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Assessing The Impact of Habitat Loss and Human Development on Proboscis Monkey Distribution in South Kalimantan

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Abstract. *The proboscis monkey (Nasalis larvatus) is an endemic primate species of Borneo that plays a crucial role in maintaining the health of riparian forest ecosystems. However, habitat loss due to deforestation, land conversion, and urbanization has led to significant population declines. This study aims to analyze the habitat characteristics and dispersal patterns of the proboscis monkey in the riparian zone of the Tabunio Watershed, South Kalimantan, Indonesia. Geospatial modeling techniques, including Kernel Density Analysis (KDA) and spatial regression, were employed to assess habitat suitability and predict species dispersal. Sentinel-2 multispectral imagery from 2018, 2019, and 2021 was utilized to extract vegetation biophysical parameters, such as Leaf Area Index (LAI), Canopy Chlorophyll Content (CCC), and Fraction of Vegetation Cover (FVC), which were integrated with field survey data. The results indicate a significant correlation between the distribution of proboscis monkeys and vegetation health, with dense riparian vegetation providing optimal habitat conditions for these monkeys. The findings also highlight the adverse impact of human-induced changes in land cover on populations of the proboscis monkey. Conservation measures, including habitat restoration and the establishment of protected areas, are recommended to mitigate habitat fragmentation and ensure the long-term survival of the species. This study contributes to the understanding of habitat dynamics and provides valuable insights for the sustainable management of riparian ecosystems in South Kalimantan.*

Keywords: *geospatial modelling, habitat dynamics, Nasalis larvatus, riparian ecosystem*

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INTRODUCTION

Wetland and riparian ecosystems are among the most productive and ecologically significant landscapes in tropical regions. These ecosystems not only regulate hydrological cycles but also sustain a wide range of biodiversity, including species of high ecological and conservation value. Among these, the proboscis monkey (*Nasalis larvatus* Wurmb), an arboreal primate endemic to Borneo, plays a vital role in maintaining ecological balance through its interactions with vegetation structure and nutrient cycling. Its natural habitats are predominantly located in mangrove forests, peat swamp forests, and riparian forests along riverbanks (Matsuda et al., 2018; Wardatutthoyyibah et al., 2019). However, human activities, including deforestation, land conversion, and infrastructure development, have led to significant habitat destruction and fragmentation, posing considerable threats to the survival of this species (Wardatutthoyyibah et al., 2023).

Despite its ecological importance, the proboscis monkey faces severe and escalating threats across its range. Deforestation, agricultural expansion, and infrastructure development have accelerated habitat degradation and fragmentation, thereby reducing both habitat quality and connectivity. Such anthropogenic pressures directly affect survival rates, population distribution, and the long-term viability of the species. Moreover, the proboscis monkey is highly dependent on riverine and estuarine habitats, making it particularly vulnerable to alterations in land use and water systems (Rezeki et al., 2023; Santoso et al., 2023).

Comparative studies across Borneo illustrate that while the ecological dependencies of proboscis monkeys remain relatively consistent, the drivers of habitat decline vary regionally. In East Kalimantan, the expansion of oil palm plantations and coastal infrastructure projects has led to the degradation of estuarine habitats (Yusuf et al., 2021). In West Kalimantan, populations persist in fragmented production forests, yet their dependence on specific riparian trees indicates heightened vulnerability to logging and settlement expansion (Kusuma et al., 2023). In Central Kalimantan, recurrent peatland fires and hydrological disruptions within Sebangau National Park have isolated small populations, limiting connectivity and increasing extinction risks (Harrison et al., 2019). In South Kalimantan, recent applications of Sentinel-2 satellite imagery, Kernel Density Analysis (KDA), and Geographically Weighted Regression (GWR) have revealed that canopy chlorophyll content strongly predicts habitat suitability, and habitat contraction between 2018 and 2021 has been primarily driven by human expansion (Meijaard & Nijman, 2000).

South Kalimantan is a critical province for proboscis monkey conservation, yet it faces increasing threats from urban expansion in the Banjarbakula metropolitan area, seasonal wildfires in shrublands, and agricultural conversion. These disturbances compromise habitat connectivity, exacerbate erosion, and heighten the risk of population isolation. The forests of Tanah Laut Regency, particularly along the Tabunio River, have the potential to provide suitable habitats for the proboscis monkey (Fithria et al., 2021).

This study aims to analyze the habitat characteristics and dispersal patterns of the proboscis monkey within the riparian zone of the Tabunio Watershed. The novelty of this research lies in its systematic approach to linking vegetation quality with dispersal patterns at the watershed scale, addressing a critical knowledge gap. While previous studies have explored habitat use and threats, few have integrated geospatial modelling with field-based observations to create predictive frameworks for conservation planning.

By employing Kernel Density Analysis (KDA) to assess dispersal patterns and combining it with Geographically Weighted Regression (GWR) to model the influence of vegetation parameters, this research aims to refine our understanding of habitat suitability and population dynamics. The findings are expected to offer a scientific basis for developing integrated conservation strategies, including habitat restoration, cross-provincial collaboration, and long-term monitoring, thereby contributing to the long-term persistence of *N. larvatus* in South Kalimantan and across Borneo.

MATERIALS AND METHODS

Study Area and Data Collection

This study was conducted within the Tabunio Watershed in Tanah Laut Regency, South Kalimantan, Indonesia, specifically in the riparian zone near the estuary of the Tabunio River, as illustrated in Figure 1. The site was selected based on preliminary observations indicating a substantial population of proboscis monkeys in the area. Furthermore, the habitat of this species faces significant threats due to surrounding human activities, particularly from urbanization, agriculture, and plantations.

Geospatial data from various sources were utilized as input for the study, including digital topographic maps from the Indonesian Geospatial Information Agency (BIG), watershed boundary data from the Barito Watershed Management Centre (BPDAS Barito), and free Sentinel-2 Multispectral Instrument (MSI) imagery provided by the European Space Agency (ESA).

