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Original Research Article

Spatial Modelling of Orangutan Habitat Suitability Based on Environmental Parameters in East Kutai, Indonesia

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Abstract

Habitat loss and forest degradation affect the environment used by Bornean orangutans. This study modelled environmental suitability for orangutan habitat in East Kutai, Indonesia, using four variables: the Normalized Difference Vegetation Index (NDVI), slope, distance from rivers, and distance from roads. Parameter weights were derived through expert judgement using the Analytical Hierarchy Process (AHP), and the variables were integrated using a GIS-based weighted overlay. NDVI received the highest weight (49.66%), followed by distance from rivers (30.17%), reflecting their importance in the expert-based framework. The model classified 11,414.50 km² (36.15%) as suitable, 19,373.08 km² (61.36%) as less suitable, and 785.11 km² (2.49%) as unsuitable. Higher-scoring areas occurred mainly in western and central East Kutai, while lower-scoring areas were concentrated along the eastern coast. These classes represent relative environmental suitability based on the four modelled variables, not confirmed orangutan occurrence or habitat use. NDVI indicates vegetation greenness and relative density but cannot distinguish natural forest from plantations or other dense vegetation. Forest type, fragmentation, settlements, land-use intensity, food-plant distribution, and fire history were not included. The map provides a spatial basis for habitat assessment and conservation planning; field verification and additional ecological data are needed to assess the relevance of areas for orangutans.

Keywords: Analytical Hierarchy Process (AHP); Geographic Information System (GIS); environmental suitability; orangutan; weighted overlay

1. Introduction

The Bornean orangutan (*Pongo pygmaeus*) is an arboreal great ape whose survival depends on suitable forest ecosystems. Habitat loss, degradation, fragmentation, and agricultural conversion reduce food availability, alter habitat continuity, and restrict orangutan movement, contributing to population decline and its classification as Critically Endangered by the International Union for Conservation of Nature (IUCN) (Meijaard et al., 2011; Wich et al., 2012; Ancrenaz et al., 2016, 2021; Oram et al., 2022). East Kutai Regency, East Kalimantan, lies within the distribution range of the northeastern Bornean orangutan (*Pongo pygmaeus morio*) and retains extensive forest cover. However, spatial variation in vegetation

conditions, river systems, terrain, and road accessibility means that forest cover alone does not necessarily indicate a suitable habitat, highlighting the need for a spatially explicit assessment.

Spatial modelling provides a way to assess environmental conditions relevant to wildlife by integrating multiple variables within a geographic information system (GIS). Previous studies have applied spatial models to identify areas with environmental conditions associated with orangutan habitat, using variables such as vegetation indices, topography, and proximity to rivers and human infrastructure (Prayogo et al., 2016; Pramuja, 2018; Fithria et al., 2019). However, the interpretation of the modelled suitability depends on the variables and data used. In particular, NDVI represents vegetation greenness and relative density but does not distinguish natural forest from plantations or other densely vegetated land covers. The resulting model should therefore be interpreted as a measure of environmental suitability based on selected parameters rather than direct confirmation of orangutan habitat use.

This study addresses this gap by applying the analytical hierarchy process (AHP) as a structured, expert-based framework for determining the relative importance of environmental parameters in East Kutai. Unlike purely data-driven weighting, AHP incorporates ecological judgement through systematic pairwise comparisons and provides a consistency measure for evaluating expert judgements (Saaty, 2008). The novelty of this study lies not in introducing AHP as a new modelling technique, but in applying a transparent, landscape-specific weighting framework that links expert judgement with spatially explicit environmental data for orangutan habitat assessment in East Kutai. Four variables were selected: the normalized difference vegetation index (NDVI), distance from rivers, distance from roads, and slope, representing vegetation condition, riparian characteristics, anthropogenic accessibility, and terrain, respectively.

Therefore, this study aimed to model the spatial distribution of environmental suitability relevant to orangutan habitat in East Kutai Regency, East Kalimantan, using a GIS-based AHP approach. Four environmental parameters—NDVI, slope, distance from rivers, and distance from roads—were weighted using expert judgement and combined through weighted overlay analysis. The resulting map identifies areas with relatively favorable environmental conditions according to these parameters; however, it does not confirm orangutan presence or habitat use.

2. Methods

This study used a GIS-based multicriteria approach that integrated four environmental variables: NDVI, slope, distance from rivers, and distance from roads, using AHP-weighted overlay analysis.

2.1 Study Area

This study was conducted in East Kutai Regency, East Kalimantan Province, Indonesia, located between 115°56′26″–118°58′19″ E and 1°17′1″ S–1°52′39″ N. The regency covers approximately 31,572.69 km² and consists of 18 administrative districts. The landscape includes extensive lowland forests, river systems, and hilly terrain that form part of the distribution range of the northeastern Bornean orangutan (*Pongo pygmaeus morio*). East Kutai was selected because it retains extensive forest landscapes and exhibits spatial variation in vegetation condition, topography, river distribution, and road accessibility. The location of the study area is presented in Figure 1.

