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Habitat suitability and distribution of Sumatran serow (*Capricornis sumatraensis sumatraensis*) in a Leuser ecosystem, Indonesia

SUTOPO SUTOPO[1], DEDE AULIA RAHMAN[1,2,♥], IKSAN GUSTIAWAN[1], MISBAH SATRIA GIRI[3], MAFRIKHUL MUTTAQIN[4], MUHAMMAD SAUKI AKBAR[1]

[1]Tropical Biodiversity Conservation Study Program, Department of Forest Resources Conservation and Ecotourism, Faculty of Forestry and Environment, Institut Pertanian Bogor. Jl. Ulin, Lingkar Akademik Kampus IPB, Dramaga, Bogor 16680, West Java, Indonesia. Tel./fax.: +62-274-580839, ♥email: dedeaulia@apps.ipb.ac.id

[2]Department of Forest Resources Conservation and Ecotourism, Faculty of Forestry and Environment, Institut Pertanian Bogor. Jl. Ulin, Lingkar Akademik Kampus IPB, Dramaga, Bogor 16680, West Java, Indonesia

[3]Directorate of Species and Genetics Conservation, Ministry of Forestry. Manggala Wanabakti Block VII, 7th Floor, Jl. Gatot Subroto, Senayan, Central Jakarta 10270, Jakarta, Indonesia

[4]Department of Biology, Faculty of Mathematics and Natural Sciences, Institut Pertanian Bogor. Jl. Raya Dramaga, Kampus IPB Darmaga, Bogor 16680, West Java, Indonesia

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Abstract. *Sutopo S, Rahman DA, Gustiawan I, Giri MS, Muttaqin M, Akbar MS. 2025. Habitat suitability and distribution of Sumatran serow (*Capricornis sumatraensis*) in a Leuser ecosystem, Indonesia. Biodiversitas 26: 3875-3885.* Determining the distribution of species and suitable habitats is a fundamental part of planning for the protection of key species. Mount Leuser National Park (MLNP), Indonesia, is habitat to the Sumatran serow (*Capricornis sumatraensis sumatraensis*), an endangered ungulate species. Habitat loss due to deforestation for agriculture, oil palm plantations, illegal hunting, and illegal trade in body parts are factors contributing to the increasing pressure on this species in its natural habitat. Therefore, this study aims to model the distribution of the Sumatran serow and identify priority conservation zones based on habitat suitability models. We conducted ensemble modelling implemented in the R package 'ENMTML' using 3 modelling techniques (MaxEnt, Random Forest, and Boosted Regression Tree) and an ensemble model. We combined 282 Sumatran serow occurrence points with 9 climate, topography, vegetation, and anthropogenic variables. The Random Forest model performed best among the three models in predicting Sumatran serow habitat, with an AUC value of 0.89 and TSS of 0.62. The Random Forest model predicts a larger area with low habitat suitability, covering 74% (610,520 ha) of the total area, with moderate habitat suitability covering 16% (131,090 ha) and high habitat suitability covering only 10% (78,139 ha) of the Sumatran serow distribution across the study area. Our model can help identify potential protection areas for this species to support its conservation. This has implications for knowledge about the current distribution and suitable habitat for Sumatran serow. Conservation efforts can be focused more effectively on core zones, particularly in Section III, Blangkejeren, and Section IV, Badar. By utilising the results of the habitat suitability model for several actions such as evaluating MLNP zoning, prioritising monitoring areas, considering corridors for connectivity, and evaluating habitat restoration programmes, conservation strategies for Sumatran serows in MLNP will be improved, and the chances of survival for Sumatran serow populations in the future can be maintained.

Keywords: *Capricornis sumatraensis,* ecological niche modeling, endangered ungulates, habitat suitability, Leuser ecosystem

INTRODUCTION

The Sumatran serows (*Capricornis sumatraensis sumatraensis* (Bechstein, 1799)), is a medium-sized, goat-like ungulate species belonging to the Bovidae family and Caprinae subfamily. This species is a protected mammal under Indonesia's wildlife law, Appendix I of Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), and classified as "Vulnerable" by the Union for Conservation of Nature and Natural Resources (IUCN) Red List (Phan et al. 2020). The species is known for its elusive nature and ability to adapt to mountain environments. Its geographical distribution in Indonesia is limited to the mountainous regions of Sumatra Island, particularly in the Bukit Barisan Mountain range, such as the highlands of Aceh in the north and the Kerinci highlands in the central part (Susanti et al. 2006). The existence of this species is highly dependent on the integrity of its specific habitat, namely mountain forests with steep topography and rough terrain as shelter (Livet 2012; Phan et al. 2020). Habitat preference varies with altitudinal extremes, but in Sumatra it has been recorded as low as 200 m (Carr et al. 2023) and more frequently at moderate altitudes (500-1,500 m) (Phan et al. 2019; Faiznur et al. 2020). Sumatran serows play an important role as prey species in the food chain of carnivores such as Sumatran tigers (Hadi et al. 2025).