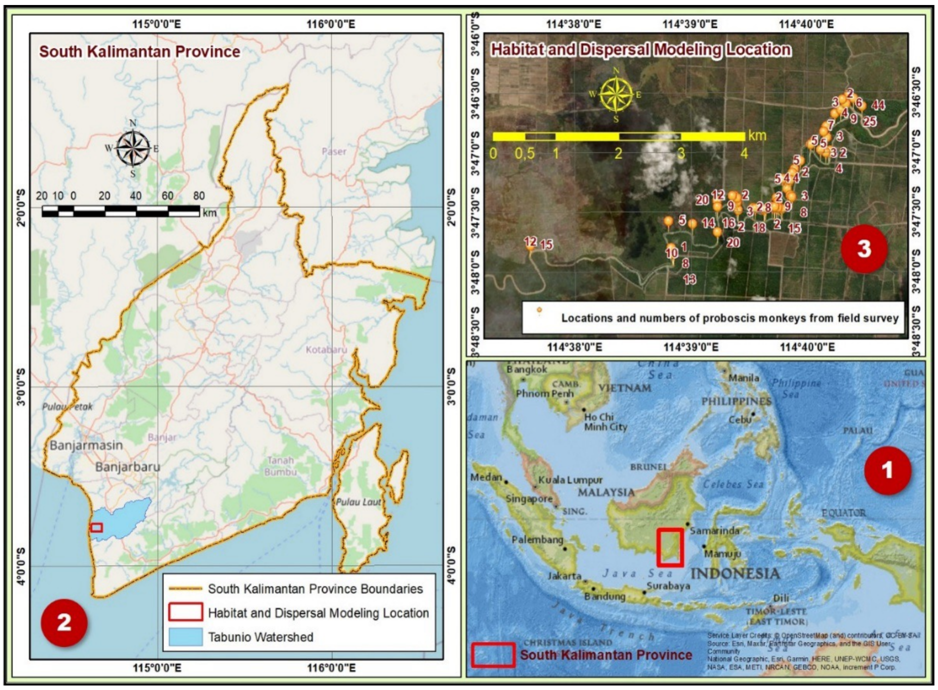

Figure 1. Research the location and the location of encounters with proboscis monkeys

Multitemporal Sentinel-2 images from 2018, 2019, and 2021 were employed for analysis.

Field Survey

One of the primary inputs for modelling habitat suitability and species dispersal was the location and population count of proboscis monkeys, which were collected through a field survey conducted in April 2021. The sampling method used was accidental sampling. GNSS coordinates for each observed location, along with the number of monkeys at each site, are presented in Table 1 and Figure 1. Due to accessibility constraints during data collection, surveys were conducted via boat along the river, a method similarly used by Bernard et al. (2021). Given that direct proximity to the monkeys would interfere with their natural behaviours and likely cause them to flee, only the observer's coordinates were recorded, not the exact location of the monkeys. In some instances, multiple groups of proboscis monkeys were observed at different points along the riverbank, resulting in similar coordinates for different groups at the exact general location. The specific details of these observations are further addressed in the Habitat Suitability and Dispersal Mapping section.

Geospatial Modelling and Validation

Roads, Rivers, and Land Cover

In this study, road networks, river systems, and urban areas were incorporated as spatial variables for habitat suitability simulations, as these factors influence the movement and settlement patterns of proboscis monkeys. The spatial data for roads and rivers were obtained from the 1:50,000-scale digital topographic maps produced by BIG in 2017. Land cover data was extracted from these topographic maps and updated using visual interpretation of Sentinel-2 MSI images from 2018, 2019, and 2021. This provided land cover information for the years 2018, 2019, and 2021.

Sentinel-2 Imagery and Vegetation Biophysical Data

Three Sentinel-2 multitemporal images were analysed in this study: Sentinel-2B imagery from May 6, 2018, Sentinel-2A imagery from July 25, 2019, and Sentinel-2B imagery from April 10, 2021. All images were calibrated to bottom-of-atmosphere reflectance using the Sen2Cor tool (Louis et al., 2016; Main-Knorn et al., 2017) in the free Sentinel Application Platform (SNAP) software provided by ESA. The Sentinel-2 MSI captures 13 spectral bands at varying spatial resolutions (10m, 20m, and 60m), and all bands were resampled to 10m for uniformity in analysis. Figure 2 depicts the details of the Sentinel-2 imagery over the entire Tabunio watershed. A challenge arose in obtaining cloud-free images from 2020, necessitating the selection of 2018 as the base year for habitat and dispersal predictions.

Additionally, various vegetation biophysical parameters, such as Leaf Area Index (LAI), Canopy Chlorophyll Content (CCC), Canopy Water Content (CWC), Fraction of Vegetation Cover (FVC), and Fraction of Absorbed Photosynthetically Active Radiation (FAPAR), were extracted from Sentinel-2 level 2A imagery. These parameters were chosen because they correlate with habitat suitability and the occurrence of proboscis monkeys, influencing factors like vegetation density, health, and food availability.

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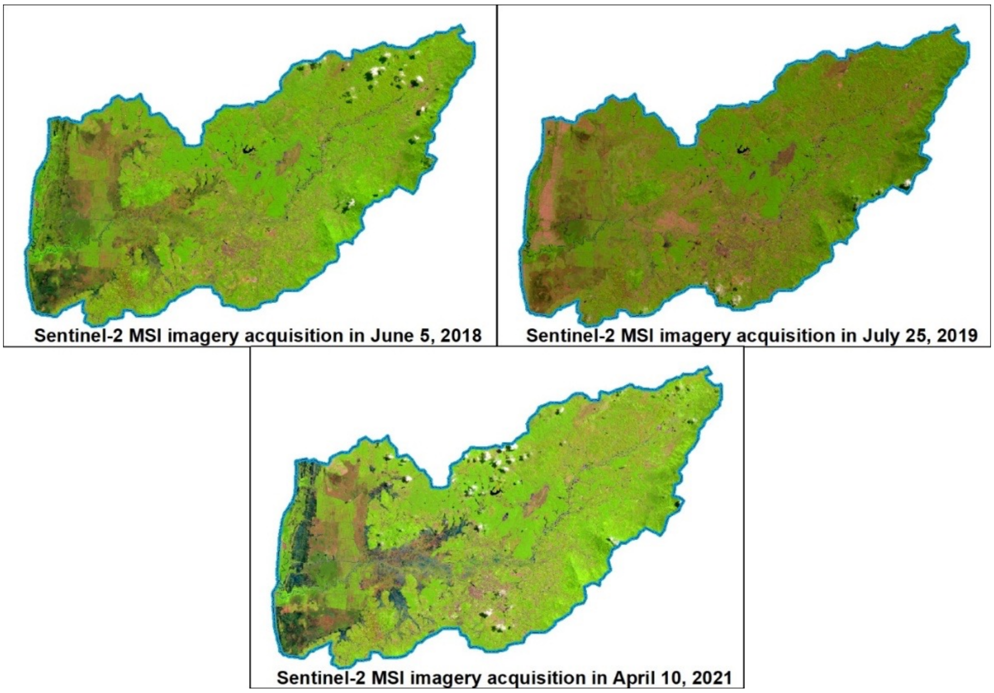

