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Research Article

Habitat Suitability Analysis of Javan Leopard (*Panthera pardus melas* Cuvier, 1809) in Gunung Gede Pangrango National Park (GGPNP) and Its Management Implications

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ABSTRACT

The Javan leopard (*Panthera pardus melas*) is an endangered apex predator that functions as an umbrella species for tropical montane rainforest ecosystems, such as in Java Island's Gunung Gede Pangrango National Park (GGPNP), Indonesia. This study aimed to assess habitat suitability, evaluate socio-economic impacts on buffer-zone communities, and formulate adaptive management strategies in Gunung Gede Pangrango National Park (GGPNP). A multidisciplinary approach was employed, integrating Maximum Entropy (MaxEnt) modelling for spatial analysis, social surveys to examine human–wildlife interactions, and the Analytic Hierarchy Process (AHP) to prioritise management strategies. The results indicate strong model performance (AUC = 0.870). Prey availability was identified as the most influential environmental predictor (54.5%), followed by distance from roads (16.2%) and distance from rivers (5.3%). Highly suitable habitat was estimated to cover an area of 2,482.89 ha. Socio-economic findings reveal that road accessibility facilitates illegal poaching of natural prey, triggering prey-switching behaviour in leopards in the form of livestock depredation and increasing the risk of retaliatory actions by local communities. The priority strategies identified comprise three levels of intervention: macro-level measures involving regulatory synchronisation and the implementation of SMART Patrols; meso-level actions focusing on habitat restoration in key resource hotspots; and micro-level initiatives emphasising ecotourism development and community economic empowerment. This study concludes that integrating ecological protection with the enhancement of community economic capacity is essential for the sustainable conservation of the Javan leopard in GGPNP.

Key words: Javan Leopard, Habitat Suitability, Human–Wildlife Conflict, MaxEnt Modelling, Adaptive Management

INTRODUCTION

The Javan leopard (*Panthera pardus melas*) is the last remaining apex predator on the island of Java and plays a crucial ecological role in maintaining the balance of montane forest ecosystems, including those within Gunung Gede Pangrango National Park (GGPNP) (Wibisono *et al*., 2021; As'ary *et al*., 2023). As an apex carnivore, the species regulates prey populations and supports ecosystem stability, making it an important umbrella species for biodiversity conservation. Owing to its endangered status (Endangered, CITES Appendix I), this endemic species is strictly protected under a range of national regulations, including Law No. 32 of 2024 that amends to Law No. 5 of 1990, as well as Minister of Environment and Forestry Regulation Number P.106/2018. This comprehensive legal framework reflects the urgent need to safeguard the species from imminent extinction.

Despite these protections, their implementation faces serious challenges as a result of rapid habitat loss. Over the past two decades, suitable habitat on Java has declined to approximately 1,429.65 km² due to deforestation and land-use change, which have intensified human–leopard conflicts (Gunawan *et al*., 2012; As'ary *et al*., 2023). Consequently, the total population is estimated at only around 319 individuals, with GGPNP recognised as a key stronghold supporting the highest density (16.04 individuals/100 km²) and an estimated local population of 24 individuals (Wibisono *et al*., 2021; Ario *et al*., 2022a). Nevertheless, even within this priority area, the species remains threatened by poaching and poorly regulated tourism activities in critical habitats (Rustiadi & Prihatini, 2015). The effectiveness of conservation in GGPNP therefore depends on the integration of ecological, social, and economic dimensions, which continue to face obstacles such as unsustainable agricultural practices and limited community participation (Ario *et al*., 2022a; Wibisono *et al*., 2021).

However, previous studies in GGPNP have largely focused on population estimates (Ario *et al*., 2018; Ario *et al*., 2022a), human-leopard conflict documentation (Rustiadi & Prihatini, 2015), and general habitat descriptions (Rustiadi & Prihatini, 2015; Gunawan & Sihombing, 2017; Ario *et al*., 2022a), while spatially explicit assessments of habitat suitability that incorporate socio-economic drivers remain limited. Few investigations have attempted to integrate ecological

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modelling with community perceptions and participatory planning to support adaptive management at the landscape level (Gunawan & Sihombing, 2017; Priatna *et al*., 2022). As a result, there is still a knowledge gap regarding how environmental determinants interact with local socio-economic conditions to influence the persistence of the Javan leopard and the effectiveness of conservation interventions.

This study seeks to address these gaps by integrating habitat suitability modelling with an assessment of human–wildlife interactions and strategic management prioritisation. Specifically, the study aims to: (1) identify the key environmental variables determining habitat suitability for the Javan leopard in GGPNP; (2) evaluate socio-economic factors influencing human–leopard interactions in buffer-zone communities; and (3) formulate adaptive and participatory management strategies to enhance coexistence and habitat protection. By aligning ecological evidence with community-based perspectives, this study is expected to provide a more comprehensive framework for conservation planning.

The results of this study are intended to contribute to science-based decision-making for GGPNP and to support the implementation of national action plans for *P. p. melas*. Strengthening the linkage between ecological protection and local livelihoods is essential to ensure long-term conservation outcomes. Therefore, this research emphasises the importance of integrating environmental management with community economic capacity as a foundation for the sustainable conservation of the Javan leopard in GGPNP (As'ary *et al*., 2023).

MATERIALS AND METHODS

Study Area

The study was carried out within five months from November 2025 to February 2026 in the Gunung Gede Pangrango National Park (GGPNP), West Java Province, Indonesia (Figure 1). This area was selected due to its intricate biological features and the strain of human activity (Pramesti *et al*., 2020; Sofiyudin *et al*., 2021; Priatna *et al*., 2022). GGPNP comprises an area of 21,975 hectares of natural ecosystems, which was established initially in 1980 through the Decrees of the Minister of Agriculture in 1980 and was extended in 2003 through the Decree of the Minister of Forestry in 2003. The park area starts at an elevation of 700 m and extends upwards to the areas of twin mountains, Mount Gede (2,962 m asl) and Mount Pangrango (3,019 m asl), connected by a saddle-shape ridge at an elevation of 2,400 m asl at Kandang Badak (Sadili *et al*., 2009; Sadili *et al*., 2023). In addition, the national park area, which is the core zone of the Cibodas Biosphere Reserve, one of the first UNESCO biosphere reserves in Indonesia, is one of the habitats of the Javan leopard with a strong population (Ario *et al*., 2022a).