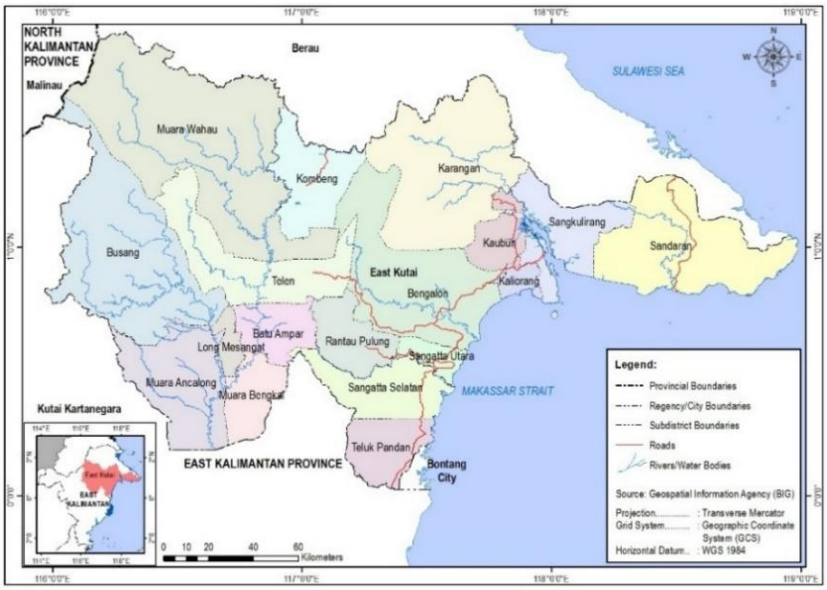

Figure 1. Location of the study area in East Kutai Regency, East Kalimantan, Indonesia

2.2 Data and Spatial Processing

Four environmental variables were selected for the environmental suitability model: the normalized difference vegetation index (NDVI), slope, distance from rivers, and distance from roads. Spatial data were obtained from relevant government and remote-sensing sources and processed in a GIS environment. The NDVI was included to represent vegetation greenness and relative vegetation density, which may indicate structural conditions relevant to orangutan activities, such as arboreal movement and nest construction. The NDVI was not treated as a direct indicator of orangutan presence or as a means of distinguishing natural forest from plantations and other dense vegetation.

All spatial datasets were projected into a common coordinate reference system and clipped to the administrative boundary of East Kutai. The slope was derived from DEMNAS, while the NDVI was calculated using Equation (1).

$$NDVI = \frac{NIR - Red}{NIR + Red} \quad (1)$$

where NIR and Red represent near-infrared and red-band reflectance, respectively. NDVI was interpreted as an indicator of vegetation condition and relative vegetation density rather than natural forest cover. Its classification was visually assessed using Google Earth Pro at six reference points per NDVI class. The <0 class corresponded to water and non-vegetated surfaces; 0–0.3 to relatively sparse vegetation, including shrubs, agriculture, and plantations; 0.3–0.4 to relatively dense vegetation; and 0.4–0.5 and >0.5 to dense and very dense vegetation, respectively. All 30 reference points showed correspondence between the classified NDVI and visually interpreted conditions. This visual assessment evaluated vegetation conditions only and did not validate orangutan occurrence or confirm that high-NDVI areas represented natural forest or orangutan habitat. A forest or land-cover mask was not applied because restricting the analysis to mapped forest categories could exclude densely vegetated areas outside those categories, even when they exhibited high NDVI values. Therefore, NDVI was retained as an indicator of vegetation condition across the study area, irrespective of mapped forest status.

The distance from rivers and roads was represented using multiple-ring buffer zones based on predefined distance intervals in the environmental suitability classification scheme. The resulting buffer polygons were converted to raster layers and standardized using the same scoring system before weighted overlay analysis. Other ecological factors, including forest type, elevation, land use change, fruit tree distribution, habitat fragmentation, settlements, and fire history, may also influence orangutan habitat suitability. However, these variables were not included in the present model because comparable and

spatially consistent datasets covering the entire study area were not available at a level suitable for integration into the modelling framework. In addition, some of these variables may represent environmental characteristics or anthropogenic pressures that require different types of data or modelling approaches and were therefore considered beyond the scope of the present environmental suitability model. Therefore, the model should be interpreted as a spatial assessment of environmental suitability based on four selected environmental dimensions rather than as a comprehensive representation of all ecological determinants of orangutan habitat. No independent orangutan occurrence data covering the study area were available for model validation. Therefore, the modelling framework was designed to estimate environmental suitability based on the selected environmental variables and AHP-derived weights rather than confirmed orangutan occurrence or habitat use.

2.3 Parameter Classification and Scoring

The four environmental variables differed in their measurement units and numerical ranges. To integrate them into the environmental suitability model, each variable was reclassified into an ordinal scoring system. Classes were assigned scores from 1 to 5 based on the criteria adapted from Prayogo (2014), with higher scores representing conditions considered more favorable within the scope of this study. The scoring system reflects the relative environmental characteristics represented by the selected variables and does not independently establish orangutan presence or habitat use.