Figure 2. Multitemporal Sentinel-2 MSI imagery of the Tabunio Watershed

Habitat Suitability and Dispersal Mapping

Proboscis monkey habitats are closely linked to specific land cover types, proximity to human activities, and water sources. In this study, the most suitable land cover types for proboscis monkeys were identified as shrubs, bushes, and forests. Conversely, areas covered by plantations were excluded due to the presence of human activities. The proximity to river streams, human settlements, and road networks further influenced habitat suitability. The actual distances from these features were estimated based on coordinates from field surveys. However, as the field survey did not encompass all possible habitats, the locations recorded represent observer positions rather than the precise locations of the monkeys. To address this limitation, Kernel Density Analysis (KDA) was used to estimate the actual dispersal of the monkeys, providing a more accurate representation of their spatial distribution.

The dispersal of proboscis monkeys was modelled using spatial regression techniques, incorporating biophysical vegetation parameters (LAI, CCC, CWC, FVC, and FAPAR) as independent variables and dispersal estimates from KDA as the dependent variable. Exploratory Regression (ER) was initially performed to identify the variables most strongly correlated with dispersal and to check for multicollinearity. The final regression model was selected based on the highest adjusted R2 value, with a preference for models exhibiting low or zero Mean Absolute Percentage Error (MAPE). The accuracy of the dispersal model was validated by comparing the estimated dispersal in 2021 with actual data from KDA. Dispersal predictions for 2018, 2019, and 2021 were subsequently overlaid with habitat suitability data to generate geospatial maps depicting the spatial dynamics of proboscis monkey populations across these years. The entire geospatial analysis process is summarised in the flowchart presented in Figure 3.

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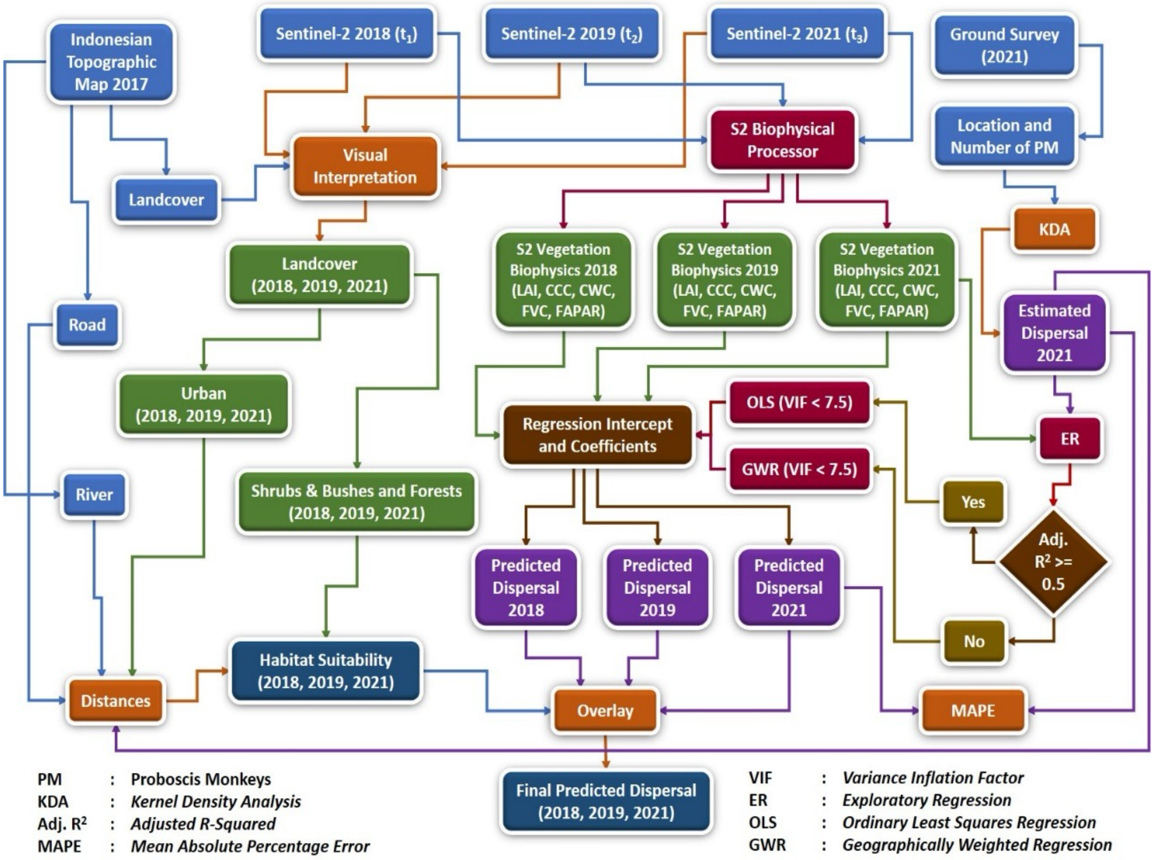

Figure 3. Geospatial information analysis flowchart

RESULTS AND DISCUSSION

Dynamics of Proboscis Monkey Habitat Suitability

The Tabunio watershed, located in Tanah Laut Regency, South Kalimantan, is significantly impacted by human activities, including urbanisation, transportation, agriculture, and plantation development. These human-induced changes have led to a gradual decline in environmental quality in the region. Consequently, the habitats of wildlife species, particularly the proboscis monkey (*Nasalis larvatus*), are also under threat. Proboscis monkeys are susceptible to human presence and tend to avoid areas with human activity, even when humans are not directly visible. However, in some cases, these monkeys may enter human-dominated areas, such as settlements, plantations, or roads, particularly when human activity is minimal or absent.