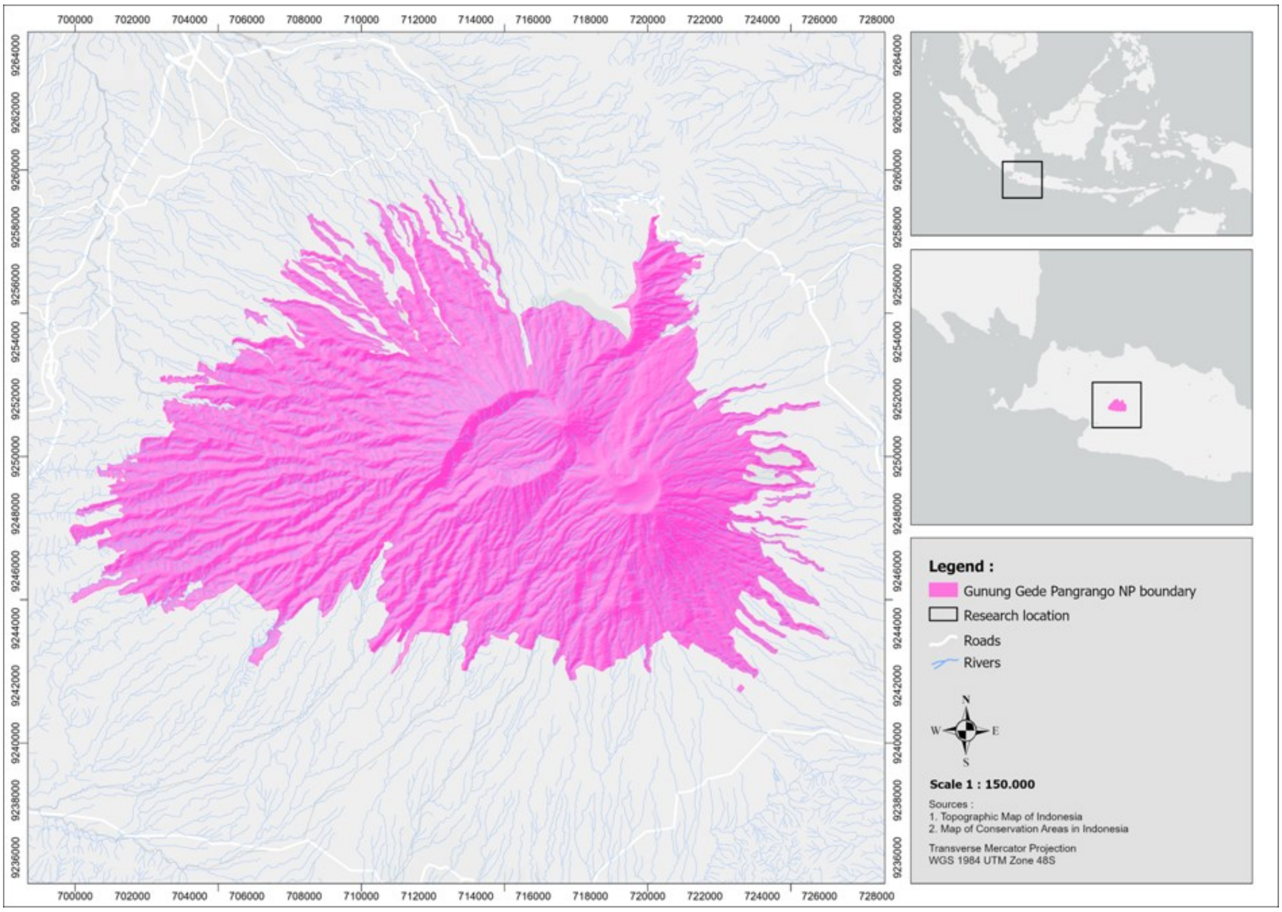

Figure 1. Research location in Gunung Gede Pangrango National Park (GGPNP), West Java Province, Indonesia.

Data Collection

Data collection integrated ecological survey methods, socio-economic surveys, and expert insights. Data on the presence of Javan leopards were sourced from camera-trap monitoring, direct encounters, and other field-verified secondary signs (footprints, scratches, and feces) collected between 2021 and 2025. This data was then compared with environmental variables (such as topography, slope, and land use) obtained through satellite imagery (Priatna, 2020). For socio-economic aspects, structured interviews were conducted with 26 respondents using a purposive sampling method (Tongco, 2007). The selected respondents were representatives of the community and conservation area managers. Furthermore, a questionnaire survey was used to obtain expert insights, and the results were applied in formulating management strategies based on ecological, socio-economic, institutional, policy, and research criteria (Martin *et al.,* 2012).

Species Presence Data

A total of 122 Javan leopard verified location data points used in the analysis were obtained through a review of official wildlife monitoring reports conducted by GGPNP officers. These reports included camera trap monitoring and direct encounter reports (generated 11 data points), reports of secondary signs such as footprints, feces, or scratches(generated 111 data points), and reports of human-Javan leopard conflicts or tnegative interaction throughout the GGPNP area during he 2021-2025 period. In addition, direct field observations and interviews with national park officers were conducted randomly to verify the presence of Javan leopards. Furthermore, using ArcGIS version 10.8 software, an Average Nearest Neighbour (ANN) analysis was conducted on all Javan leopard data points to determine and test the spatial pattern of their distribution, whether the pattern was clustered, random, or evenly distributed.

Environmental Variables

Environmental variable data for Javan leopard habitat modeling in GGPNP are grouped into three main categories of spatial variables (Table 1). First, topographical variables, which include elevation, slope, slope orientation (aspect), and access to water sources. Second, land-use variables that consider anthropogenic impacts, which are measured through distance analysis from roads and settlements, as well as the type of land cover. Third, biophysical variables that measure habitat quality through the Normalized Difference Vegetation Index (NDVI) and the availability of potential prey.

All presence data points of the Javan leopards and environmental variables, which are mostly generated from satellite imagery, are integrated and processed using ArcGIS software. Integration and processing of this data will produce a precise map of habitat suitability as a basis for spatial analysis in the GGPNP area.

Table 1. The variables that will be used in building the MaxEnt model on the Javan leopard in GGPNP

Distribution Data				
Type	Data	Source	Processing	Format
Data points	Presence data	Report on the results of inventory/ monitoring during 2021-2025	Sorting, Formatting	Shapefile (shp), Comma Delimited (csv)
Research Location (Mask)				
GGPNP Area	Mask	Conservation Areas in Indonesia (https://geoportal.menlhk.go.id/)	Split	Shapefile (shp)
Environmental Variables				
Type	Data	Source	Processing	Format
Topographic Variables	Elevation, Slope, Slope orientation (aspect)	Geospatial Information Agency (Badan Informasi Geospasial/BIG) https://tanahair.indonesia.go.id/ DEMNAS	Slope, Aspect, Masking, Converting	ASCII (asc)
	Rivers	Geospatial Information Agency (Badan Informasi Geospasial/BIG) https://tanahair.indonesia.go.id/	Euclidean distance, Masking, Converting	ASCII (asc)
Land-use Variables	Roads	OpenStreetMaps 2020 (https://www.openstreetmap.org/)	Euclidean distance, Masking, Converting	ASCII (asc)
	Settlements	OpenStreetMaps 2020 (https://www.openstreetmap.org/)	Euclidean Distance, Masking, Converting	ASCII (asc)
	Land cover	Ministry of Forestry 2022 (https://geoportal.menlhk.go.id/)	Masking, Converting	ASCII (asc)
Biophysical Variables	Normalized Difference Vegetation Index (NDVI)	USGS EarthExplorer Year 2025 (https://earthexplorer.usgs.gov/)	Cliping, Raster calculating, Masking, Converting	ASCII (asc)
	Potential prey	Survey results using camera traps in 2021	Euclidean distance, Masking, Converting	ASCII (asc)

Species Distribution Modelling (SDM)

Before modelling is created, Pearson correlation tests are performed to make sure that there is no redundancy between environmental variables. Raster data is extracted using the feature of Extract Multi Values to Points in ArcGIS, and then continue processed in Microsoft Excel. Variables with a correlation coefficient or determination of $R \geq 0.7$ will be eliminated and only one will be retained to maintain the performance of the MaxEnt model (Rahman *et al.*, 2022; Pearson *et al.*, 2007).

The MaxEnt method was chosen for its effectiveness in processing presence-only data to produce accurate habitat suitability probability maps (Philips *et al.*, 2006). This process begins with the preparation of species presence data in CSV (species, longitude, latitude) format, as well as the conversion of environmental variables to ASCII format with geographic reference and uniform pixel sizes via ArcGIS. To build the model, standard parameters were employed, which included 10 replicates with the subsample technique, as well as the allocation of 25% of the random test data (Merow *et al.*, 2013). To ensure model convergence and improve prediction accuracy, the simulation involves 10,000 background points and a maximum of 5,000 iterations.

The evaluation of model performance was carried out using the Receiver Operating Characteristic (ROC) method with the Area Under Curve (AUC) parameter (Hanley & McNeil, 1982). Employing the criteria of Pearce & Ferrier (2000), an AUC value above 0.9 is categorized as "Excellent," while a range of 0.8 - 0.9 is considered "Good." In addition to measuring accuracy, the model outputs were analyzed based on Percent Contribution and Permutation Importance to identify the most influential environmental variables, as well as a response curve that illustrates the correlation between those variables and the probability of animal presence. The final stage involves visualizing the probability output (values 0 - 1) using ArcGIS 10.8, which is classified through the equal training sensitivity method into the Low, Medium, and High suitability categories that will be used as an instrument to determine conservation priorities in GGPNP.