Table 1. Classification and scoring of environmental parameters used to model environmental suitability for orangutans

No	Parameter	Class	Score
1.	Distance from roads	0-1000 m	1
		1000-3000 m	2
		3000-5000 m	3
		5000-7000 m	4
		>7000 m	5
2.	Distance from rivers	0-1000 m	5
		1000-3000 m	4
		3000-5000 m	3
		5000-7000 m	2
		>7000m	1
3.	Slope	0-8 %	5
		8-15 %	4
		15-25 %	3
		25-40 %	2
		>40 %	1
4.	NDVI	<0	1
		0-0.3	2
		0.3-0.4	3
		0.4-0.5	4
		>0.5	5

Source: Adapted from Prayogo (2014)

The scoring scheme reflected the assumed ecological relationship between each environmental variable and conditions relevant to orangutans. Areas with gentle slopes received higher scores because they may provide more favorable terrain for arboreal movement and access to resources. Areas closer to rivers received higher scores because riparian environments may be associated with orangutan occurrence. Higher NDVI values received higher scores to represent denser vegetation, which may provide canopy structure for movement and nest construction. However, NDVI alone cannot distinguish

natural forest from plantations or other dense vegetation; therefore, its scores were interpreted together with the other environmental parameters.

The parameter thresholds presented in Table 1 were adapted from Prayogo (2014), an earlier study of Bornean orangutan habitat suitability, and were used as literature-based operational thresholds for classifying the environmental variables into five ordinal classes for habitat suitability. This approach provides a consistent scoring framework for integrating variables measured in different units using weighted overlay analysis. The scoring directions reflected the assumed environmental relationships adopted in this study: higher scores were assigned to denser vegetation, gentler slopes, locations closer to rivers, and locations further from roads. However, these thresholds were adopted as a starting point based on previous research rather than as locally calibrated ecological thresholds for the East Kutai region. Because independent orangutan occurrence data were unavailable, the suitability of these thresholds for predicting orangutan occurrence in the study area could not be evaluated directly. Accordingly, the scores represent the relative environmental conditions under the selected criteria.

2.4 AHP Weighting and Environmental Suitability Modelling

The relative importance of each environmental variable was determined using AHP. The AHP assessment involved six professional experts with academic and professional backgrounds relevant to orangutan conservation, forestry, habitat management, conservation program management, orangutan rescue, and related conservation activities. The experts were purposively selected based on their relevant professional experience and expertise, considering three criteria: (1) involvement in orangutan conservation; (2) experience or expertise in forestry and/or habitat-related fields; and (3) experience in orangutan management or rescue. Each expert independently completed the AHP pairwise-comparison form to assess the relative importance of the four environmental parameters using Saaty's nine-point preference scale. Their contribution was limited to providing expert judgements for the AHP weighting process, and no personal, health, or other sensitive information was collected. Individual pairwise comparison judgements were aggregated using the geometric mean method to obtain a group comparison matrix. The aggregated matrix was then used to derive the priority weights of the environmental variables. The consistency of the aggregated judgement was evaluated using the Consistency Index (CI) and Consistency Ratio (CR). The resulting CR was 0.0045, which was below the commonly accepted threshold of 0.10, indicating a consistent pairwise comparison matrix. The resulting aggregated pairwise comparison matrix is presented in Table 2.

Table 2. Aggregated pairwise comparison matrix of environmental parameters

Environmental parameter	Distance from roads	Distance from rivers	Slope	NDVI
Distance from roads	1.000	0.3878	0.6618	0.2357
Distance from rivers	2.5786	1.000	3.4110	0.6287
Slope	1.5111	0.2175	1.000	0.1669
NDVI	4.2426	1.5907	5.9925	1.000

Source: AHP analysis, 2026

The derived weights were assigned to the standardized environmental layers and combined using weighted overlay analysis. The modelled environmental suitability score for each raster cell was calculated as the weighted sum of the scores for the four parameters, according to Equation (2). The resulting index expresses relative environmental suitability according to the selected variables and expert-derived weights; it does not directly represent observed orangutan occurrence.

$$HSI = \sum_{i=1}^{n}(w_i \times s_i) \quad \text{..... (2)}$$

where HSI denotes the model index used in this study to represent relative environmental suitability, w_i is the weight of parameter i and s_i is the score assigned to that parameter. The index is a

model output based on the selected environmental variables, not an independently verified measure of orangutan presence.

The model index was classified into three environmental suitability classes (suitable, less suitable, and unsuitable) using the equal interval method. The weighted overlay produced a continuous index, which was divided into three classes to facilitate interpretation and spatial comparison across East Kutai. The class labels describe the relative environmental conditions according to the selected parameters and should not be interpreted as confirmation that orangutans occupy all areas classified as suitable. The classification interval for each suitability class was determined according to Equation (3):

$$I = \frac{X_{max} - X_{min}}{3} \quad (3)$$

where I is the class interval, the maximum and minimum values refer to the range of the model index, and k is the number of classes. With three classes, the index range of 1.00–5.00 resulted in an equal interval of 1.33. The resulting classes were used to represent relative environmental suitability.

The equal-interval method was selected because it divides the HSI range into intervals of equal width, producing clearly defined and reproducible class boundaries. The same class boundaries were applied to the baseline model and all sensitivity scenarios to ensure that changes in class area could be compared under a consistent classification scheme. Maintaining matched class boundaries facilitates comparison across a series of maps (Brewer and Pickle, 2002). Because conventional classification methods perform differently depending on the distribution of the underlying data (Smith, 1986), the equal-interval method was adopted to provide a consistent basis for comparing the model outputs across sensitivity scenarios.