Habitat fragmentation and degradation can significantly reduce the carrying capacity of an environment, which in turn can hinder population growth and survival rates of species such as the proboscis monkey. For the long-term viability of primate populations, it is essential to maintain high-quality habitats with sufficient spatial extent. Various biotic and abiotic factors influence the selection of habitats by wildlife. Water, for example, is a critical resource for mammals, providing both hydration and playing a vital role in metabolic processes (Jayasukma et al., 2022; Fithria et al., 2021; Retanti et al., 2021).

In an ideal scenario, individuals will evaluate trade-offs between risks and rewards, selecting habitats that maximise their reproductive success. In cases where survival opportunities are limited, individuals may exploit suboptimal niches even if better habitats are available elsewhere. Key factors influencing habitat selection include predation risks, physiological tolerance, and social interactions. The density of vegetation, species diversity, and the availability of food also play crucial roles, as primates such as colobines tend to utilise vertical space for activities, resulting in smaller areas of horizontal space being required. High vegetation density, species diversity, and abundant food sources encourage primates to exploit more vertical space than horizontal (Lisnaini et al., 2020; Jayasukma et al., 2022).

Habitat selection is a vital aspect of wildlife behaviour, as it enables animals to transition between habitats to meet their needs for food, water, reproduction, and optimal living conditions. Some species are selective in their habitat choices, minimising negative interactions (e.g., predation or competition) while maximising positive factors, such as prey availability. Temperature is one of the environmental variables that can significantly influence wildlife, affecting life processes, distribution, and abundance. Temperature variations can serve as a limiting factor, with both intrinsic variables (such as an animal's physiological state) and extrinsic factors (such as environmental conditions) influencing animal behaviour and habitat use (Fithria et al., 2021; Retanti et al., 2021).

Field Survey Findings

A total of 58 locations with proboscis monkey sightings were identified during the field survey, with an observed population of 644 individual monkeys, as detailed in Table 1. It is important to note that the coordinates listed in Table 1 correspond to the locations of the observers, not the exact positions of the proboscis monkey themselves. The actual locations of the monkey groups were not directly recorded due to the non-invasive survey methodology. Observations and population counts were conducted from a distance using telephoto lenses to minimise disturbance to the animals.

The data presented in Table 1 reflect an uneven distribution of proboscis monkeys across the various surveyed locations. This variation can be attributed to several factors, such as differences in group size or the availability of essential resources, including food and shelter. Proboscis monkeys are social animals that typically move in groups, yet Table 1 also indicates instances where only a single individual was observed at specific sites. Such occurrences may be incidental, with a lone individual potentially separated from its group due to activities like foraging or playing.

Figure 4 illustrates that plantations, particularly oil palm plantations, predominantly characterise the land cover of the Tabunio watershed. Forested areas are more abundant in the upper reaches of the river, which is part of the Meratus Mountain tropical rainforest ecosystem. In contrast, the lower reaches of the watershed, characterised by relatively flat terrain, are primarily influenced by human activities, including settlements, agriculture, plantations, and road networks.

The region also includes the city of Pleihari, which serves as the administrative capital of Tanah Laut Regency. The observation focus, the riparian zone along the Tabunio River, is situated in the lower watershed and is heavily impacted by human activities. Even the Tabunio River itself is utilised as a transportation route in the downstream region. In this area, the proboscis

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Table 1. Locations and numbers of proboscis monkeys from the field survey

Point Number	Coordinate of Proboscis Monkeys		Number of Proboscis Monkeys
	X	Y	
1	241508	9582185	2
2	241468	9582049	3
3	241144	9581676	1
4	241211	9581323	2
5	241145	9581283	4
6	240961	9581460	5
7	240739	9581156	5
8	240646	9581034	12
9	240615	9580976	2
10	240502	9580874	8
11	240525	9580729	68
12	240324	9580435	44
13	240164	9580401	2
14	239986	9580434	2
15	239414	9580542	20
16	240361	9580583	2
17	240576	9580862	5
18	241159	9581692	7
19	241059	9581328	3
20	240898	9581414	5
21	240504	9580883	4
22	240457	9580878	4
23	240583	9580627	8
24	239728	9580551	2
25	239418	9580057	20
26	240388	9580531	15
27	241161	9581526	3
28	241114	9581606	29
29	241293	9581890	4
30	240190	9580411	10
31	236456	9579899	12
32	239748	9580402	15
33	240024	9580423	8

Point Number	Coordinate of Proboscis Monkeys		Number of Proboscis Monkeys
	X	Y	
34	238719	9579719	13
35	240288	9580448	18
36	240448	9580416	12
37	239736	9580516	14
38	240175	9580411	12
39	236439	9579846	15
40	238711	9579750	8
41	238724	9579722	10
42	239021	9580185	14
43	239709	9580604	16
44	240361	9580439	18
45	239695	9580621	12
46	240388	9580429	15
47	240335	9580445	9
48	239732	9580582	3
49	241384	9581945	9
50	241465	9582043	6
51	241405	9582110	15
52	241587	9582127	25
53	241725	9582005	44
54	240602	9580604	3
55	239659	9580618	2
56	239424	9580450	9
57	238646	9580231	5
58	238684	9579817	1