Socio-Economic Analysis and Mitigation of Negative Interaction between Human and Leopard

Socioeconomic data was collected through interview surveys of key stakeholders, including local communities, national park managers, and other related parties. The main method used was structured interviews (Newing, 2010), with questionnaire instruments covering seven crucial aspects: demographic data; perceptions of wildlife conservation and negative interaction or human-Javan leopard conflict; local or regional economic impact on livelihoods; levels of community participation in conservation programmes, as well as the chronology of conflicts or negative interactions. This last aspect is important for the future human-leopard conflict mitigation. The interview involved 26 respondents who were selected through purposive sampling techniques (Tongco, 2007) to gain an in-depth qualitative understanding and not for statistical analysis representation. 15 people of interviewed respondents are representing elements of the local community, such as community leaders, members of KTH (Kelompok Tani Hutan/ Forest Farmer Group), members of MMP (Masyarakat Mitra POLHUT/Forest Ranger Partner Community), and members of MPA (Masyarakat Peduli Api/Fire Care Community). The other interviewees were 3 (three) people of GGPNP managers, 2 (two) people from conservation support parties (members of NGOs and Nature Lover Group/KPA/Kelompok Pencinta Alam), and 3 (three) tourists/visitors, as well as 3 (three) representatives from village-level governments.

All collected qualitative data was analyzed using a thematic analysis approach (Georgiou, 2024). This method is applied inductively so that patterns or themes can emerge organically from field data without being constrained by the initial theoretical framework. The step of analysis started with data familiarization through verbatim transcription and intensive reading to capture the essence of the conversation. Furthermore, initial coding is conducted to break down the data into smaller and descriptive units of meaning. The process continues with a search for themes through the grouping of codes that have a common meaning, which are then visualized in a conceptual map (Fereday & Muir-Cochrane, 2006). These potential themes are then critically reviewed to ensure internal consistency and clear boundary differences between themes. Once the final theme is formed, the researcher provides a representative definition and naming as well as chooses the key quotes (verbatim) as empirical evidence.

The final stage is the presentation of the results of the analysis in a systematic and coherent manner, which relates socio-economic findings to the research objectives and their implications for adaptive management strategies in GGPNP.

Formulation of Recommendations for the Conservation Strategy of the Javan leopard

The scenarios of management strategy of Javan leopard conservation in the GGPNP were formulated through structured expert interviews and evaluated using the Analytic Hierarchy Process (AHP) method (Saaty & Vargas, 2012). This approach is suitable for establishing the most effective and sustainable strategies by taking into account five main criteria, i.e., ecological, socio-economic, institutional, policy and regulatory, as well as research and monitoring. The panel of experts involved was selected based on their specific competencies and knowledge of Javan leopard conservation and GGPNP management, including representatives from the GGPNP, local governments, academia, members of conservation NGOs, and community leaders. The hierarchical structure of AHP is structured to achieve the main focus, which is the strategy for the sustainable management of GGPNP.

At Level-1 (Criteria), the assessment is focused on ecological aspects (habitat conditions and prey populations), socio-economic aspects (conflict mitigation and ecotourism potential), institutional aspects (human resource capacity and funding), policy aspects (implementation of regulations and spatial planning), and research aspects (effectiveness of utilization of camera traps and GIS tools). Furthermore, at Level-2 (Alternative Strategy), there are five options of concrete action: (1) protection and restoration of priority or important habitats; (2) community-based conservation and mitigation of conflicts or negative interactions; (3) development of integrated conservation ecotourism and empowerment of local economies; (4) strengthening regional governance and increasing internal institutional capacity; and (5) synchronization of cross-sectoral regulations and enforcement of conservation laws.

Furthermore, the process of data analysis was carried out through the creation of a pairwise comparison matrix using the Saaty Importance Scale (1–9) (Saaty & Vargas, 2012). This stage begins with calculating the Priority Weight (Eigenvector) through normalization of the matrix to determine the relative importance value of each criterion. To ensure the validity of the results, a consistency test was carried out by calculating the Consistency Index (CI) and Consistency Ratio (CR) through the following formula:

$$CI = \frac{\lambda\_max - n}{n-1}\,\mathrm{V} \quad \text{and} \quad CR = \frac{CI}{RI}$$

If the CR value is < 0.1, then the assessment is considered consistent and acceptable. This analysis's final output is an overall weighting that sorts alternative strategies from highest to lowest priority. The formulation of this strategy holistically integrates the spatial findings of the MaxEnt modelling with socio-economic realities, resulting in comprehensive policy recommendations for the conservation of Javan leopards in GGPNP.

RESULTS AND DISCUSSION

Distribution of Javan Leopards in GGPNP

The analysis of Average Nearest Neighbor (ANN) of the presence data points of the 2021–2024 period confirms that the distribution of Javan leopards in GGPNP forms a significant clustering pattern (Figure 2). This is indicated by the Nearest Neighbor ratio of 0.573 (z-score = -9.554; p < 0.001) with a closer average distance distance between individuals (i.e., 420.93 m) than a random simulation. This pattern indicates intensive use in areas with critical resources by the Javan leopards, which, according to Ariyanto *et al*. (2025) and Rustiadi & Prihatini (2015), are highly dependent on the availability of resources of prey and water as well as forest cover as ecological refuges. The concentration of the population in these good-quality habitat pockets emphasizes the role of GGPNP in providing a source of productive habitat for the Javan leopards. Noer *et al*. (2021) argue that primary or undisturbed forest is the most preferred habitat for the Javan leopard, although they also regularly use secondary and managed forests when these areas provide cover and connectivity (Gunawan *et al*., 2012).

The result of MaxEnt modelling indicated a very strong performance with an Area Under the Curve (AUC) value of 0.870 ± 0.025 (Figure 3), which is higher than the accuracy of some other previous studies, such as in Gunung Sawal with an AUC value of 0.85 (Rahman *et al*., 2020) and other Javan leopard habitat modelling with an AUC value of 0.812 (As'ary *et al*., 2023). High accuracy of the model in this study most likely is driven by the use of the prey distribution variable as a primary biological predictor (Noer *et al*., 2021; As'ary *et al*., 2023). With a 10th percentile training presence threshold, the model accurately maps the supporting habitat of the population while at once confirming that the long-term viability of this species is highly sensitive to damage to the core habitat (Wibisono *et al*., 2018). With the high stability of the model, this suitability map can be utilized as an instrument for developing a reliable zoning policy in GGPNP.

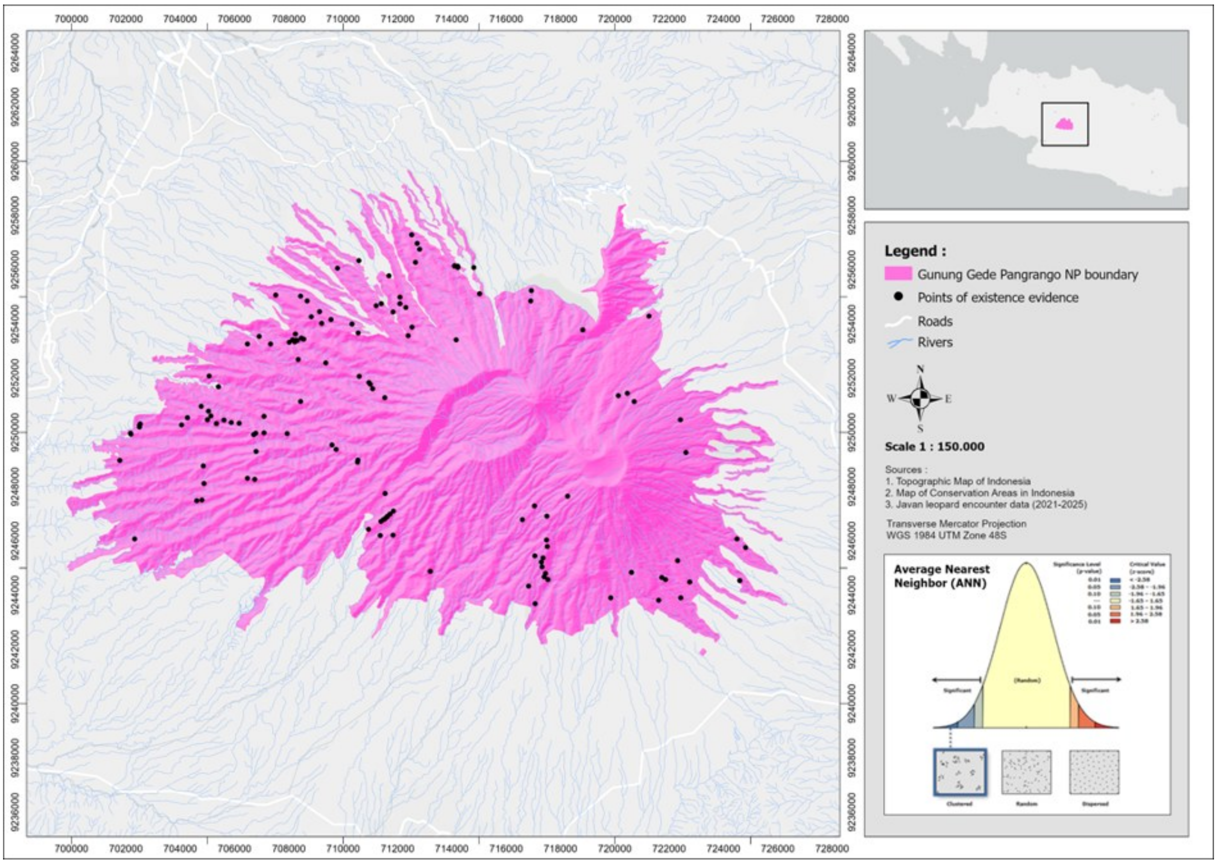

Figure 2. Location points where evidence of the presence of Javan leopards was found based on camera traps, direct sightings, and other secondary signs in the GGPNP area.