2.5 Sensitivity Analysis of AHP Weights

A sensitivity analysis was conducted to evaluate the effect of uncertainty in the AHP-derived parameter weights on the environmental suitability model. In GIS-based multicriteria decision analysis (MCDA), criteria weights are an important source of uncertainty because they reflect the relative importance assigned to each parameter. Changes in these weights may affect the model output; therefore, sensitivity analysis can be used to assess the stability of the results under variations in parameter weights (Feizizadeh and Blaschke, 2014). In this study, the analysis assessed how the modelled environmental suitability classes changed when individual parameter weights were perturbed.

The analysis followed a one-at-a-time (OAT) approach, in which the weight of one parameter was changed at a time, and the resulting change in the model output was evaluated. This approach allows the influence of individual parameter weights to be examined separately. In GIS-based MCDA, sensitivity analysis can be used to assess the response and stability of spatial evaluation results to changes in criterion weights (Chen et al., 2010).

The baseline model (M0) used AHP-derived weights of 0.4966 for NDVI, 0.3017 for distance to rivers, 0.1011 for distance to roads, and 0.1006 for slope. For the sensitivity analysis, the weight of each parameter was individually increased and decreased by 10% relative to its baseline value, resulting in eight sensitivity scenarios (M1–M8). When the weight of one parameter was modified, the weights of the remaining parameters were proportionally adjusted so that the sum of all weights remained equal to 1.00. Each scenario was recalculated using the same environmental datasets, scoring scheme, and weighted overlay procedure as the baseline model. This proportional adjustment follows the weight sensitivity procedure described by Chen et al. (2010). The same HSI classification limits were maintained across the baseline model (M0) and all sensitivity scenarios (M1–M8). Accordingly, unsuitable, less suitable, and suitable classes were consistently defined as 1.00–2.33, >2.33–3.67, and >3.67–5.00, respectively. This ensured that the differences in the area of each suitability class resulted from changes in the AHP-derived weights rather than changes in the classification thresholds.

Sensitivity analysis was applied with ±10% relative perturbations to the baseline AHP-derived weights using a one-at-a-time (OAT) approach. This perturbation range was selected to examine the model's local sensitivity to small changes in the relative importance of individual parameters. Each

parameter weight was increased and decreased individually, while the remaining weights were proportionally adjusted to maintain a total weight of 1.00. The environmental datasets, scoring scheme, and HSI classification thresholds were held constant across all scenarios. The resulting changes in the environmental suitability classes were then compared with the baseline model to evaluate the sensitivity of the model output to the tested weight variations (Chen et al., 2010).

The results of each sensitivity scenario were compared with those of the baseline model based on the area and proportion of the three environmental suitability classes: suitable, less suitable, and unsuitable. Changes in the area and proportion of each class were used to evaluate the response of the model to variations in the parameter weights and to identify the parameters that produced relatively larger changes in the model output.

The change in the proportion of each environmental suitability class relative to the baseline model was calculated using Equation (4).

$$\Delta A_i = A_{i,s} - A_{i,b} \quad (4)$$

where ΔA_i is the change in the proportion of suitability class i expressed in percentage points; $A_{i,s}$ is the percentage of the study area assigned to class i under a sensitivity scenario, and $A_{i,b}$ is the corresponding percentage under the baseline model.

Model stability was assessed by examining the magnitude of the changes in the proportions of the three suitability classes across the eight sensitivity scenarios. Smaller changes indicate lower sensitivity of the class proportions to the tested weight perturbations, whereas larger changes indicate a greater response to changes in the individual parameter weights (Chen et al., 2010). This assessment evaluated the model's sensitivity to the tested ±10% weight variations but did not establish predictive accuracy or confirm orangutan occurrence or habitat use. It also does not capture all sources of uncertainty in GIS-based multicriteria decision analysis, which may arise from input data, model structure, and expert judgement (Feizizadeh and Blaschke, 2014).

3. Results and Discussion

Environmental suitability varied across East Kutai Regency, reflecting differences in vegetation condition, river proximity, topography, and road accessibility. The results describe the relative conditions represented by the four modelled environmental variables and should not be interpreted as confirmed orangutan distribution or habitat use.

3.1 Parameter Weighting Using AHP

Before constructing the environmental suitability model, the relative importance of the four environmental variables was quantified using the AHP. AHP provides a structured approach for converting expert judgement into quantitative priorities through pairwise comparisons. The resulting weights represent the relative importance assigned to each variable within the model and do not indicate that any variable independently confirms orangutan habitat.

Table 3. Environmental parameter weights derived from AHP

Rank	Parameter	Weight	Percentage (%)
1	NDVI	0.4966	49.66
2	Distance to rivers	0.3017	30.17
3	Distance to roads	0.1011	10.11
4	Slope	0.1006	10.06
	Total	**1.0000**	**100.00**

The AHP results showed a clear difference in the relative priorities assigned to the four environmental variables. NDVI received the highest weight (49.66%), followed by distance from rivers (30.17%), distance from roads (10.11%), and the slope (10.06%). Vegetation condition and river proximity

together accounted for 79.83% of the total weight, indicating that these two variables received substantially greater priority than road accessibility and terrain conditions within the expert-based weighting framework. These percentages represent relative priorities within the AHP framework, rather than direct measures of ecological effects or causal influences.