Source: Primary data from field survey results

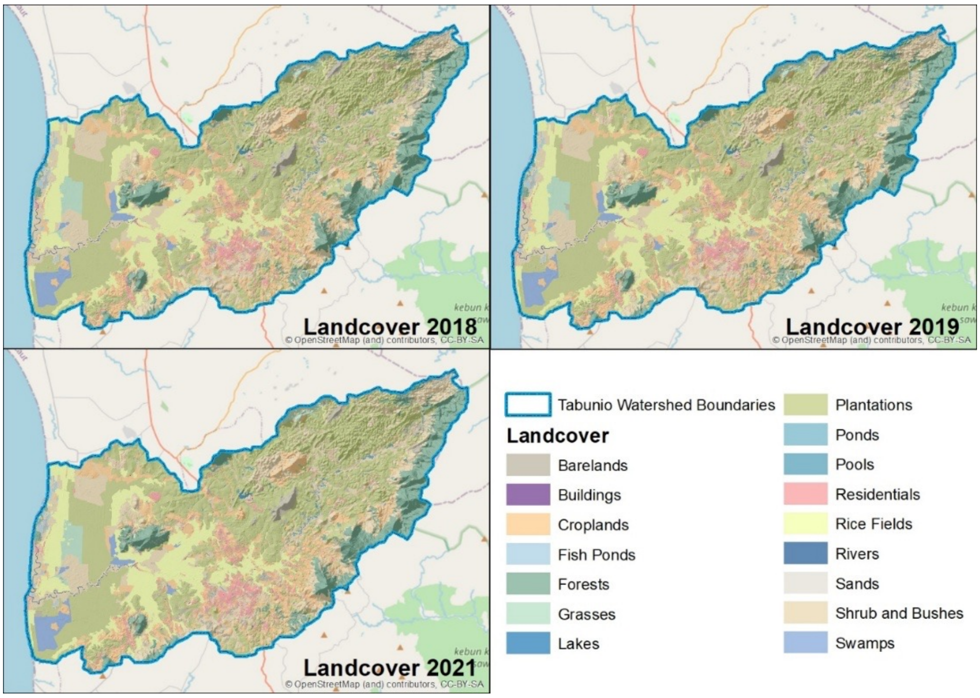

Figure 4. Multitemporal land cover of the Tabunio Watershed

monkeys' habitat is limited to remnants of shrubland and bushes that have not yet been encroached upon by human development. However, these habitats are at risk of further decline due to ongoing regional development, particularly the expansion of settlements and agriculture.

The dynamic modelling conducted in this study spans short time intervals, specifically one to two years, which offers both advantages and disadvantages. A key benefit is that parameters such as human accessibility (i.e., the road network), which may change annually, are assumed to remain constant for the purposes of this study. As a result, the road network condition is considered unchanged between 2018 and 2021. However, a limitation of short-term dynamic analysis is that it may fail to capture minor changes, such as the development of new settlements. Given the relatively slow pace of regional development over two- to three-year periods, these minor alterations are often not detectable.

Furthermore, the geospatial data used to extract landcover information is derived from moderate-resolution satellite imagery, such as that provided by Sentinel-2. Small-scale changes, such as the construction of a few housing units within a one- or two-year span, are unlikely to be visible in the imagery, which can result in the appearance of no significant change in the distribution of distances from urban areas over time, as depicted in Figure 5. In reality, small changes do occur, though they may be too subtle to detect within the temporal constraints of this study.

Moreover, the Euclidean distance method used in the analysis and mapping of distances in Figure 5 calculates flat distances, which may not accurately reflect the actual terrain. This method is suitable for flat areas, such as the study site. However, its application to more rugged topographies (e.g.,

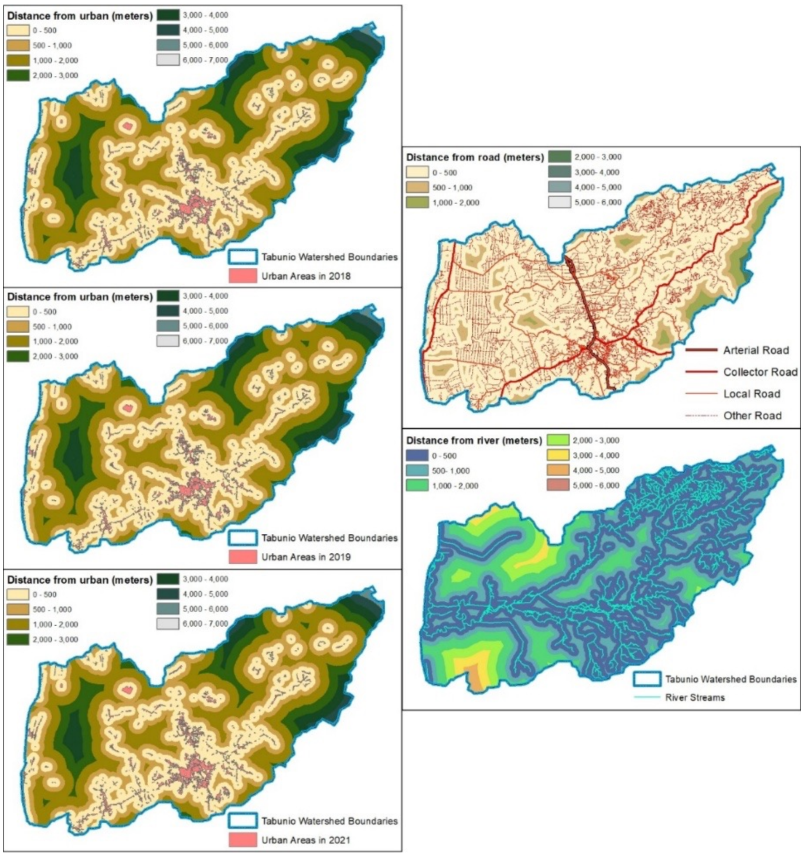

Figure 5. Distance from urban areas, roads, and rivers

mountainous regions) may lead to significant biases in estimating physical barriers to wildlife habitats. Based on the geospatial data from the KDA (Figure 7) and the distance information presented in Figure 5, various parameters, such as the minimum and maximum distances from urban areas, road networks, and river streams, were calculated. These results are summarised in Table 2.

Table 2 presents that the distribution of distances between the estimated locations of proboscis monkeys and road networks or river streams exhibits considerable heterogeneity, as evidenced by the high standard deviation values relative to the mean. This variability arises from the uneven spatial distribution

Table 2. Distance parameters of the estimated proboscis monkey's dispersal from urban, road, and river

Parameter	Minimum Distance (meters)	Maximum Distance (meters)	Average Distance (meters)	Standard Deviation
Distance from urban areas	0	3,114	2,407	662.87
Distance from road networks	0	418	107.5	82.97
Distance from the river streams	0	154.6	56	30.41

Source: Primary data from geospatial analysis results of settlements, road networks, and river streams within the study area. Regarding the distances, the analysis considers the minimum Distance for both the proximity to urban areas and road networks, as it is assumed that proboscis monkeys tend to move as far away as possible from human presence. In contrast, for the Distance from river streams, the maximum Distance is used as the parameter, acknowledging that proboscis monkeys prefer to remain as close as possible to water sources.