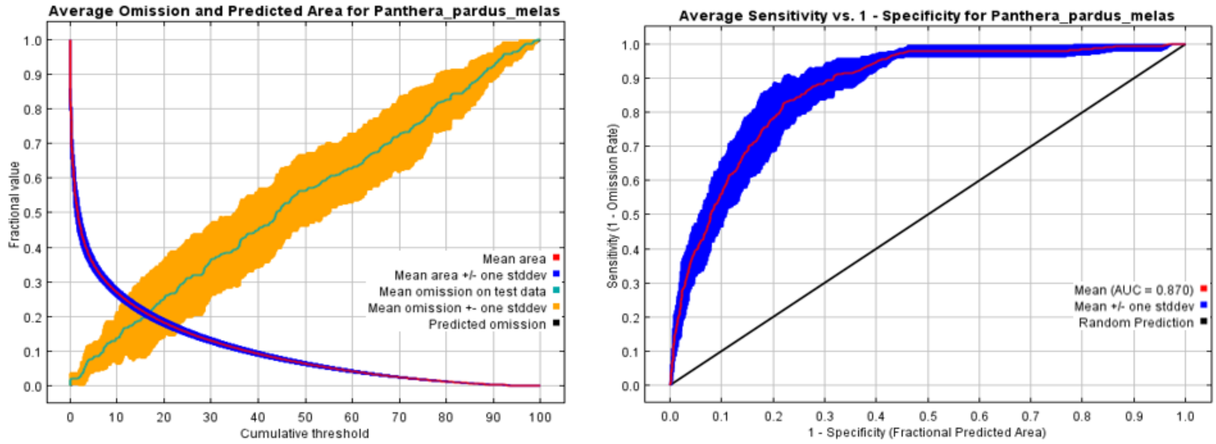

Figure 3. The mission rate curves and AUC values of the MaxEnt model of the Javan leopard in GGPNP

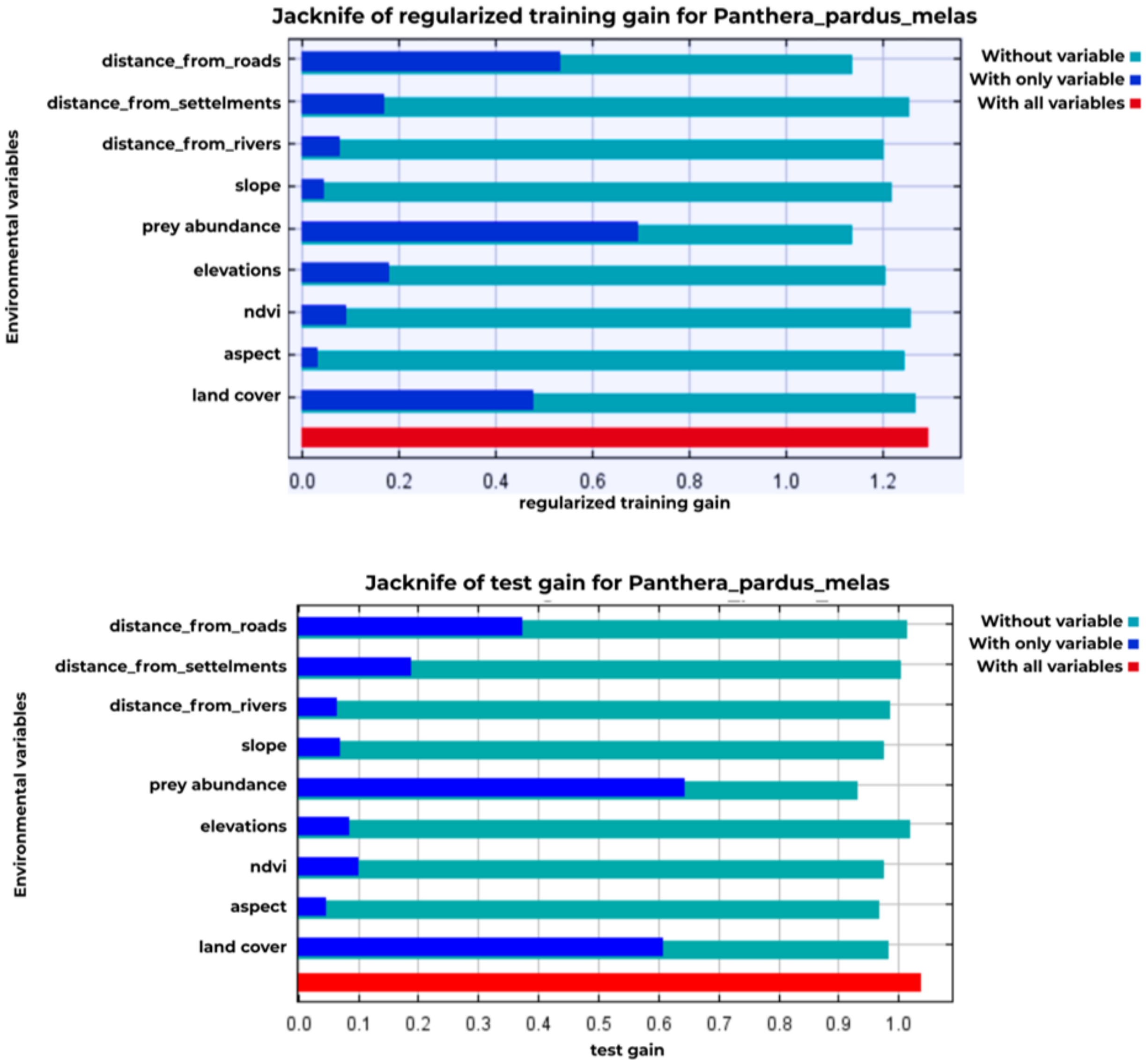

Figure 4. The Jacknife test results.

Table 2. Relative contribution of environmental variables to the MaxEnt model for GGPNP.

Variable	Percentage of Contribution (%)	Permutation interest (%)
Abundance of prey	54.5	47.7
Distance from roads	16.2	14.9
Elevation	6.6	10.6
Distance from rivers	5.3	3.7
Slope	4.9	6
Land cover	4.7	3
Distance from settlements	3	7.1
Aspect (slope orientation)	2.4	4.4
NDVI	2.4	2

The Jackknife test confirms that the variable of prey abundance is the fundamental factor with the highest contribution (gain) in developing the habitat suitability model in this study (Figure 4). The result of the test is consistent with the findings of Noer *et al*. (2021), which stated that the limiting factors for large carnivores like the Javan leopard are prey availability, topography, and intensity of human disturbance. In contrast, the variable of distance from roads is the most significant indicator of human disturbance that affected the model's performance. This indicates that although the GGPNP is relatively intact, the road accessibility remains a major source that drives a human disturbance to leopard habitat preferences (Gunawan & Sihombing, 2017). The integration of biological and anthropogenic variables employed in this study results in robust predictive evaluations, although with limited sample sizes (Shcheglovitova & Anderson, 2013).