The high AHP weight assigned to NDVI reflects the importance given to the vegetation condition within the weighting framework. NDVI provides spatial information on vegetation greenness and relative vegetation density, which are relevant environmental characteristics for orangutan habitats because orangutans depend on forest vegetation for feeding, travelling, resting, and nest construction. The NDVI assessment using Google Earth Pro supported the interpretation of higher NDVI classes as increasingly dense vegetation. In the 30 reference points, the 0.4–0.5 class consistently corresponded to dense vegetation, while the >0.5 class consistently corresponded to very dense vegetation. These higher NDVI classes visually represented continuous and dense vegetation cover, although NDVI alone cannot distinguish natural forests from plantations or other dense vegetation types. Therefore, the 49.66% weight assigned to NDVI represents the relative priority given to vegetation condition within the AHP framework and should not be interpreted as a direct measure of natural forest cover or orangutan habitat use.

The distance to rivers received the second-highest weight (30.17%), highlighting the importance of riparian environments within the East Kutai landscape. Areas close to rivers may provide favorable vegetation conditions, water availability, and relatively productive environments that support orangutan habitat use. Prayogo et al. (2016) similarly identified river proximity as an important characteristic of orangutan habitat in Kalimantan. Their analysis showed that 88.79% of recorded orangutan nests occurred within 4,000 m of small rivers, indicating a strong spatial association between orangutan occurrence and riparian environments. Therefore, the relatively high weight assigned to distance to rivers in the present study is supported by previous empirical evidence. However, the magnitude of this weight remains specific to the expert judgement and environmental context of East Kutai and should not be considered universally applicable to other orangutan landscapes.

Road distance and slope received relatively lower weights (10.11% and 10.06%, respectively), indicating a lower relative priority within the AHP framework. Road distance remains relevant because roads can facilitate human access and disturbance, whereas slope may influence habitat conditions and accessibility. Previous research has similarly associated orangutan habitats with greater distances from roads and relatively gentle slopes (Prayogo et al., 2016).

The weighting pattern obtained in this study differs from previous habitat suitability studies that used principal component analysis (PCA), including Fitriana (2013), Prayogo et al. (2016), and Pramuja (2018), because PCA derives variable importance from statistical relationships in observed data, whereas AHP incorporates expert ecological judgement through structured pairwise comparisons and provides a consistency measure. Therefore, differences between PCA- and AHP-derived weights should be interpreted in relation to the underlying data, environmental context, parameter selection, and weighting approach rather than as evidence that one method is superior. In this study, AHP provides a transparent framework for incorporating ecological knowledge into the East Kutai context; however, the resulting weights remain subject to expert judgement and should be interpreted as context-specific priorities rather than universal ecological coefficients.

3.2 Spatial Distribution of Environmental Suitability

The weighted overlay analysis produced an index of environmental suitability based on the four selected environmental variables and AHP-derived weights. The resulting classes represent areas with environmental conditions that are relatively more or less favorable, according to the modelling criteria. Because independent orangutan occurrence data were not available for validation, the spatial patterns should not be interpreted as confirmed orangutan distribution or habitat use patterns. The model index

was classified into three environmental suitability classes: suitable, less suitable, and unsuitable for the species. The spatial distribution is shown in Figure 2.

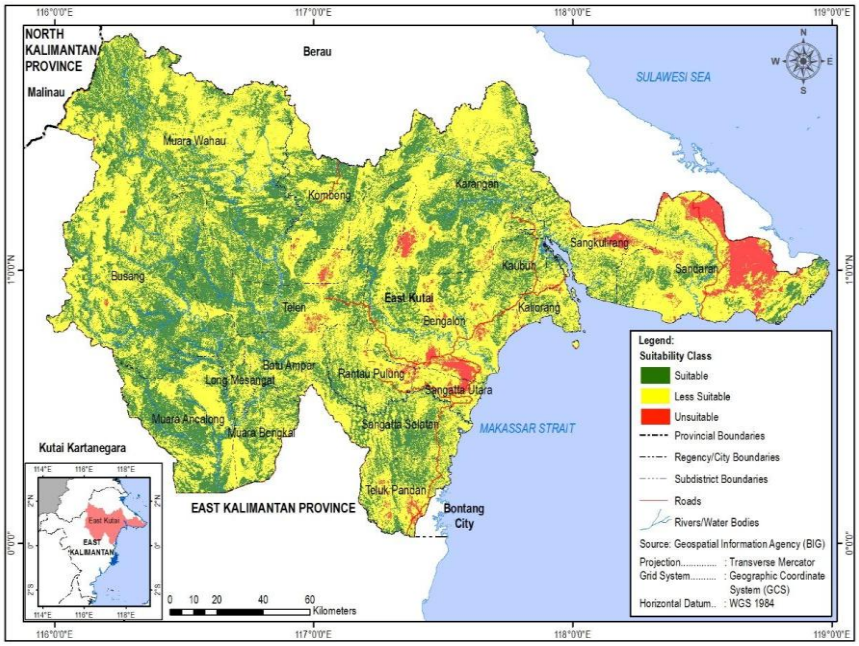

Figure 2. Spatial distribution of modelled environmental suitability for orangutans in East Kutai Regency, East Kalimantan, Indonesia

Areas classified as environmentally suitable are concentrated predominantly in the western and central parts of East Kutai, particularly within Muara Wahau, Busang, Telen, Kombeng, and parts of Bengalon, although smaller suitable patches are also distributed across several eastern subdistricts. These locations have relatively favourable combinations of the environmental variables included in the model. Their spatial pattern may help identify areas for further habitat assessment, but it does not confirm that orangutans occur in or use all of these areas.