Based on the data presented in Table 2 and the field observations, which reveal that the proboscis monkey's habitat primarily consists of shrubs, bushes, or forests, the mathematical framework for determining habitat suitability and the subsequent results, as illustrated in Figure 6, can be explained as follows:

*Habitat Suitability = Distance from urban areas > 0 * Distance from road networks > 0 * Distance from river streams <= 154.6 * Shrub and Bushes * Forests*

The computational results, as outlined above, indicate a continuous decline in the suitability of proboscis monkey habitats from 2018 to 2021, as detailed in Table 4. This reduction in habitat availability is primarily attributed to the expansion of human settlements, without considering the dynamics of the road network in this study. It is important to note that the spatial distribution of proboscis monkey habitat suitability shown in Figure 6 merely identifies areas that are deemed suitable for the species, and it does not necessarily reflect actual proboscis monkey presence. Areas recognised as suitable habitats, yet uninhabited by proboscis monkeys during field surveys, could serve as potential reserve areas for relocation in emergencies, such as when current habitats are significantly converted for agricultural use or infrastructure development.

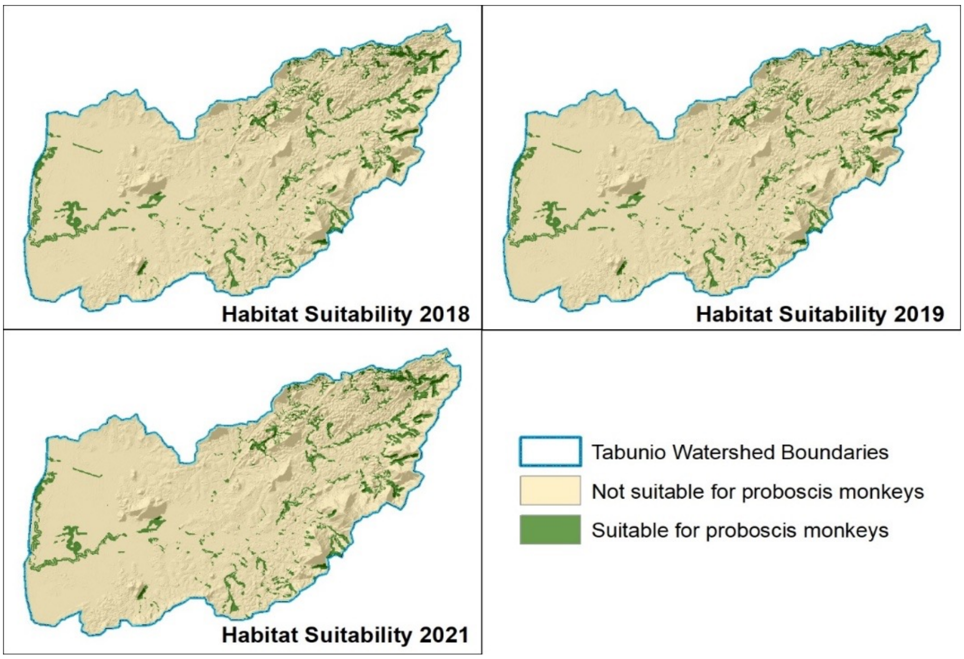

Figure 6. Proboscis monkey habitat suitability dynamics in 2018, 2019, and 2021 at Tabunio Watershed

Proboscis Monkey Dispersal Dynamics

A significant challenge in observing wild animals, such as the proboscis monkey, is the difficulty in directly approaching their exact coordinates. This could disrupt the animals' natural behaviour and, under certain circumstances, pose a risk. Even if observers were to approach, the animals would likely flee, making the recorded locations unrepresentative of their proper positions. Therefore, to minimise disruption and maintain natural animal movements, remote observation is the preferred method. Consequently, although the precise coordinates of the animals may be slightly biased, the coordinates of the observers in the field were used as input parameters for estimating the locations of proboscis monkeys. The simulation of these locations was carried out using Kernel Density Analysis (KDA), which models the population density of proboscis monkeys in a specified area based on field survey data. The estimated dispersal of proboscis monkeys derived from KDA is presented in Figure 7.

The dispersal of proboscis monkeys estimated using Kernel Density Analysis (KDA), as shown in Figure 7, serves as the dependent variable (y) in the spatial regression analysis. The independent variables (x) include LAI, CCC, CWC, FVC, FAPAR, and various combinations of these parameters. Before conducting the regression analysis, an Exploratory Regression (ER) process must first be completed. The ER results are presented in Appendix B. As indicated by the ER analysis in Appendix B, none of the correlation coefficients exceeded a threshold of 0.5, which renders Ordinary Least Squares (OLS) regression unsuitable for this study. As a result, the spatial regression method was switched to Geographically Weighted Regression (GWR), and the outcomes of the GWR analysis are provided in Table 3.

The GWR analysis employed several regression models, starting with simple regressions involving individual independent variables, such as LAI, CCC, or others, and progressing to multiple regression models that incorporated combinations of parameters, including LAI and CCC, LAI and CCC and CWC, and so on. However, in conducting regression analyses, the issue of multicollinearity must be addressed. Ideally, the independent variables in a multiple regression model should be completely independent of one another, with no interdependencies between them. In the case of correlated independent variables, multicollinearity arises. In such cases, only one of the correlated variables should be retained, while the others should be excluded from the model.

The multicollinearity test is automatically performed during the ER analysis. The presence of multicollinearity between independent variables is indicated by a Variance Inflation Factor (VIF) value of 7.5 or greater. Therefore, only combinations of variables with VIF values below 7.5 are considered suitable for constructing a multiple regression model. As seen in Appendix B, for multiple regression, the CCC-CWC and CCC-CWC-FVC combinations are the only variable sets with VIF values below 7.5. Consequently, apart from the single GWR models for each of the five vegetation biophysical parameters (LAI, CCC, CWC, FVC, and FAPAR), multiple GWR models for the CCC-CWC and CCC-CWC-FVC combinations can be implemented.