The Influence of Environmental Variables on Habitat Suitability

MaxEnt's modelling places the variable of prey abundance as the most dominant single predictor with a contribution of 54.5% and a permutation importance of 47.7% (Table 2). This dominance confirms that the availability of feed (prey species) is the main limiting factor for the spatial distribution of leopards in GGPNP (Figure 5). This finding is consistent with previous research conducted by Noer *et al*. (2021) in the Gunung Sawal area of West Java and Ariyanto *et al*. (2025), which stated that the distribution of Javan leopards in an area is greatly influenced by the abundance of prey species in that area.

These findings are also consistent with several field studies and MaxEnt modeling analyses conducted on the Indian leopard (*Panthera pardus fusca*) in India, which show a consistent positive relationship where the presence of prey is the main driving factor determining habitat selection (Mondal *et al*., 2013; Kshettry *et al*., 2017; Puri *et al*., 2022). The presence of diverse prey species ensures energy stability for apex predators, and large carnivores are vital regulators of forest ecosystems, influencing prey populations and maintaining ecological balance through top-down control (Santhosh *et al*., 2025).

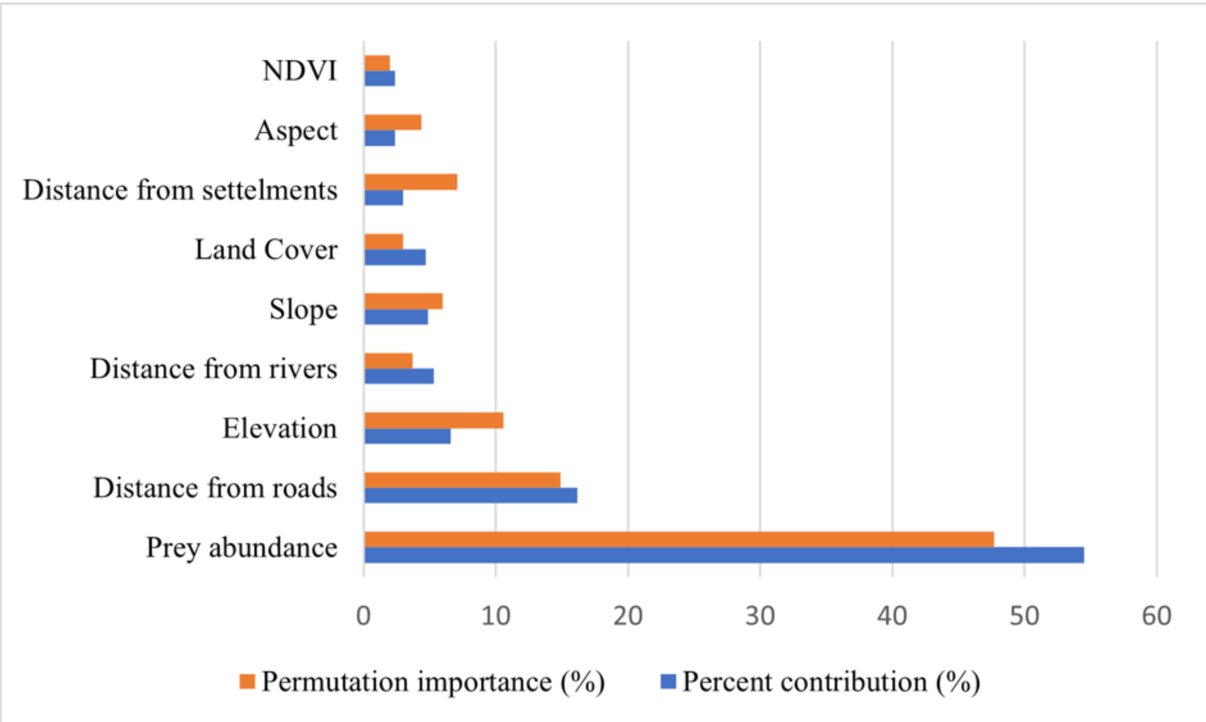

Figure 5. The relative contribution and importance of environmental variable permutations to the model

The results of MaxEnt modeling for the suitability of Javan leopard habitat in GGPNP obtained the following important following findings:

Prey Availability as a key habitat determinant

The modeling results showed that the prey availability variable dominated the model with a contribution of 54.5% and a permutation importance of 47.7%. The high level of this metric indicates that prey is the most robust predictor in determining the distribution of Javan leopards, in line with the predator-prey ecology theory, which states that the distribution of apex predators is limited by their trophic resources. According to Noer *et al.* (2021), prey availability is a major factor limiting predator distribution. Carnivores like the Javan leopard tend to stay close to prey to hunt and survive more efficiently. In GGPNP, habitat preferences of this species include primary forests and steep slopes that provide water and an abundance of prey such as wild boar (*Sus scrofa*), barking deer (*Muntiacus muntjak*), and primates (Rustiadi & Prihatini, 2015; Noer *et al.*, 2021; Rizaldi *et al.*, 2022; Ariyanto *et al.*, 2025).

Gunawan & Alikodra (2013) argued that the decline of prey populations due to forest fragmentation and poaching could expand the home range of Javan leopards, thereby increasing the risk of their interactions with humans (Gymnastian, 2019). Another fact, camera trap surveys' data in the Bodogol area of GGPNP show that although wild boars are abundant, the capture rate of Javan leopards remains low, which indicates their avoidance behaviour towards humans (Rustiadi & Prihatini, 2015). This is strengthened by the findings of Ariyanto *et al.* (2025) that 94.3% of the Javan leopards' presence points are in areas with high prey density.

Influence of anthropogenic variables

The distance from roads variable contributed significantly, 16.2%, where the optimal habitat for the Javan leopards in GGPNP is concentrated in the buffer zone at a distance of 1,000–2,000 m from the road access. According to Noer *et al.* (2021), the existence of a road network will increase human access and their activities within forest areas. Human activities such as land clearing, settlements, and non-forest land use can limit Javan leopards' movement by reducing habitat quality, disrupting roaming patterns, and increasing the risk of conflict. Roads in tropical ecosystems have been shown to reduce connectivity and break down the intact ecosystem into "islands" of habitats that are vulnerable to genetic isolation (Mohammadi & Fatemizadeh, 2021; Widyastuti *et al.*, 2023). Leopards show high sensitivity to infrastructure, in contrast to some more tolerant herbivores (Underhill & Angold, 2011; Gunawan & Sihombing, 2017).

This fragmentation triggers and amplifies an edge effect that forces leopards to move into steeper areas, where prey densities may be lower (Ariyanto *et al.*, 2025). Therefore, mitigation through wildlife crossings or corridors, as well as strengthening of conservation zones, is crucial to maintain gene flow (Frankham, 2015; Kautz *et al.*, 2021; Quintana *et al.*, 2022).

Complexity of other variables Interaction

The elevation variable contributes 6.6% to the developed model, with the highest probability of presence in mountainous primary forests above 1,000 meters above sea level. This area is proven to function as a natural refuge for Javan leopards in GGPNP to avoid human activities (Gunawan & Sihombing, 2017). However, substantial elevation plasticity was observed by Ariyanto *et al.* (2025), indicating that elevation serves as a better indicator of low anthropogenic disturbances and forest integrity. A similar finding is explained by As'ary *et al.* (2023) that human disturbances is relatively low in high elevations (As'ary *et al.*, 2023).

On the other hand, the land cover variable contributes 4.7%, as leopards rely heavily on vegetation architecture for stalking hunting strategies (As'ary *et al.*, 2023). In GGPNP, the highest probability of Javan leopards' presence was found in secondary dryland forests and plantation forests that cover 74.5% of the area. This proves the adaptability of this species to various types of land cover as long as its canopy protection function is maintained (As'ary *et al.*, 2023).

Secondary forests and plantation forests in GGPNP serve as vital supports and alternative living spaces for Javan leopards in the midst of a fragmented landscape (Wibisono *et al.*, 2021). Although this species prefers primary forests with rich biodiversity as their main protection, they tend to avoid areas that have been converted to plantations due to high human disturbance (Gunawan & Sihombing, 2017). On the other hand, biophysical variables such as NDVI and aspect showed minimal contribution due to the masking effect of the more dominant prey variables. However, slope (4.9%) and distance from rivers (5.3%) variables remain crucial elements; steep terrain serves as a natural refuge to avoid humans (Kolekar *et al*., 2024; Noer *et al*., 2021), while rivers serve as trophic interaction zones and movement corridors that determine the spatial distribution of these predators. Some studies argued that the key environmental strategies to preserve the Javan leopard's natural mobility and spatial ecology include preserving and restoring forest cover, preserving habitat corridors, and sustaining prey populations both inside and outside of protected areas (Rahman *et al*., 2018; Wibisono *et al*., 2018; Snider *et al*., 2021).