In Sumatra, pressure on the survival of the Sumatran serow population is increasing. The main threat is habitat loss due to deforestation for agriculture, oil palm plantations, and development such as road networks (Carr et al. 2023). Illegal hunting is one of the most dominant threats, driven by demand for its meat, which is consumed as a source of protein, or parts of its body believed to have traditional medicinal value (Shepherd and Krishnasamy 2014; Leupen et al. 2017; Phan et al. 2019). Although Sumatran serows tend to avoid human contact (Bhattacharya et al. 2012; Phan et al. 2019), negative interactions with anthropogenic activities can occur, particularly in buffer zones of protected areas where agricultural and settlement activities intersect with forest boundaries (Harahap et al. 2012). A multisectoral approach is needed to integrate strong law enforcement and community education to reduce conflict and the demand for wildlife products. The lack of accurate data on the distribution and abundance of serows is a serious obstacle to conservation efforts. Without this information, it is challenging to identify key habitats and establish effective conservation priorities, especially given the various threats faced by the serow (Phan et al. 2020; Chen et al. 2021).

Habitat selection is a hierarchical process by which animals fulfil their habitat requirements at different ecological scales, and understanding these preferences is crucial for determining their distribution and abundance (Bhandari et al. 2021). Some of the factors that influence habitat choice include predation (McMahon et al. 2021), resources (Dupke et al. 2016), physiological tolerance and social interactions (Gersick and Rubenstein 2017). Ecological Niche Models (ENMs) have been used to interpret distribution patterns according to ecological niches (Feng et al. 2019a; Zurell et al. 2020), provide knowledge about species biology and biogeography (Melo-Merino et al. 2020), predict species responses to climate change (Condro et al. 2021), and estimate the potential for invasive species (Broennimann et al. 2007; Tingley et al. 2014; Sales et al. 2017) and assess conservation area priorities (Ribeiro et al. 2018; Fuller et al. 2020; Rahman et al. 2020; Rahman et al. 2022). This approach enables the identification and prediction of ecologically suitable areas for Sumatran serows. For example, previous studies have used Maxent to model the distribution of Sumatran serows in the Himalayas and across Asia (Joshi et al. 2022; Carr et al. 2023), but habitat suitability studies for local-scale coverage in important protected areas in Sumatra remain limited.

Mount Leuser National Park (MLNP) is one of the important conservation areas in Sumatra that is habitat to various key species, including the Sumatran serow. Here, we developed an ENM specifically for the Sumatran serow in MLNP. Our objectives were (i) to identify the potential distribution of Sumatran serows using ensemble modelling and (ii) to identify priority conservation zones based on habitat suitability. The distribution map generated from the model has important applications not only for the conservation of this species but also serves as an indicator of threats to habitat and possible disturbances. The resulting information could provide a more precise guide in developing Sumatran serow conservation strategies, especially in MLNP.

MATERIALS AND METHODS

Study area

This research was conducted in Mount Leuser National Park (MLNP), covering 830,268.95 ha or 8302.69 km², located in the northern part of Sumatra Island, Indonesia. MLNP covers two provincial administrative areas: Aceh and North Sumatra, Indonesia (Figure 1). MLNP is also crossed by the Trans-Sumatra Highway, which connects the main routes of the two provinces, and the Alas River, which flows from north to south. MLNP has ecosystems ranging from lowland forests to mountain forests, with steep topography and good forest cover as the Sumatran Tropical Rainforest Heritage for four charismatic species, namely the Sumatran rhinoceros (*Dicerorhinus sumatrensis*), Sumatran tiger (*Panthera tigris sumatrae*), Sumatran elephant (*Elephas maximus sumatrensis*), and Sumatran orangutan (*Pongo abelii*) (Figure 1). According to the IUCN, these species are classified as Critically Enandgered or will become extinct in the near future if no appropriate conservation measures are taken (Lubis et al. 2020).

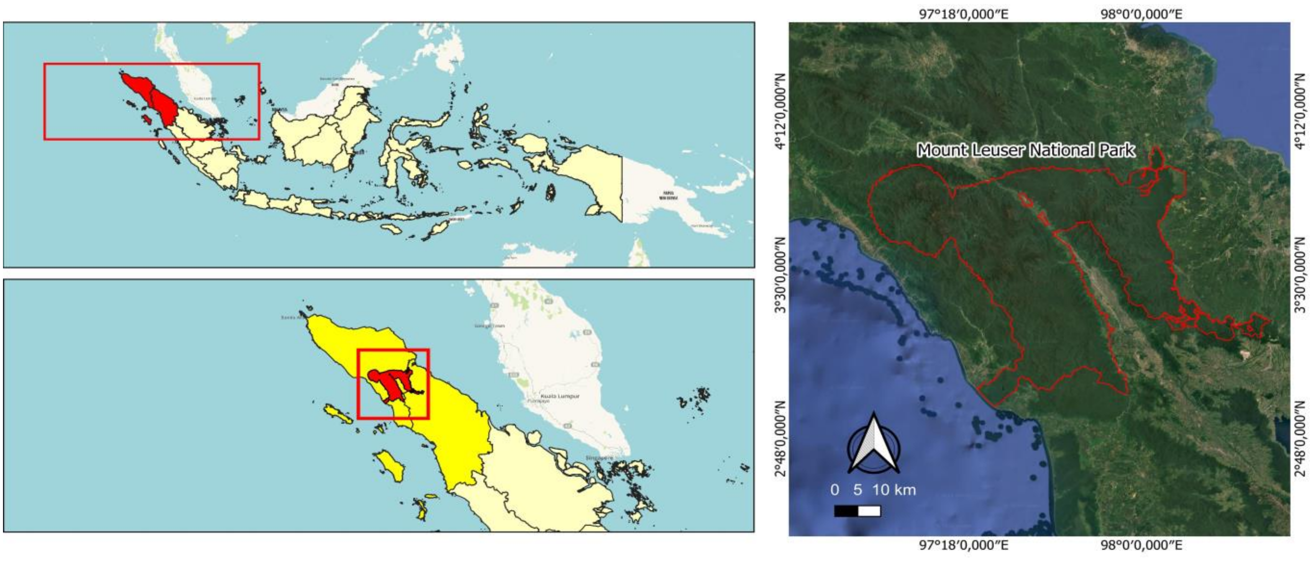

Figure 1. Study area Mount Leuser National Park, Aceh and North Sumatra Province, Sumatra, Indonesia