All processes were conducted using

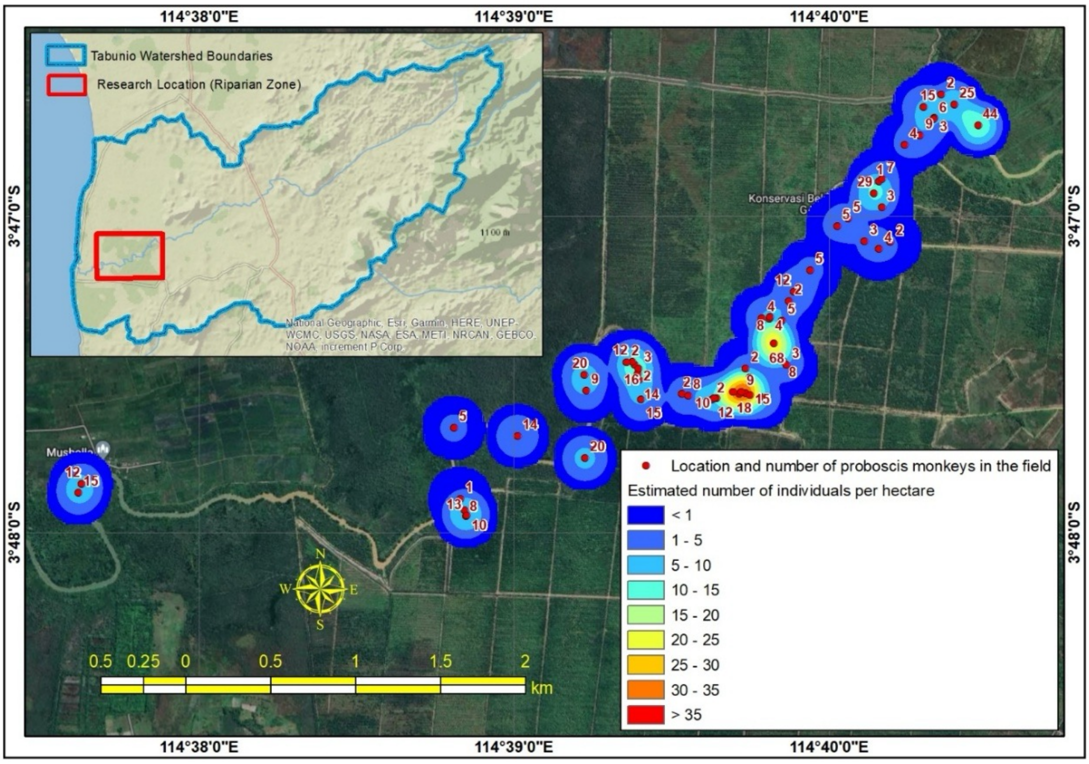

Figure 7. KDA-based estimated proboscis monkey's dispersal

the Geographically Weighted Regression (GWR) tool within the ArcGIS application. When the ArcGIS GWR was executed, the multiple GWR model incorporating the CCC-CWC-FVC combination of independent variables failed to run, despite the Exploratory Regression (ER) indicating that the Variance Inflation Factor (VIF) for this variable combination was below the threshold of 7.5, as shown in Appendix B. This failure could be attributed to the nature of GWR, which involves local intercepts and coefficients. At the same time, the ER analysis is more suited to Ordinary Least Squares (OLS), which uses global intercepts and coefficients. Therefore, the multiple GWR model with the CCC-CWC-FVC combination was not applied in this study.

In contrast to OLS, which provides scalar values for intercepts and coefficients, GWR, a geospatial regression method, generates intercepts and coefficients in the form of matrix data, represented as either vector or raster data, as shown in Appendices C and D. In GWR, each spatial point or pixel has its own intercept and coefficient for the independent variables. Additionally, each location has its local correlation coefficient (R^2), although a global R^2 value is also computed, as presented in Table 3. Table 3 reveals that the highest adjusted R^2 values are associated with the CCC and CWC variables, indicating their potential as key predictors for proboscis monkey dispersal. However, further evaluation of model accuracy is required.

To assess the accuracy of the proboscis monkey dispersal predictions, the Mean Absolute Percentage Error (MAPE) was used. MAPE measures the percentage deviation between predicted dispersal results and observed data. The predicted dispersal values were derived from the six GWR models presented in Table 3, while the actual dispersal data for 2021 were based on KDA estimations, as shown in Figure 7. The six model predictions for 2021 were compared using MAPE, and the model with the smallest MAPE value was considered the most accurate.

From Table 3, it is evident that the single GWR model using CWC as the independent variable yields the lowest MAPE value. However, CWC has a lower adjusted R^2 than CCC. Consequently, the chosen model for mapping the proboscis monkey dispersal from 2018 to 2021 is the single GWR with CCC as the independent variable. Additionally, the MAPE value for CCC is only marginally higher than CWC (by 0.1%), a difference considered negligible for the analysis. The dynamics of proboscis monkey dispersal from 2018 to 2021, predicted using the CCC GWR model, are shown in Figure 8. This dispersal data was overlaid with habitat suitability maps from Figure 6, resulting in slight differences compared to the KDA-based dispersal estimates shown in Figure 7.

Table 3. Geographically Weighted Regression parameters and validation

Independent Variables	Adjusted R2	MAPE
LAI	0.8987	22.68%
CCC	0.9248	21.70%
CWC	0.9151	21.60%
FVC	0.7865	28.51%
FAPAR	0.7137	39.73%
CCC-CWC	0.8376	26.86%

Source: Primary data from geospatial analysis results

Figure 8 illustrates that visual distinctions in proboscis monkey dispersal across years are challenging to observe, primarily due to the relatively small changes in dispersal patterns over the short analysis interval. More extended observation periods, such as five-year intervals, would allow for more noticeable trends in habitat suitability and distribution dynamics. However, due to the limited availability of high-resolution spatial data for the desired time frame, particularly before 2015, detailed monitoring remains difficult. Moreover, obtaining cloud-free Sentinel-2 imagery in the study area, located near the equator, presents an additional challenge. Future studies might consider using remote sensing technologies less affected by atmospheric disturbances, such as Synthetic Aperture Radar (SAR), to overcome these limitations.

By utilising geospatial data from habitat suitability mapping and annual predictions of proboscis monkey dispersal, the dynamics of potential proboscis monkey habitats were assessed. Additionally, the predicted average number of proboscis monkeys per hectare and the total population of proboscis monkeys were estimated. The results are presented in Table 4. This table indicates a decline in areas that are suitable or potential habitats for proboscis monkeys from year to year, as well as a corresponding decrease in the predicted number of proboscis monkeys. As noted earlier, the reduction in habitat space within the Tabunio watershed is primarily attributed to the expansion of human settlements. Consequently, the decrease in both habitat area and proboscis monkey population in this region can be attributed mainly to anthropogenic pressures. A similar

