality in degraded habitat in the peripheral areas of the park (i.e., the area of Resort Gunung Bongkok, Cisoka, and Gunung Talaga) is crucial to improve the low-medium suitable habitat adjacent to higher-quality habitat patches, especially in the corridor area connected the region of Halimun and Mount Salak as part of their conservation management strategy.

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Indonesian abstract: Pemodelan distribusi spesies menjadi sebuah alat penting untuk memahami ekologi suatu spesies dan telah banyak diaplikasikan dalam bidang konservasi. Melalui pemodelan Maximum Entropy (Maxent), kami mengidentifikasi faktor-faktor kunci untuk menentukan sebaran potensial bagi Owa Jawa *Hylobates moloch* yang terancam punah di salah satu habitat tersisa di Taman Nasional Gunung Halimun Salak (TNGHS), Indonesia, antara bulan Oktober dan November 2015, serta bulan April dan Mei 2016. Hasil analisis Maxent menunjukkan bahwa kerapatan tajuk pohon dan suhu menjadi faktor utama dalam memprediksi sebaran Owa Jawa. Kedua faktor utama tersebut memiliki skor kontribusi masing-masing sebesar 53.9% dan 35.6%. Sementara, peta prediksi sebaran Owa Jawa menunjukkan bahwa habitat yang sesuai tersebar secara tidak merata di dalam kawasan TNGHS. Habitat yang memiliki kesesuaian tinggi memiliki proporsi terbesar, dimana 42.1% kawasan TNGHS diklasifikasikan sebagai habitat dengan tingkat kesesuaian tinggi, sedangkan 24.7% dari total luas kawasan memiliki tingkat kesesuaian sedang, dan 33.2% merupakan habitat dengan kesesuaian rendah. Prioritas pengelolaan kawasan harus difokuskan untuk meningkatkan kualitas habitat di kawasan terdegradasi, serta perlu dilakukan patroli rutin dan penegakan hukum untuk mengurangi kerusakan habitat di Kawasan TNGHS.

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