The less suitable class forms the dominant landscape matrix around areas with higher model scores. Its widespread distribution indicates that the selected environmental conditions vary gradually across East Kutai, rather than forming distinct boundaries between suitable and unsuitable environments. Some areas may have favorable scores for one or more variables but not for all four simultaneously. Therefore, these areas should be interpreted according to their modelled environmental conditions rather than assumed to represent confirmed orangutan habitats.

Areas classified as environmentally unsuitable occupy a relatively small proportion of the regency and are concentrated mainly in the eastern coastal region, particularly around Sandaran District. Smaller patches also occur in Bengalon, Rantau Pulung, Sangatta Utara, and Teluk Pandan. These classifications indicate less favorable combinations of the environmental parameters included in the model; they do not establish the absence of orangutans.

The spatial arrangement of the environmental suitability classes reflects the weighting pattern derived from the AHP analysis. NDVI and distance from rivers together accounted for 79.83% of the total parameter weight, making vegetation condition and river proximity the principal contributors within the weighting framework. Areas with high NDVI values and favorable river proximity therefore tend to receive higher model scores. However, because NDVI cannot distinguish natural forests from plantations or other dense vegetation, high NDVI values alone should not be interpreted as evidence of confirmed orangutan habitat.

Area statistics quantify the relative extent of each environmental suitability class across the East Kutai. The area and proportion of each class are presented in Table 4.

Table 4. Area and proportion of environmental suitability classes in East Kutai Regency

Environmental suitability class	Area (km²)	Percentage (%)
Suitable	11,414.50	36.15
Less suitable	19,373.08	61.36
Unsuitable	785.11	2.49
Total	**31,572.69**	**100.00**

The model classified 19,373.08 km² (61.36%) of the study area as less suitable, 11,414.50 km² (36.15%) as suitable, and 785.11 km² (2.49%) as unsuitable according to the selected environmental criteria. These proportions describe the spatial distribution of modelled environmental conditions; they do not indicate that all areas classified as suitable are confirmed orangutan habitat or that orangutans are absent from areas in the other classes.

Pramuja (2018) reported a comparable pattern in which areas classified as having intermediate suitability occupied a larger proportion of the landscape than areas classified as highly suitable. Although differences in modelling approaches and environmental variables prevented direct comparison, both studies illustrated how modelled suitability patterns varied according to the environmental variables and modelling approaches applied.

The proportion of the study area classified as environmentally suitable in East Kutai can be compared with the results from previous orangutan habitat suitability studies, although differences in study area, environmental variables, classification schemes, and modelling methods should be considered. Prayogo et al. (2016) reported that 49.94% of the study area in a wildlife corridor in Kalimantan was classified as highly suitable, compared with 36.15% of the study area classified as suitable in the present study. Their model incorporated a broader set of variables, including distance from settlements, roads, rivers, slope, elevation, and NDVI, and used PCA to derive variable contributions. Fithria et al. (2019) classified 4,950 ha as suitable in Hulu Sungai Utara, South Kalimantan, using vegetation and human-activity-related variables. Therefore, differences in the proportions and spatial extent of suitability classes are more appropriately interpreted in relation to differences in study area, environmental conditions, selected parameters, and modelling approaches rather than as direct differences in habitat quality.

3.3 Role of Environmental Parameters in the Environmental Suitability Pattern

The environmental suitability pattern identified in East Kutai reflects the interaction among vegetation condition, river proximity, road accessibility, and topographic characteristics. Although NDVI and distance from rivers contributed the largest weights in the AHP analysis, higher model scores occurred where favorable conditions were represented across multiple variables. This pattern shows that the model output depends on the combined environmental criteria rather than NDVI alone.

NDVI received the highest weight in the AHP model because the expert judgements assigned the greatest relative importance to the vegetation condition among the four selected parameters. NDVI provides information on vegetation greenness and relative density, which may be relevant to the canopy structure used by orangutans for arboreal movement and nest construction. However, NDVI does not directly measure tree species, food availability, nesting trees, natural forest status, or orangutan occurrence. Therefore, the high weight of NDVI reflects its relative importance within this study's expert-based model, not proof that high-NDVI areas are confirmed orangutan habitat.

The distance from rivers received the second-highest weight (30.17%), indicating its relative importance within the AHP framework. Riparian environments may provide vegetation and landscape conditions relevant to orangutans. Prayogo et al. (2016) reported that 88.79% of orangutan nests in their study occurred within 4,000 m of small rivers. This supports the use of river proximity as an

environmental variable, although the relationship may vary across landscapes and does not independently confirm orangutan presence in the areas mapped here.

The comparatively lower weights assigned to road distance and slope do not imply that these variables are ecologically unimportant. Instead, their effect appears to depend on local environmental conditions. Roads primarily affect habitat through indirect processes by increasing human access, encouraging forest disturbance, and facilitating land use conversion. Likewise, slope rarely determines habitat quality independently but modifies local environmental conditions that affect vegetation development and accessibility. Prayogo et al. (2016) reported a higher concentration of orangutan nests in areas farther from roads and on relatively gentle slopes.

This interaction among environmental variables helps explain the predominance of the less suitable class across East Kutai. Many parts of the landscape have favorable scores for one or two variables but lack the full combination of conditions represented in the model. Therefore, the classes express relative environmental suitability under the selected criteria, rather than a definitive distinction between areas used and unused by orangutans.