Data collection

Research data collection and pre-processing

We compiled a dataset consisting of 554 unique sightings of Sumatran serows (Table 1). This data was compiled from several unpublished data archives from the MLNP Office and field surveys, collected between 2018 and 2025. The data comes from patrol records in the form of footprints, feces, and feeding traces stored in the Spatial Monitoring and Reporting Tool (SMART) and camera trap data from the MLNP Office and the Global Biodiversity Information Facility (GBIF). The filtering of Sumatran serow presence data was carried out with several considerations, such as: (i) points with geographical coordinate information within the research area boundaries, namely MLNP; (ii) removing duplicate data based on geographical information; (iii) removing Sumatran serow presence points outside the research area; (iv) ensuring that the data is georeferenced. Finally, we collected 282 Sumatran serow records from the compiled data. Thinning was also performed using the cell size method in the spThin package to reduce autocorrelation and potential sampling bias by retaining unique cells in a grid twice the size of the original cells (Velazco et al. 2019). We performed thinning using a cell size with a resolution of 100 metres.

Environmental covariates

To conduct a comprehensive analysis and compile various aspects, based on documented species-habitat associations (Paudel and Kindlmann 2012; Joshi et al. 2022; Carr et al. 2023). We selected environmental variables describing landscape (i.e. elevation, slope, and aspect), habitat type (i.e. vegetation) extracted from MoEF Land Cover Map data (MoEF 2024). Human influences (i.e. distance to the nearest village and roads) based on the documented habitat affinities (Paudel and Kindlmann 2012). Normalized Difference Vegetation Index (NDVI) (Camps-Valls et al. 2021; Wang et al. 2023) was extracted from Sentinel-2A imagery using Google Earth Engine. We used bioclimatic data from BIOCLIM data, namely average temperature and precipitation variables from WorldClim v.2.0 (Fick and Hijmans 2017). Furthermore, we followed the delta method (Navarro-Racines et al. 2020) by performing statistical downscaling to obtain bioclimatic information with a more detailed spatial resolution of 100 m, all variables also use the same resolution. Furthermore, the elimination of one predictor that has a Pearson correlation of more than 0.7 ($|r| > 0.7$) is done to avoid these problems (Dormann et al. 2012; Feng et al. 2019b). A buffer of 1 km^2 has been used for all variables to avoid bias. Further details about the variables from the model can be seen in (Table 2).

Table 1. Data sources of Sumatran serow occurrence records

Programs and organizations	Number of occurrences	Included in the model	Year
SMART Patrol - MLNP Agency	513	255	2018-2025
Trap cameras and records during installation process - MLNP Agency	18	18	2018-2020
GBIF	13	9	2025
Total	544	282	

Note: MLNP: Mount Leuser National Park, GBIF: Global Biodiversity Information Facility

Table 2. Datasets used in species distribution modelling

Environmental variables	Data sources	Data type / Resolution	Pre-processing
Distance from Rivers	Field observation and Landforms of Indonesia (https://tanahair.indonesia.go.id/portal-web/)	Vector to raster / 100m	Euclidean distance and extracted by mask MLNP
Distance from Roads	Field observation and Landforms of Indonesia (https://tanahair.indonesia.go.id/portal-web/)	Vector to raster / 100m	Euclidean distance and extracted by mask MLNP
Distance from Settlements	Field observation and Landforms of Indonesia (https://tanahair.indonesia.go.id/portal-web/)	Vector to raster / 100m	Euclidean distance and extracted by mask MLNP
Distance from Agricultural	Field observation and Land Cover (https://sigap.menlhk.go.id/)	Vector to raster / 100m	Euclidean distance and extracted by mask MLNP
Distance from Forest Edges	Field observation and Land Cover (https://sigap.menlhk.go.id/)	Vector to raster / 100m	Euclidean distance and extracted by mask MLNP
NDVI	Prepared by the author – Sentinel 2A (https://earthengine.google.com/)	Raster / 10m resampling to 100m	Google Earth Engine and extracted by mask MLNP
Elevation	DEMNAS - Landforms of Indonesia (https://tanahair.indonesia.go.id/portal-web/)	Raster/8m resampling to 100m	Reclassified and extracted by mask MLNP
Slope	DEMNAS - Landforms of Indonesia (https://tanahair.indonesia.go.id/portal-web/)	Raster/8m resampling to 100m	Reclassified and extracted by mask MLNP
Aspect	DEMNAS - Landforms of Indonesia (https://tanahair.indonesia.go.id/portal-web/)	Raster/8m resampling to 100m	Reclassified and extracted by mask MLNP
Average Temperature	WorldClim V2.1 (https://www.worldclim.org/)	Raster/8m resampling to 100m	Reclassified and extracted by mask MLNP
Precipitation	WorldClim V2.1 (https://www.worldclim.org/)	Raster/1km resampling to 100m	Interpolation, Raster Calculator, Reclassified and extracted by mask MLNP

Data analysis

Ecological niche model of sumatran serows

This study performed the Ecological Niche Modelling at The Metaland Ecology Lab (ENMTML) package (Andrade et al. 2020) to analyse the distribution of Sumatran serows (Figure 2). This package offers a range of alternatives for different methodological steps, such as variable collinearity control, bias control, accessible region restrictions, and more. Users can easily customize, project, evaluate models, and present results. We are following three main steps: (i) pre-processing, (ii) processing, and (iii) post-processing.