Javan leopards generally exhibit a natural tendency to avoid human presence; however, intensive poaching that reduces wild prey availability frequently compels them to move closer to residential areas (3.0%) and target livestock as an alternative food source (Gunawan & Sihombing, 2017). This situation generates significant risks and fosters negative attitudes among local communities toward leopards, particularly among farmers (62% of respondents) who perceive direct economic losses. In the Gunung Sawal area, the frequent occurrence of livestock attacks reflects inadequate management of prey resources within the core habitat (Dewanti & Marhaento, 2021). This observation supports Rahman *et al*. (2018), who reported a decline in leopard occurrence near human-dominated landscapes as a consequence of edge effects. Accordingly, mitigation efforts should prioritize practical measures such as improving nighttime livestock protection and rehabilitating natural prey populations to lessen the species' reliance on domestic animals.

Map of Habitat Suitability of the Javan Leopard

The map of Javan leopard habitat suitability in the GGPNP generated through MaxEnt modelling has an excellent level of accuracy (AUC 0.870) (Figure 6), which represents the spatial distribution of the species based on the integration of variables of prey availability, land cover, topography, and anthropogenic pressure. The visualization of high, medium, and low suitability

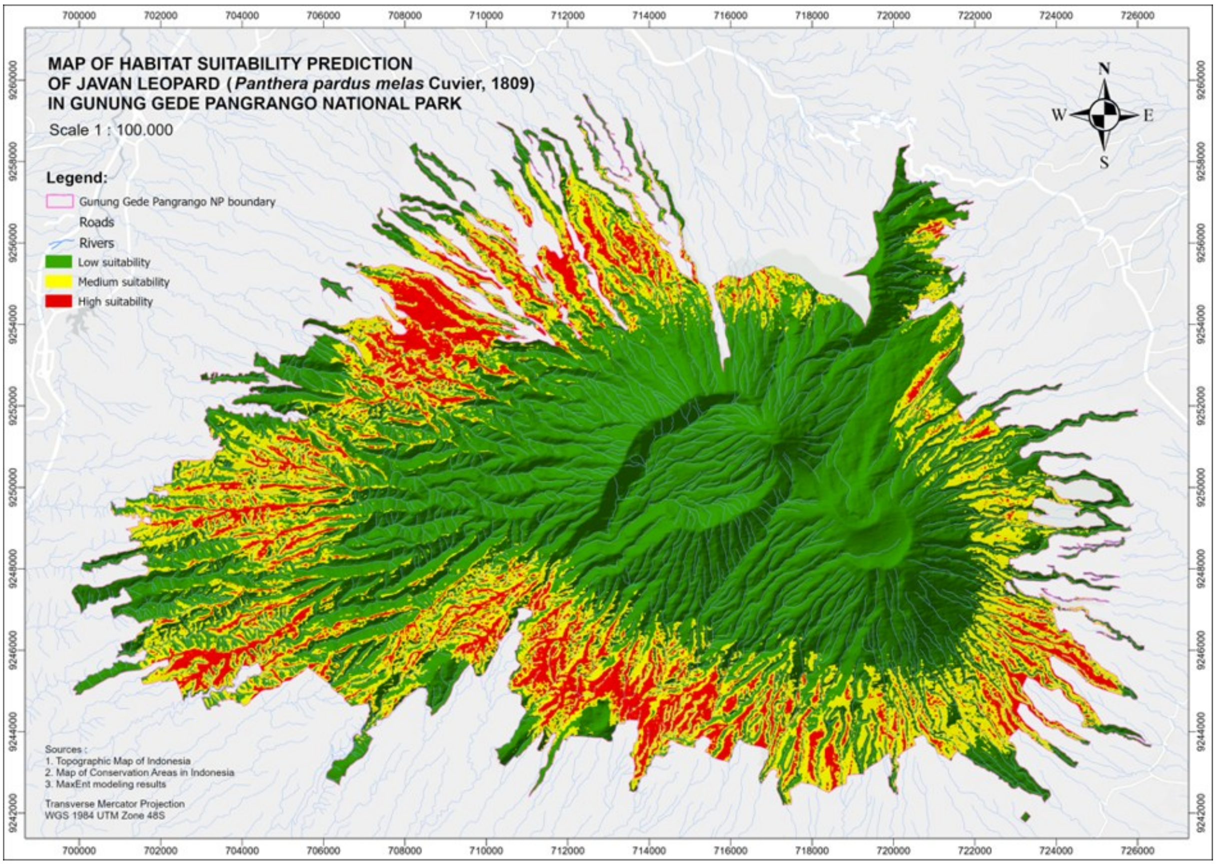

Figure 6. Map of habitat suitability prediction of Javan leopard in GGPNP.

classes drawn in the map follows the gradation of slope contours as well as valley networks, which effectively identifies refugia areas and critical tangents between potential habitats and human activities. By utilizing biophysical data such as NDVI (Normalized Difference Vegetation Index) and distance to rivers, this map serves as a reliable strategic instrument in determining habitat protection priorities and mitigation of negative interactions throughout national park areas. A study of Ariyanto (2015) on the Javan leopard indicates that NDVI consistently contributed to predicting leopard distribution and designing connectivity, with models identifying the most suitable area inside protected parks and corridors characterized by sufficient vegetative cover. Higher NDVI (more vegetation cover) commonly corresponds with greater leopard habitat suitability, but leopards often select intermediate-cover habitats where prey and water are abundant (Mondal *et al*., 2013).

Based on MaxEnt modeling, Javan leopard habitats in GGPNP are divided into three categories: low suitability (16,162.11 ha), medium suitability (5,637.86 ha), and high suitability (2,482.89 ha). The area of high suitability is concentrated on the middle to foothills of the mountain (750 - 1,764 meters asl), which are covered by dense mountain forests and steep slopes rich in prey and water sources. The dominance of prey variables in the model (±54.5%) confirms that prey availability is the main determinant of core habitat quality (Rustiadi & Prihatini, 2015; Wibisono *et al*., 2018). Javan leopards occur across a range of elevations but show a consistent preference for mid- to higher elevations and steep, rugged topography that provides shelter and hunting terrain (Gunawan *et al*., 2012; Gunawan & Sihombing, 2017; Setiawan & Rinaldi, 2023). However, because some of these optimal habitats are adjacent to settlements, the risk of negative interactions becomes very high and requires targeted mitigation.

On the other hand, low suitability areas for Javan leopards in GGPNP are areas above 2,000 meters asl, where within this elevation there is naturally low prey availability, but a study by Gunawan & Sihombing (2017) found that the Javan leopard (*Panthera pardus melas*) shows a preference for higher elevation areas, often above 1,000 m above sea level, likely because these mountain habitats offer better shelter (cover) and lower levels of human disturbance compared to lower elevations. In the case of GGPNP, in addition to the low availability of prey animals, the highland areas of this national park have very high human disturbance because it is one of the most favorite mountain climbing areas in Indonesia, with many trekking routes (Dente *et al*., 2025).

Areas of moderate suitability serve as important transition zones for Javan leopards in the GGPNP, although they are beginning to be threatened by landscape fragmentation (Wibisono *et al*., 2018). Considering that high-quality habitats are limited to topographic security "pockets," the park's management priorities should be focused on the strict protection of core habitat blocks, maintaining connectivity corridors, and controlling the pressure at the edges of the park to ensure the sustainability of the Javan leopard population in the GGPNP. Gippoliti & Meijaard (2007) and Wibisono *et al*. (2018) stated that conservation priority to sustain the Javan leopard population in the wild is protecting and connecting remaining forest patches, i.e., between national parks and all adjacent production and secondary forests.

Table 3. AHP analysis results for key criteria.