Areas with high environmental suitability scores can be considered for further habitat assessment, but the suitability class alone should not determine conservation priority. Additional information on natural forest cover, fragmentation, land-use history, orangutan occurrence, and field conditions is needed before specific sites can be designated as conservation priorities. Areas with intermediate scores may also warrant attention, as they could contribute to habitat continuity or restoration.

3.4 Sensitivity Analysis of the Environmental Suitability Model

The sensitivity analysis evaluated whether changes in the AHP-derived weights affected the modelled environmental-suitability classes. The baseline model (Mo) was compared with eight sensitivity scenarios (M1–M8), generated by applying ±10% changes to individual parameter weights while maintaining a total weight of 1.00. Table 5 presents the changes in the area and proportion of the three environmental suitability classes for these scenarios.

Table 5. Sensitivity analysis of environmental suitability classes under ±10% variation in AHP-derived weights

Model	Scenario	Unsuitable (km^2)	(%)	Less suitable (km^2)	(%)	Suitable (km^2)	(%)
Mo	Baseline	785.11	2.49	19,373.08	61.36	11,414.50	36.15
M1	NDVI –10%	1,236.89	3.92	18,920.39	59.93	11,415.41	36.16
M2	NDVI +10%	1,355.72	4.29	19,702.35	62.40	10,514.62	33.30
M3	River distance –10%	1,472.61	4.66	19,845.95	62.86	10,254.13	32.48
M4	River distance +10%	1,403.30	4.44	18,789.67	59.51	11,379.72	36.04
M5	Road distance –10%	1,475.53	4.67	18,656.95	59.09	11,440.21	36.23
M6	Road distance +10%	1,470.03	4.66	18,662.90	59.11	11,439.76	36.23
M7	Slope –10%	1,523.90	4.83	18,694.90	59.21	11,353.89	35.96
M8	Slope +10%	1,357.76	4.30	18,778.54	59.48	11,436.39	36.22

Across the eight sensitivity scenarios, the three environmental suitability classes exhibited different responses to the tested ±10% weight perturbations. The unsuitable class increased from 2.49% in the baseline model to 3.92–4.83%, corresponding to an increase of 1.43–2.34 pp. The less suitable class ranged from 59.09% to 62.86%, compared with 61.36% at baseline, representing changes of –2.27 to +1.50 pp. The suitable class ranged from 32.48% to 36.23%, compared with 36.15% at baseline, with changes ranging from –3.67 to +0.08 pp. In six of the eight scenarios, the proportion classified as suitable remained within 0.19 pp of the baseline, whereas larger decreases occurred under the NDVI +10% and river distance –10% scenarios. These findings indicate that the suitable-class proportion remained relatively stable

under most tested perturbations, although the distribution of suitability classes responded differently to changes in the parameter weights. Stability in the class area does not necessarily imply stability in the spatial distribution of the mapped classes, and the sensitivity analysis does not validate the model against observed orangutan occurrence or habitat use.

3.5 Conservation Implications, Study Limitations, and Future Research

The environmental suitability map provides an initial spatial basis for identifying areas that warrant further habitat assessment and may inform conservation planning in the East Kutai region. Spatial information on orangutan distribution can support conservation prioritization and land-use planning (Santika et al., 2022). Areas classified as suitable may be prioritized for field surveys and detailed assessments of natural forest cover, orangutan occurrence, and habitat conditions. However, these areas should not automatically be considered the highest conservation priorities because the model incorporates only four environmental parameters and has not been validated against independent orangutan occurrence data. Less suitable areas should not be regarded as having low conservation importance, particularly where they adjoin higher-scoring areas, may provide transitional habitats, or contribute to habitat continuity and restoration. Conservation decisions should therefore integrate environmental suitability maps with additional ecological information, including vegetation condition, habitat fragmentation, land-use history, and field verification.

The spatial relationship between higher- and intermediate-scoring areas provides an initial basis for identifying locations that warrant further investigation of potential ecological connectivity. Intermediate-scoring areas situated between relatively large areas of higher environmental suitability may function as transitional areas and as potential habitat linkages. However, connectivity was not explicitly modelled in this study, and these areas should not be interpreted as confirmed orangutan corridors in the wild. Maintaining connectivity is relevant to orangutan conservation because habitat fragmentation can restrict movement between forest blocks and affect the persistence of the population (Ancrenaz et al., 2021). Further analysis using forest connectivity, land cover continuity, and orangutan occurrence or movement data is therefore required to delineate and prioritize specific corridors.

The environmental suitability map can serve as a spatial input for regional land-use planning and environmental assessment. Proposed infrastructure, agricultural expansion, and other land-use changes in higher-scoring areas can be examined more closely to assess their potential implications for orangutan habitat, particularly in relation to habitat conversion and fragmentation. Less suitable areas adjacent to higher-scoring areas should also be assessed for their potential contribution to habitat connectivity and restoration before being allocated for intensive land use. The map can provide a spatial basis for comparing land-use alternatives and identifying areas where development may pose greater potential conservation risks. This approach is consistent with previous conservation research showing that spatial information on orangutan distribution and its overlap with land-use categories can support conservation prioritization and land-use planning (Wich et al., 2012). However, the environmental suitability map should be considered alongside land-cover information, habitat fragmentation, land-use history, and field observations rather than used as a stand-alone basis for land-use decisions.