In pre-processing, response variables with fewer than ten events were excluded from the analysis to ensure the accuracy of the model required for the sample size (van Proosdij et al. 2016). Thinning was also performed using the cell size method in the spThin package to reduce autocorrelation and potential sampling bias by retaining unique cells in a grid twice the size of the original cells (Velazco et al. 2019). Random allocation was also used to obtain background points or pseudo-absence data in this model (Zaniewski et al. 2002). Multicollinearity testing was performed to prevent overfitting due to strong linear relationships between environmental variables. Variables with Pearson correlation coefficients $|r| < 0.7$ were retained to improve prediction accuracy (Siddiq et al. 2023). Based on the correlation matrix, several variables showed high pairwise correlations, particularly between temperature and elevation, which were negatively correlated ($r = -0.99$), and distance from roads and distance from agriculture ($r = 0.91$). To reduce correlation and maintain model simplicity, elevation was retained due to its direct ecological relevance to Sumatran serow ecology, while temperature was excluded from the final model. Similarly, distance from roads was selected as a more comprehensive representation of anthropogenic factors than distance from agriculture, as it is associated with high access to Sumatran serow hunting in MLNP. Elevation was retained over distance to shrubland, as it serves as a proxy for topography that influences habitat distribution. This variable selection process enhances the robustness and interpretability of the constructed model by minimizing the risk of bias associated with multicollinearity.

In the processing step, three algorithms were used to build ENMs: Boosted Regression Tree (BRT), Random Forest (RDF), and the default feature Maximum Entropy Default (MXD). All models use the default settings from the ENMTML package, which includes functions from different packages based on the algorithms used to model the data. This study uses the bootstrap method, where the dataset is divided with a proportion of 70% for the training model, and the remaining 30% is used for validation (Fielding and Bell 1997; Andrade et al. 2020). Predictions were generated based on the degree of conformity of survey data points with the probability model using accuracy measures (Araújo et al. 2019). The Bootstrap method with five folds was used in this study for model evaluation (Fielding and Bell 1997; Andrade et al. 2020).

In the post-processing step, we created an ensemble model using the Weighted Mean (WMEAN) method to create a habitat suitability map. To evaluate the model, we used several different metrics: Area Under the Curve (AUC), Kappa coefficient, True Skill Statistic (TSS), Jaccard index, and Sørensen index (Andrade et al. 2020). All modelling steps have already fulfilled the ODMAP (Overview, Data, Model, Assessment, Prediction) species distribution modelling protocol (Zurell et al. 2020). We select the best algorithm from the highest value of the accuracy metrics that have been carried out on the models for further analysis. These features are conveniently organised within a single function available through the R package ENMTML. The quantile distribution (Q) was employed using the ArcGIS application, resulting in three classes to classify the probability values. Quantile classification is a method that categorizes data distribution by weighing the distances of each observation component from the quantile in question (Hennig and Viroli 2016). The first class (low) is either 0 or Q1 the second class (medium) is >Q1 to Q2, and the third class (high) is >Q2 to 1.

Habitat management was analysed by overlaying the habitat map of Sumatran serows with the management section map of MLNP as the management unit. This habitat management analysis also provides management recommendations on habitats that have threats by considering disturbances to the habitat.

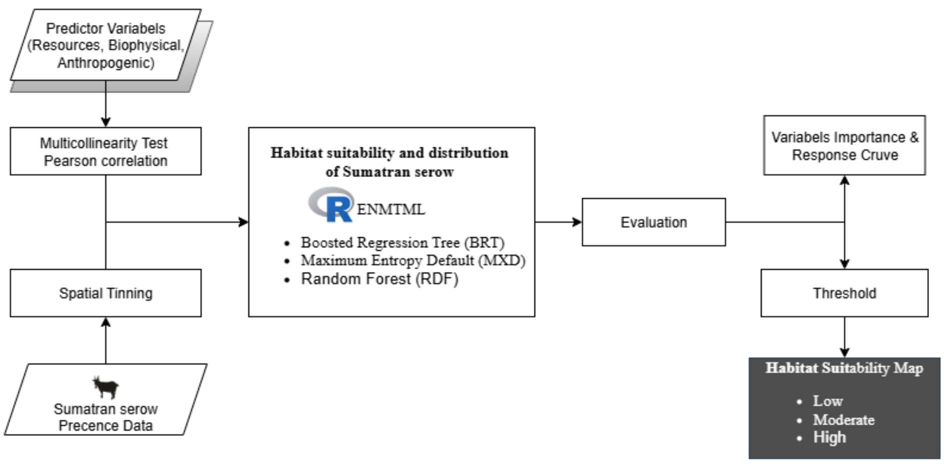

Figure 2. Procedure for the habitat suitability model of Sumatran serow in Mount Leuser National Park, Indonesia