No.	Criteria	Weight	Percentage
1.	Ecology	0.298	29.8%
2.	Socio-Economic	0.137	13.7%
3.	Institutional	0.149	14.9%
4.	Policies and Regulations	0.214	21.4%
5.	Monitoring and Research	0.202	20.2%

Table 4. AHP analysis results for alternative strategies.

No.	Criteria	Weight	Percentage
1.	Restoration and protection of priority habitats	0.301	30.1%
2.	Community-based conservation and mitigation of negative interactions between Javan leopards and humans	0.123	12.3%
3.	Development of integrated conservation ecotourism and empowerment of local economies	0.074	7.4%
4.	Strengthening regional governance and increasing internal institutional capacity	0.127	12.7%
5.	Synchronization of cross-sector regulation and enforcement of conservation laws	0.375	37.5%

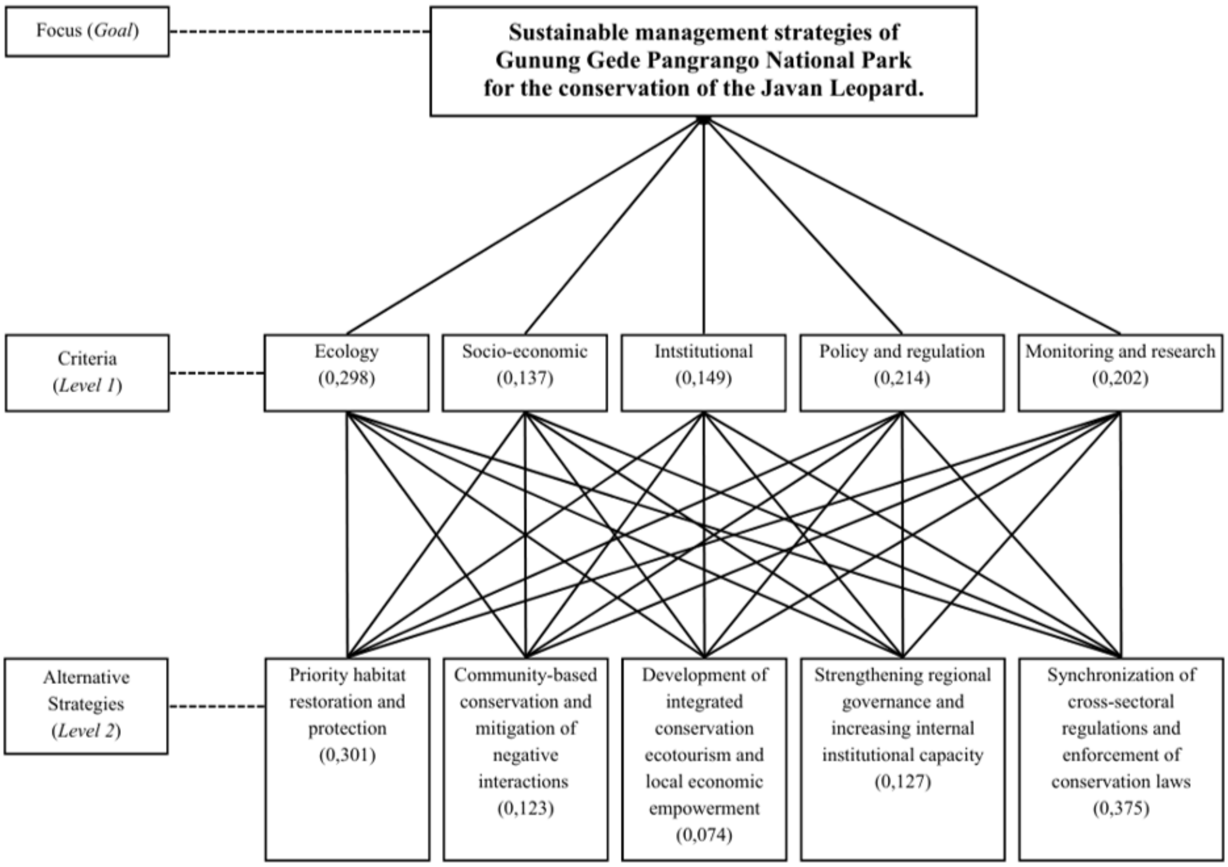

Figure 7. Hierarchical structure of GGPNP management strategy for Javan leopard conservation.

The Effectiveness of Socio-economic and Human-Wildlife Conflict Mitigation Programmes

All 26 respondents, who are the community members who live in the buffer zone of GGPNP, received economic benefits from the region, although 70–80% of their livelihood still depended on the agricultural and livestock husbandry sectors, which are vulnerable to human-wildlife conflict. Continuous negative interactions between humans and Javan leopards around GGPNP (high-frequency, low-severity) occur 1 to 5 times per year (88.5%), mainly in the form of livestock grazing during the night (between 8.30pm and 4.00am) at the boundaries of the optimal habitat for Javan leopards. Despite financial losses they face, community support for conservation remains high (92.3%) because the Japan leopards are considered as natural controllers of the pest species (wild boars). According to Gunawan *et al*. (2017), 71 human-Javan leopard conflict incidents were documented over 15 years in Western Java, with local occurrence records classed as 30% high, 25% moderate, and 46% low conflict potential areas. However, the community support for the Javan leopard conservation suggests positive support when conservation is paired with local benefits (Wibisono *et al*., 2018).

GGPNP's success in mitigating human-Javan leopard conflicts is rooted in the transformation of the community into environmental service actors. Diversification of community income through the ecotourism sector in the area has increased community tolerance to the presence of Javan leopards by up to 45% and has changed the perception of leopards from "competitor" or "enemy" or "pest" to tourism "assets" (Wibisono *et al*., 2021; Ariyanto *et al*., 2025). However, a study shows that the phenomenon of prey switching from natural wild species to livestock still occurs, triggered by the energy needs of a mother leopard with cubs (up to 4.9 kg of meat/day) in an area of declining of natural prey (San Diego Zoo Wildlife Alliance Library, 2026).

Therefore, mitigation of human-Javan leopard conflict in the GGPNP should integrate an ecological approach through the recovery or enrichment of prey species population programme into an existing social capital that has been formed. The involvement of local knowledge-based Forest Ranger Partner Communities (Masyarakat Mitra Polhut/MMP) has been proven to cut conflict response time from 48 to less than 12 hours (Gunawan *et al*., 2024). The combination of technical (safe cages) and structural (access to tourism services) mitigations has been creating a stable coexistence model that positions the community as a prosperous conservation subject.

Integration of Ecological and Socio-economic Analysis

The effective conservation strategy needs to integrate spatial ecological parameters and socio-economic dimensions through a transdisciplinary approach (Zhao *et al*., 2023). The analysis of the location data of Javan leopard findings in GGPNP shows that the Average Nearest Neighbour (ANN) ratio is 0.573 (Figure 2), which means that the distribution of the Javan leopard population in GGPNP tends to be clustered. Therefore, management interventions should be prioritized in resource hotspots covering an area of 2,482.89 ha in the GGPNP area, which can function as natural refuges for Javan leopards at an altitude of 750-1,764 meters asl (Gunawan & Sihombing, 2017). The MaxEnt modelling confirms that prey availability is the main limiting factor with a contribution of 54.5% (Ariyanto *et al*., 2025), while the distance from the road variable accounts for 16.2% of the Javan leopard resistance in high-accessibility zones (Dildar *et al*., 2025). Considering the drastic decline in Javan leopard habitat in the last two decades, from approximately 2,481.00 km² in 2000 to 1,429.65 km² in 2020 (or approximately 40%), GGPNP now plays an important role as a primary source of Javan leopard habitat through the maintenance of ecological corridors and strict monitoring of ecosystem integrity (As'ary *et al*., 2023; Wibisono *et al*., 2021).

The success of this strategy is also highly dependent on Javan leopard conflict mitigation in villages along the buffer zone of GGPNP, where community dependence on the agricultural and livestock husbandry sectors has created high-risk tangents. The phenomenon of prey switching from wild prey to domestic livestock—such as what happened in the Loji Kolot and Pasir Salam Blocks within the GGPNP area—was identified as the impact of the decline of natural prey due to poaching and habitat degradation (Damaris, 2025). Although 92.3% of the community supports Javan leopard conservation because of the role of animals as pest controls, economic losses of up to IDR 12,000,000 per incident can erode this tolerance if it is not immediately accompanied by a fair mitigation scheme (Dewanti & Marhaento, 2021). The focus of the intervention must be proactive through optimizing cage security during Javan leopards' active hours (which are between 8.30pm and 04.00am) by integrating sensor light technology (foxlights) and traditional knowledge as an early warning system (Santoso *et al.*, 2022).