Several limitations should be considered when interpreting the model. The four selected environmental variables represent only some of the ecological dimensions relevant to orangutan habitat. Forest type, food-plant distribution, habitat fragmentation, settlements, land-use intensity, and fire history may also affect habitat conditions but were not included in the model. Their incorporation in future work, where reliable spatial data are available, could provide a more comprehensive assessment of environmental suitability.

NDVI should be interpreted as an indicator of vegetation greenness and relative density rather than vegetation type. The reference assessment using Google Earth Pro showed correspondence between the NDVI classes and visually interpreted vegetation density at the sampled locations. However, this assessment did not validate orangutan occurrence and could not establish that high-NDVI areas were

natural forest or confirmed orangutan habitat. A forest or land-cover mask was not applied because restricting the analysis to areas classified as forest could exclude densely vegetated areas outside those categories that may also have high NDVI values. Accordingly, the NDVI layer represents vegetation conditions across the study area and may include plantations or other dense vegetation.

The model's reliance on NDVI without a forest or land-cover mask is therefore an important interpretive limitation. Although high NDVI values indicate relatively dense or green vegetation, they do not distinguish natural forests from plantations or other dense vegetation types. The environmental suitability classes should consequently be understood as the combined result of the four selected environmental variables, not as a map of confirmed natural forest or orangutan habitat use.

The weighting process relied on expert judgement through AHP, allowing ecological knowledge to be incorporated while providing a consistency measure for pairwise comparisons. Nevertheless, the resulting weights remain subject to expert interpretation and may vary among different expert groups or weighting approaches. The ±10% sensitivity analysis indicated that the area classified as environmentally suitable remained relatively close to the baseline in six of the eight scenarios but decreased by 2.85 and 3.67 percentage points under the NDVI +10% and river distance –10% scenarios, respectively. These results indicate that the model's response varied across parameter-weight scenarios and that the suitable-class area was sensitive to changes in the selected parameter weights. Future studies could compare AHP-based weighting with alternative approaches, including Principal Component Analysis (PCA), and evaluate the resulting suitability patterns using data-driven models, such as machine learning or species distribution models, where sufficient orangutan occurrence data are available.

The independent validation is an important limitation of the present model. The predicted environmental suitability classes could not be evaluated against field-based orangutan occurrence data because systematic observations covering the study area were not available. Therefore, the results describe the spatial distribution of environmental conditions considered relatively favorable according to the selected AHP criteria, rather than confirming orangutan occurrence or habitat use, and do not provide a quantitative measure of predictive accuracy. Future studies incorporating independent occurrence data could evaluate the relationship between orangutan observations and the modelled class.

The model should be regarded as an initial spatial framework that can be refined as more ecological information becomes available. Combining the environmental suitability map with forest cover data, field observations, and orangutan occurrence information could improve its relevance for habitat assessment and conservation planning in East Kutai.

4. Conclusions

Environmental suitability for orangutan habitats varied across East Kutai, reflecting differences in vegetation conditions, river proximity, road accessibility, and terrain. The AHP-weighted GIS model assigned the highest weights to NDVI (49.66%) and distance from rivers (30.17%), whereas road distance and slope received comparatively lower weights. The model classified 11,414.50 km² (36.15%) as suitable, 19,373.08 km² (61.36%) as less suitable, and 785.11 km² (2.49%) as unsuitable, according to the selected environmental criteria. These classes represent relative environmental suitability based on the four modelled parameters rather than confirmed orangutan occurrence or habitat use.

The ±10% sensitivity analysis showed that the unsuitable class ranged from 3.92% to 4.83%, the less suitable class from 59.09% to 62.86%, and the suitable class from 32.48% to 36.23%, respectively. The suitable-class proportion remained within 0.19 percentage points of the baseline in six of the eight scenarios but decreased by 2.85 and 3.67 percentage points under the NDVI +10% and river distance –10% scenarios, respectively. These results indicate relative stability in the suitable-class proportion under most tested weight perturbations, while also showing sensitivity to the selected changes in parameter weights. This analysis evaluated the model's response to the tested weight variations but did not establish predictive accuracy or confirm orangutan habitat use.

The resulting map provides an initial spatial basis for identifying areas for further habitat assessment and informing conservation planning in the East Kutai. However, the absence of independent orangutan occurrence data prevented the quantitative validation of the model. Future studies should incorporate field-based occurrence data, natural forest cover, habitat fragmentation, and other relevant ecological variables to evaluate and refine the model and determine the conservation relevance of specific areas.

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Ethics Statement

Informed consent was obtained from all six experts before they completed the AHP questionnaire survey. Their participation was limited to providing professional pairwise-comparison judgments for the four environmental parameters, and no personal or sensitive data were collected. No formal institutional ethics approval or exemption determination was obtained for this study.

CRediT Author Statement

Oktaviana Sawitri: Conceptualization, Methodology, Formal Analysis, Investigation, Data Curation, Visualization, Writing – Original Draft Preparation, and Project Administration. **Sri Rum Giyarsih:** Supervision, Methodology, Writing – Review and Editing, and Result Verification. **Prima Widayani:** Supervision, Writing – Review and Editing, and Result Verification. **Gary L. Shapiro:** Resources, Financial Support Acquisition, Writing – Review and Editing, and Conservation Perspective Review.

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