RESULTS AND DISCUSSION

Model evaluation

We evaluated three different algorithms (i.e., Boosted Regression Tree; BRT, Maximum Entropy; MXD, Random Forest; RDF) along with an ensemble model of these algorithms (using a weighted average technique). The model evaluation results showed that the RDF model excelled in five accuracy measures (AUC, Kappa, TSS, Jaccard, Sørensen) with consecutive values of 0.89 ± 0.01, 0.62 ± 0.02, 0.62 ± 0.02, 0.69 ± 0.02, and 0.82 ± 0.02, as shown in Table 3 in bold. According to the distribution model and habitat suitability for Sumatran serows, the RDF algorithm produced the most favourable results compared to other algorithms, including ensembles. Therefore, we chose to use the RDF algorithm to model the distribution of the Sumatran serow. The average performance metrics of other models for each algorithm can be seen in Table 3.

Variable contribution

Through habitat suitability models based on various algorithms, this study also aims to identify the habitat areas of the Sumatran serow by analyzing the importance values and responses of environmental variables. The ENMTML package only provides important variable values for models with a single algorithm, while important values are not available for ensemble models, so important values for ensemble models are taken from the average values of the three single models. Since the RDF model outperforms other algorithm models, important variable values are referenced from the RDF model. According to Table 4 and the Random Forest algorithm, various environmental factors influence the distribution of Sumatran serows. Among these factors, distance from roads has the largest contribution at 22%, followed by distance from settlements at 13% and rainfall at 13%. Meanwhile, physical factors contribute significantly, such as elevation at 11%, aspect at 10% and slope at 7%. Vegetation factors such as NDVI contribute 10%, while distance from forest edge has the smallest contribution at 2%. This indicates that human presence significantly influences the distribution of Sumatran serows compared to other climatic and physical factors. The findings are presented in Table 4, which includes various contribution weights of response variables from several algorithms used.

The response curve in the RDF model is a key element for interpreting the relationship between each environmental variable and the probability of species presence, in this case the Sumatran serow (Figure 3). In this study, response curves were generated for nine spatial variables: distance from roads, distance from settlements, distance from rivers, distance from forest edges, elevation, slope, aspect, NDVI, and precipitation. In all curves, the x-axis represents distance in meters, while the y-axis shows the predicted probability of occurrence, which is a predictive value that describes the probability or likelihood of a species being found.

Habitat suitability model for Sumatran serow

The results of the analysis of the habitat distribution of Sumatran serows in Mount Leuser National Park show that their distribution tends to be in the central part and that the southern part has a fairly high concentration of suitable habitat. Blue indicates habitat with a low level of suitability, yellow indicates moderate suitability, and red indicates high suitability for Sumatran serows in MLNP (Figure 4). The total area of each habitat suitability is presented in Table 5.

Table 4. Variable importance in the Species Distribution Model (SDM) of the Sumatran serow using three different algorithms

Environmental Variable	Importance in the model (%)			
	BRT	**MXD**	**RDF**	**Ensemble**
Distance from Road	**41**	**34**	**22**	**32**
Distance from Settlement	6	**18**	**13**	**12**
Distance from River	8	7	11	9
Distance from Forest	1	3	2	2
Elevation	**13**	2	12	9
Slope	8	**16**	7	10
Aspect	6	3	10	6
NDVI	7	3	10	7
Precipitation	**10**	14	**13**	**12**

Note: BRT: Boosted Regression Trees; MXD: Maximum Entropy; RDF: Random Forest; Ensambel. The three highest variable importance values are in bold

Table 5. Classification of habitat suitability probability values for Sumatran serow

Habitat suitability	Area (ha)	Proportion (%)
Low	610.520	74
Moderate	131.090	16
High	78.139	10

Table 3. Evaluation of five Sumatran serow habitat suitability models using three different algorithms and an ensemble model

Algorithm	AUC		Kappa		TSS		Jaccard		Sørensen	
	x̄	s	x̄	s	x̄	s	x̄	s	x̄	s
BRT	0.87	0.01	0.60	0.02	0.60	0.02	0.69	0.01	0.82	0.01
Maxent	0.85	0.02	0.55	0.04	0.55	0.04	0.63	0.02	0.78	0.01
RDF	**0.89**	0.01	**0.62**	0.02	**0.62**	0.02	**0.69**	0.02	**0.82**	0.02
Ensemble	0.88	0.01	0.61	0.02	0.61	0.02	0.69	0.01	0.82	0.01

Note: BRT: Boosted Regression Trees; ENS: Ensemble; MXD: Maximum Entropy; RDF: Random Forest based on five different evaluation metrics in terms of mean statistics (x̄) and standard deviation (s). The model used is shown in bold