Recommendations for the Conservation Strategy of the Javan Leopard in the GGPNP

The determination of strategy priorities for Javan leopard conservation in GGPNP was carried out through the Analytic Hierarchy Process (AHP) method to produce measurable policies that are accepted by all stakeholders. According to Sterling *et al*. (2017) and Li *et al*. (2024), early and meaningful stakeholder involvement can increase the legitimacy and acceptance of conservation strategies, thereby increasing the chances of successful wildlife policy implementation. The validity of this analysis is confirmed by a Consistency Ratio (CR) value of 0.0189 (< 0.1), which indicates the consistency of the expert's assessment. This hierarchical structure ensures that each conservation step has a strong foundation of objectivity to be implemented on the ground.

The results of the AHP analysis show a clear priority structure in the management of Javan leopards in GGPNP. The Ecology Criteria ranks first as the main pillar with a priority vector weight of 29.8%, followed by Policy and Regulation aspects (21.4%) and Monitoring and Research (20.2%) (Table 3). The dominance of these ecological criteria reflects the consensus among experts that ecosystem integrity and population viability are fundamental indicators of conservation success. Meanwhile, at the alternative strategy level, the synchronization of cross-sector regulations and the strengthening of law enforcement received the highest weight of 37.5% (Table 4), which indicates the urgency of improving legal aspects and agency collaboration as the most urgent implementation step in the field. These findings confirm that although biophysical (ecological) factors are the main substances that must be protected, policy and research instruments are the main drivers to make this happen. The priority on regulatory synchronization reflects the need for spatial harmonization between national park authorities and local governments to minimize further habitat fragmentation.

The Consistency Ratio (CR) value obtained at 0.0189—far below the threshold of 0.1—confirms that the results of this AHP analysis have a very high level of reliability and logical consistency as a reference for strategic policies. This synthesis shows that the ideal management strategy must begin with the improvement of the legal system to provide a strong foundation for habitat restoration and strengthening the capacity of management organizations. With this integration, any conservation intervention in the field is not only ecologically appropriate but also has a solid legal basis and adequate resource support for the sustainability of the Javan leopard population in the GGPNP.

The structure of the Javan leopard conservation policy in the GGPNP is arranged hierarchically based on the weight of interests to ensure effectiveness in the field (Figure 7):

1) *Synchronization of cross-sectoral regulations and enforcement of conservation laws*

Policy coherence is a fundamental prerequisite for addressing habitat fragmentation. Key steps include harmonizing the 2025–2035 GGPNP's Long Term Management Planning (RPJP) with the Spatial Planning (RTRW) of the surrounding area. Strengthening law enforcement is carried out through SMART Patrol, which is integrated with the map produced from MaxEnt modelling, to protect trophic bases (natural prey) from poaching (Hadi *et al*., 2025).

2) *Priority habitat restoration and protection*

Focuses on securing environmental determinant factors. Restoration is prioritized in a "medium suitability" area of 5,637.86 ha through planting and enrichment of native vegetation within the degraded areas. The construction of hydrological corridors at river borders is crucial to ensure animal connectivity in complex landscapes (Sutopo *et al*., 2025).

3. *Strengthening regional governance and increasing internal institutional capacity*

The transformation of scientific data into operational actions is carried out through the institutionalization of routine population monitoring using camera traps. Increasing the capacity of human resources in spatial analysis is needed so that managers are able to map the dynamics of the home range of Javan leopard in real-time (Santoso *et al*., 2021).

4. *Community-based conservation and mitigation of negative interactions*

The existence of Javan leopards depends on social dynamics in buffer zones. Mitigation is carried out technically through cage security during Javan leopard active hours (8.30pm - 04.00am) and the use of foxlights technology (Gunawan & Sihombing, 2017). The revitalization of the Forest Ranger Partner Community (MMP) by utilizing local ecological knowledge has been proven to accelerate conflict response to under 12 hours.

5. *Development of integrated conservation ecotourism and local economic empowerment*

Used to reduce dependence on the conflict-prone agricultural and livestock husbandry sectors. By positioning Javan leopards as "intellectual tourism icons" (e.g., camera-based education), citizens' tolerance and pride increase (Wiratno, 2020). Local guide certification puts citizens as conservation interpreters at the forefront.

In implementing conservation strategies, GGPNP managers are encouraged to intensify research, resource exploration, and scientific documentation in the form of national and international publications. This effort is synergized with the expansion of the conservation funding network, in line with the manifesto "Intellectual Tourism" (Wiratno, 2020). The approach emphasizes that a strong scientific database is the key foundation for adaptive and accountable management of the region.

The proposed strategies for the Javan leopard conservation in GGPNP are classified into three levels of intervention that synergize and support each other:

1) *Macro Level (Regulation)*: Focuses on legal certainty and policy harmonization across sectors. The main priority is the synchronization of regulations and law enforcement to prevent forest fragmentation and align regional spatial planning with regional management plans.
2) *Meso Level (Ecology)*: Focus on improving the quality of core habitats and prey availability through priority habitat restoration. This step aims to maintain the stability of the Javan leopard population in the core zone and strengthen the carrying capacity of the area through solid institutional governance.
3) *Micro Level (Social)*: Directed at strengthening the economic capacity of the community surrounding the park to mitigate the risk of negative interactions through the development of ecotourism and economic empowerment in buffer villages. Social tolerance is constructed on real economic benefits to reduce anthropogenic pressures on Javan leopard habitats.

The management strategy formulated, from the macro to the micro level, is a concrete step in supporting the Javan Leopard SRAK 2016–2026. Priority habitat restoration and *strengthening of SMART Patrol* address the need for population protection directly, while participatory approaches through ecotourism and conflict mitigation are crucial instruments in creating coexistence. The integration of ecological aspects and community welfare is expected to be able to strengthen the effectiveness of GGPNP while contributing to national conservation targets.

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However, the challenges ahead are increasingly complex due to climate change and human population dynamics. Without massive restoration, high-quality habitats for the leopards on Java Island are predicted to shrink by 40% by 2050 (Mowbray, 2023). This condition has placed the GGPNP which has a high population density of Javan leopards (16.04 ind/100 km^2) (Ario *et al*., 2022a), as the 'heart' of strategic conservation that supplies individuals to the surrounding area within the larger landscape (source habitat). Conversely, weak regulatory synchronization will risk isolating the area of GGPNP and triggering local extinction due to anthropogenic pressure and genetic degradation (Wibisono *et al*., 2021). The implementation of this integrated strategy is the main key to maintaining the existence of the Javan leopard as a proud identity or mascot and sustainable ecosystem service provider.

CONCLUSION

The sustainability of the conservation of the Javan leopard (*Panthera pardus melas*) in GGPNP is fundamentally determined by the synergy between the ecological integrity and socio-economic stability of the buffer communities. Spatial analysis confirmed that prey availability was the main limiting variable with a dominant contribution of 54.5%, where high-quality habitat covering an area of 2,482.89 ha was concentrated at an elevation of 750–1,764 meters above sea level. Although public support for conservation is very high (92.3%), community dependence on the agricultural and livestock husbandry sectors triggers chronic negative interactions in the form of livestock depredation during grazing. This phenomenon of prey switching from natural to livestock animals indicates the degradation of natural prey populations in the core zone of GGPNP due to poaching and habitat fragmentation that is triggered by increasing anthropogenic accessibility to the park.

To ensure the existence of species and mitigate future Javan leopard conflicts, an integrated management strategy that includes the macro, meso, and micro levels is needed. This involves synchronizing cross-sectoral policies and law enforcement through SMART Patrol to reduce the rate of disturbances regionally. At the same time, priority habitat restoration and prey population enrichment must be synergized with technical mitigation at the site level—such as the use of foxlight technology and livestock cage security. By combining ecotourism-based economic empowerment and an early warning system based on local knowledge, it is hoped that a harmonious coexistence model will be created that ensures the sustainability of the Javan leopard while improving the welfare of the community surrounding GGPNP.

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