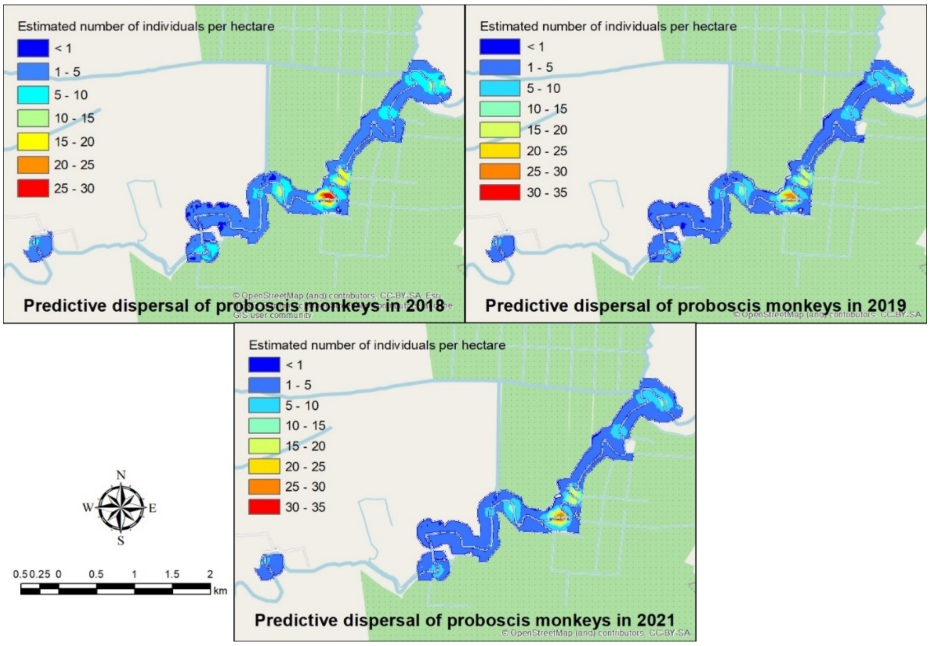

Figure 8. Predictive proboscis monkey dispersal dynamics in 2018, 2019, and 2021 in the Tabunio Watershed riparian zone

situation was observed in Balikpapan Bay, East Kalimantan, where the proboscis monkey population faces significant anthropogenic threats (Toulec et al., 2022). To ensure the long-term survival of proboscis monkeys in the Tabunio watershed's riparian zone, it is essential to implement conservation measures, such as establishing a dedicated conservation area for the species.

Further examination of the data in Table 4 reveals that the prediction error for the number of proboscis monkeys in 2021 is 13.5% when compared to the total number of proboscis monkeys observed during field surveys (as presented in Table 1). Table 4 also shows a decrease in the standard deviation of proboscis monkey dispersal over time. A reduction in the standard deviation indicates a decrease in the variation of dispersal, suggesting that the movement of proboscis monkeys across their habitat has become less diverse. In other words, a lower standard deviation implies a more homogeneous distribution of the proboscis monkey population, meaning their dispersal is less concentrated in specific areas and is more evenly distributed across the habitat.

The evidence is derived from multiple complementary approaches spanning several years. Machine learning habitat modeling revealed a maximum habitat suitability of only 11.54% across Borneo, with moderate to high predictive performance (AUC values of 74-90%) (Sakti et al., 2024). However, a decade-long population monitoring study (2007-2017) of Balikpapan Bay found no evidence of predicted population decline, despite El Niño-induced fires, with a density of 1.14 groups per km² (Toulec et al., 2022). A comprehensive 2022 census identified 359 groups, totaling 3,907 individuals, with habitat loss slowing to 0.69% annually, and potential recovery predicted within 13 years (Atmoko et al., 2024). Dispersal analysis revealed a multilevel patrilineal society where males migrate shorter distances than females (Matsuda et al., 2023). The studies suggest populations may be approaching resilience

Table 4. Predictive proboscis monkey's habitat and dispersal dynamics

Years	Habitat Area (hectares)	Average number per hectare	Standard deviation of the number per hectare	Predicted total number of proboscis monkeys
2018	5,470.79	9.45	0.2685	590
2019	5,405.88	9.24	0.2675	577
2021	5,331.19	8.91	0.2570	557

Source: Primary data from geospatial analysis results

limits despite current stability.

Although the visual difference appears minimal, Figure 8 clearly illustrates that the red area, which represents the centre of proboscis monkey dispersal concentration, gradually diminishes over time. This fading suggests a decrease in the number of proboscis monkeys that were once abundant in this area. From this observation, it can be inferred that the region previously hosted a larger population of proboscis monkeys, but they have since dispersed. Since the dispersal prediction model is based on Canopy Chlorophyll Concentration (CCC), the reduction in proboscis monkey concentration within the red area can be attributed to a decline in chlorophyll levels, which reflects a decrease in the health of the vegetation in that location.

In this research, we describe the general condition of the proboscis monkey habitat without observing specific parts of it. This allows for further studies to identify the presence of extreme habitats used by proboscis monkeys. This includes the impact of habitat change and development, as well as how these wildlife species might adapt in the future. This requires a more comprehensive field study. This research also did not specifically examine the age variable of the proboscis monkeys. For the development of more complex models in future research, the age composition of the proboscis monkeys could be presented comprehensively if data are available in the field. This includes the influence of proboscis monkey age composition on habitat change.

CONCLUSION

The ongoing rapid development within the Tabunio watershed has resulted in a reduction of the potential habitat area for proboscis monkeys in the region. This has been accompanied by a decline in the proboscis monkey population, particularly within the riparian zone of the watershed. Due to the short time interval of the dynamic analysis, changes in road infrastructure were disregarded or assumed to be constant in this study. Therefore, the observed decrease in habitat area and the dispersal of proboscis monkeys can be primarily attributed to the expansion of human settlements. To safeguard the survival of proboscis monkeys, especially in the riparian zone, it is recommended that a conservation area be established to protect their habitat. The findings also highlight a significant correlation between the dispersal of proboscis monkeys and the abundance of healthy vegetation, as evidenced by the strong relationship between monkey dispersal and canopy chlorophyll concentration.

AUTHOR CONTRIBUTION

The study and initiated the work: **A.F.** Conceived and designed the research: **A.F., R.K., S.** Carried out field work: **A.F., R.K., S., A.A.R., S.** Analysed the data: **A.F., R.K., S.** Wrote the paper: **A.F., R.K., A.A.R., S, Y.N.S.** All authors revised and approved the final version.

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CONFLICT OF INTEREST

The authors affirm that they hold no financial interests or personal affiliations that could affect, or be perceived to influence, the findings and conclusions presented in this article.

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