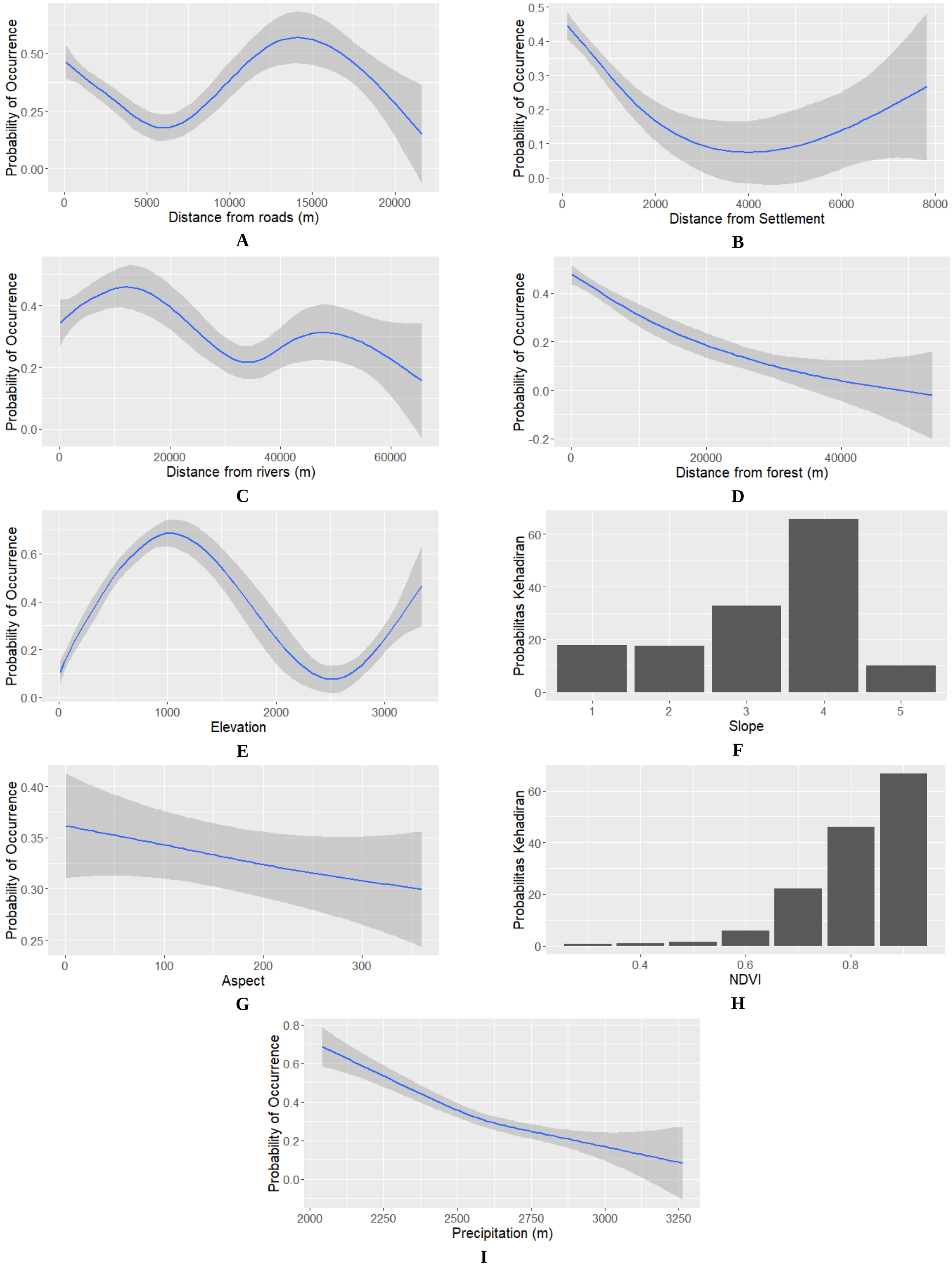

Figure 3. Response curves of environmental variables that most influence the suitability index of Sumatran serow habitat in the MLNP, Indonesia: A. Distance from Road; B. Distance from Settlement; C. Distance from River; D. Distance from Forest; E. Elevation; F. Slope; G. Aspect; H. NDVI; I. Precipitation

Direct competition with humans is clearly a cause for concern in species conservation, including the Sumatran serow. Conservation areas face significant pressure on the resources and space they occupy. We modelled the potential distribution of the Sumatran serow, with the aim of building a predictive model to identify the distribution of the Sumatran serow and management strategies in one of the important conservation areas on the island of Sumatra. Figure 4 shows the results of the RDF model for habitat suitability distribution, ranging from low, moderate to high. Generally, suitable areas are concentrated in the central part, particularly in management sections III Blangkejeren and IV Badar. In addition, suitable habitat is also slightly concentrated in the southern part of Management Section II North Kluet. Furthermore, Sumatran serow distribution is not widely found in the other three management sections, such as Section I Blang Pidie, Section V Bohorok, and Section VI Besitang (Table 6).

Table 6. Spatial area of the RDF model for the probability distribution of Sumatran serows in Mount Leuser National Park, Indonesia

RDF model for the Probability	**National Park management section**											
	Blang Pidie		**North Kluet**		**Blangkejeren**		**Badar**		**Bohorok**		**Besitang**	
	Hectare	**%**	**Hectare**	**%**	**Hectare**	**%**	**Hectare**	**%**	**Hectare**	**%**	**Hectare**	**%**
Low	62.679	98.8	67.745	87.2	118.517	58.8	174.002	63.0	79.853	90.3	107.691	96.0
Moderate	650	1.0	6.230	8.0	52.654	26.1	61.104	22.1	6.290	7.1	4.162	3.7
High	93	0.1	3.738	4.8	30.536	15.1	41.180	14.9	2.312	2.6	279	0.2
Total	63.422	100	77.713	100	201.707	100	276.286	100	88.455	100	112.132	100

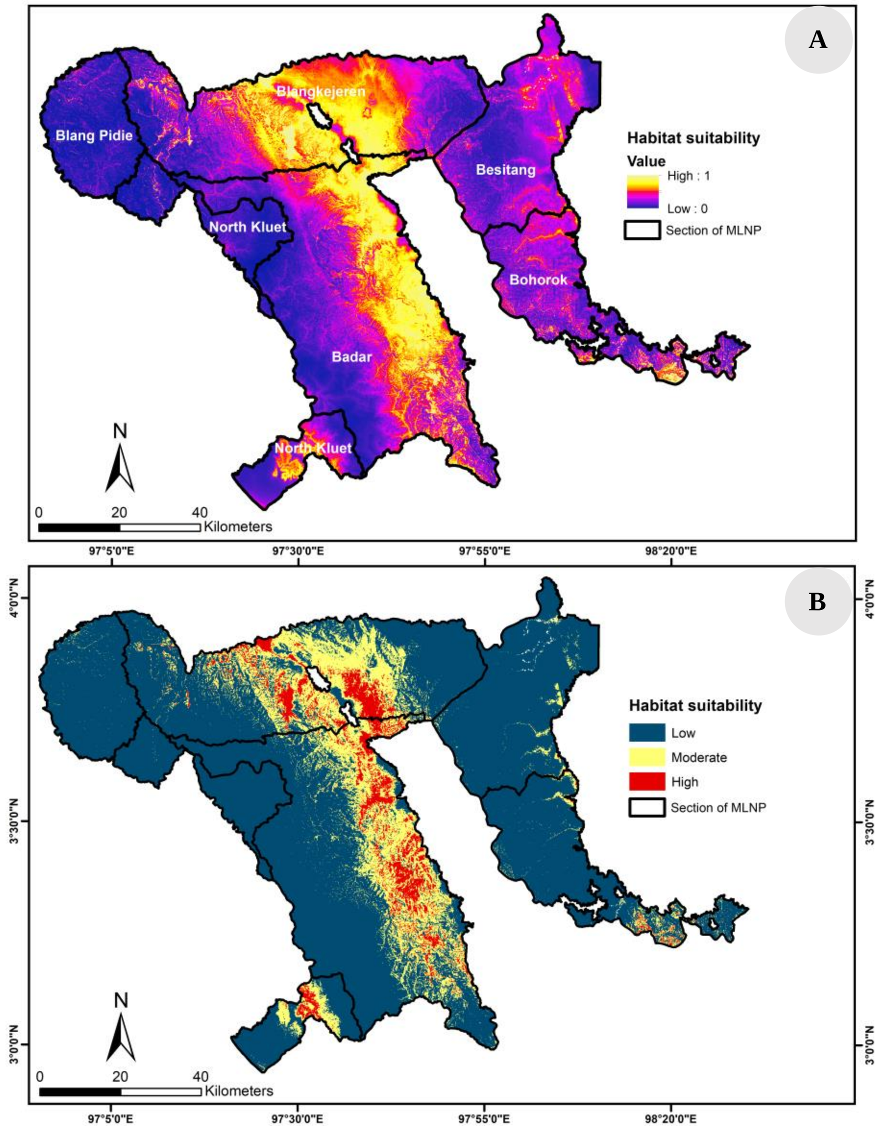

Figure 4. Habitat suitability model for Sumatran serow in Mount Leuser National Park (MLNP), Indonesia, using RDF model: A. Gradient map and B. Classification map

Discussion

This study presents a habitat suitability prediction model for Sumatran serows based on data on their presence in the MLNP area. The RDF model predicts that areas with low habitat suitability are more extensive, covering 74% (610,520 ha) of the total area, with moderate habitat suitability covering 16% (131,090 ha), and high habitat suitability covering only 10% (78,139 ha), indicating that this species has a limited distribution with specific habitat characteristics. This study simplifies the complex ENM methodology into a single function through the ENMTML package, which efficiently adjusts, projects, evaluates, and presents model results (Andrade et al. 2020; Horpiencharoen et al. 2024). The RDF model consistently outperformed other models based on five discrimination measures. Therefore, the RDF model was used to present the habitat suitability prediction model for Sumatran serow. The advantage of Random Forest lies in its ability to reduce overfitting without affecting bias, handle non-normally distributed data, and manage various types of non-homogeneous variables (Burkov 2019). Although AUC is often used to represent a model's ability to distinguish between the presence and absence of species (Bucklin et al. 2014), and TSS is still influenced by species prevalence (Somodi et al. 2017), similarity indices such as Sørensen and Jaccard offer a better alternative for model evaluation because they do not depend on prevalence, unlike AUC and Kappa (Leroy et al. 2018).

We found that the Sumatran serow has a positive relationship with anthropogenic factors (i.e., roads and settlements), as both are the most significant predictors. Our predictions differ from some previous findings, which indicate that Sumatran serows tend to avoid human activity (Bhattacharya et al. 2012; Paudel et al. 2015). This finding indicates higher pressure and disturbance in our MLNP. It is likely that roads connected to plantations indirectly facilitate access to Sumatran serow habitat both within and around the area (Carr et al. 2023). This model also predicts most areas adjacent to rivers and adjacent to forest edge areas.

Sumatran serows are known to have a strong association with steep terrain (Phan et al. 2019). The model results also show that the variables of elevation and slope affect the probability of occurrence of Sumatran serow, which tends to increase at an altitude of 1,000 m with a steep slope. This species is often found at moderate elevations (500-1,500 m) (Faiznur et al. 2020). Sumatran serows are known to have specific habitats with high elevations and rough terrain such as limestone karst or rocky outcrops, which the species uses as shelter (Lynam and Round 2006; Susanti et al. 2006; Carr et al. 2023). The Leuser Ecosystem has an elevation of up to 3,466 m above sea level with a topography dominated by the rugged and undulating Bukit Barisan mountains, interspersed with deep river valleys, steep cliffs, and several lowland areas in the east and west (Carr et al. 2023; Widyastuti et al. 2025). The ruggedness of the landscape is striking, characterised by steep, inaccessible slopes and unique karst rock formations, making it an important habitat for the Sumatran serow.

Model analysis identified areas suitable for Sumatran serow but with no record of their presence, such as in the eastern part of the Bahorok Section. This indicates that the area has habitat conditions suitable for Sumatran serows. The lack of records of Sumatran serow presence may be due to difficult access or remote areas that have not been surveyed. In the future, routine patrols and the presence of rangers need to be increased in this area, where they play a crucial role in protecting the Sumatran serow population in MLNP. Their physical presence in the field can prevent poaching activities, which are the main threat to this endangered species. Additionally, Sumatran serows are also an important prey species for Sumatran tigers in this region (Hadi et al. 2025).

We note the recent discovery of the Sumatran serow in Gunung Ledang National Park in Johor, Malaysia (Faiznur et al. 2020). This new evidence of recorded presence expands the known range of the serow and brings new steps to assess its distribution at the local level. The study by Carr et al. (2023) also recognizes that residential distribution studies of Sumatran serow sampling are still limited to Southeast Asia, such as in Myanmar and Vietnam. In addition, the spatial resolution used in predictions is often too coarse to capture specific habitat use patterns. While the Sumatran serow population may be larger than expected, concrete evidence of its presence and distribution is scarce, possibly due to under-reporting of presence points, including in the Leuser ecosystem. Occupancy survey data, camera trapping and patrol efforts by rangers have contributed to the presence of Sumatran serow, but are not widely reported. It is important to recognise that relying on presence data alone in species distribution models has significant limitations, as it does not provide information on the species' location of absence or probability of detection, potentially leading to biased predictions and overestimation of true range if other variables are not considered.

The hunting of Sumatran serows is not widely known in the local wildlife trade. Some traditional communities are known to use them for medicinal purposes and for their meat. However, Sumatran serows are known globally to be actively targeted by hunters for their meat, including their gallbladders and oil, which are used for medicinal purposes (Gomez et al. 2016). This is supported by data findings from (Hadi et al. 2025), which recorded 780 snares removed by rangers between 2015 and 2019, with poaching still a significant threat. Although management approaches such as ranger patrols and wildlife trade enforcement have been implemented, integration between the two remains limited, indicating the need for more persuasive and targeted area protection approaches. In addition, threats also come from land cover loss, which is expected to increase as climate change expands fertile land to higher elevations (Struebig et al. 2015; Brodie 2016; Zeng et al. 2018).

Much remains unknown about the diet, behaviour, habitat range, breeding season and crossbreeding of the (Phan et al. 2020), including the assessment of the impact of hunting. Further research is needed to reveal the ecological importance of this species in the Sumatran serow habitat. We highlight anthropogenic factors that have a major influence on the Leuser Ecosystem. The combination of threats (e.g., deforestation, agricultural expansion, and climate change) also affects many species and can lead to local extinction (Condro et al. 2021; El-Khalafy et al. 2025). Zoning evaluations should consider habitat suitability models to ensure that the most important areas for Sumatran serow are designated as core zones, with restricted use to minimise threats. Conservation efforts can be focused more effectively on core zones, particularly in Section III, Blangkejeren, and Section IV, Badar. As a next step, we encourage field verification and habitat protection outside protected areas or zones where signs of Sumatran serow presence are likely to be found. We also encourage policymakers to implement stricter monitoring and enforcement against poaching, as well as planning for relocation or translocation, if necessary, will maximise the chances of the Sumatran serow population's survival in the future.

Efforts to protect Sumatran serows in MLNP require serious attention to zoning evaluation and the threat of habitat fragmentation. The intact forest in MLNP, located between the eastern and western blocks, is almost completely separated by the Alas River, the Trans-Sumatra Highway, and, of course, anthropogenic land cover around the road, such as agricultural land and settlements (Mohammadi et al. 2024; Widyastuti et al. 2025). Habitat fragmentation is a major threat to the Sumatran serow population in MLNP, in addition to poaching. Connecting corridors (Rezvani et al. 2024; Serva et al. 2025) play an important role for Sumatran serows to move around and interact genetically. Therefore, serious measures such as forest restoration to create a connected canopy across rivers and highways are crucial to improve habitat connectivity (Luo et al. 2024; Rezvani et al. 2024) and the sustainability of the Sumatran serow population. According to Prober et al. (2019) to increase their resilience to future threats, it is necessary to address threats by reducing pressure on wildlife populations.

In conclusion, the study revealed that 10% (78,139 ha), MLNP has high habitat suitability for Sumatran serow, about 16% (131,090 ha) has medium suitability and 74% (610,520 ha) has low suitability. The main influential predictors were distance from road, distance to settlement, distance from river, elevation and slope. Utilising the results of the habitat suitability model for several actions such as evaluating MLNP zoning, prioritising monitoring areas, considering corridors for connectivity, especially in the western and eastern blocks and evaluating habitat restoration programmes will improve conservation strategies for Sumatran serow in MLNP.

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