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Mapping habitat suitability and connectivity for the Sunda clouded leopard (*Neofelis diardi*) in Batutegi Protected Forest, Lampung, Indonesia

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Abstract. *Malik HN, Rahman DA, Setiawan Y, Huda R. 2024. Mapping habitat suitability and connectivity for the Sunda clouded leopard (*Neofelis diardi*) in Batutegi Protected Forest, Lampung, Indonesia. Biodiversitas 25: 2249-2256.* One of the rarest and least understood species of carnivore, the Sunda clouded leopard (*Neofelis diardi* Cuvier, 1823), is facing considerable threats from continued habitat loss and fragmentation. The Batutegi Protected Forest, Lampung, Indonesia, which was recently identified as an existing but isolated habitat of this vulnerable felid, is also experiencing fragmentation and encroachment. These combined threats have led to a reduction in the availability of suitable habitats for this isolated population and created barriers restricting its movement between forested areas. Understanding the factors that influence habitat selection and developing ecological corridors to improve its connectivity is critical to the conservation of the Sunda clouded leopard in Batutegi Protected Forest. We examined camera trap data and used maximum entropy modeling to construct a habitat suitability map, which was used to develop the resistance surface. We then performed habitat connectivity analysis using least-cost modeling. Our results indicated that there was a moderate potential in some areas of the study region to support the occurrence of Sunda clouded leopard, whose presence was mainly driven by the presence of forested landscapes and higher elevations. The predicted connectivity network revealed that the most suitable corridor could facilitate the movement of Sunda clouded leopards between forested areas by avoiding the monoculture plantations and mainly crossing through a matrix of forested patches and mixed plantation areas. This study contributes important insights to assisting in the prioritization of habitat conservation for the protection of Sunda clouded leopard and overall forest biodiversity due to its capacity as an umbrella species.

Keywords: Batutegi Protected Forest, ecological corridor, habitat suitability, Sunda clouded leopard, umbrella species

INTRODUCTION

The Sunda clouded leopard (*Neofelis diardi* Cuvier, 1823) is an endemic pantherine felid that occurs on the islands of Borneo and Sumatra. It is categorized as Vulnerable on the IUCN Red List (Hearn et al. 2015), and is one of the rarest and least understood of all carnivore species (Sollmann et al. 2014; Hearn et al. 2016). In Borneo, this felid is the top apex predator (Macdonald et al. 2018b) and is considered a charismatic species that has the potential to act as a flagship for broader biodiversity conservation in Borneo (Macdonald et al. 2015). In Sumatra, by comparison, a larger predator exists, namely, the Sumatran tiger (*Panthera tigris sumatrae*) and there are numerous other charismatic species such as Sumatran elephant (*Elephas maximus sumatranus*), Sumatran rhino (*Dicerorhinus sumatrensis*), Sumatran orangutan (*Pongo abelii*), and Tapanuli orangutan (*Pongo tapanuliensis*) (Pusparini et al. 2014; Sunarto et al. 2015; Nowak et al. 2023; Rahman et al. 2022). Probably for these reasons, the Sumatran clouded leopard has been studied less intensively than its Bornean counterpart.

The greatest threat the Sunda clouded leopard is facing is habitat loss and fragmentation due to commercial logging and land conversion (Gaveau et al. 2016; Hearn et al. 2016; Cushman et al. 2017). As a forest-dependent species, the Sunda clouded leopard typically avoids non-forest vegetation, particularly areas with limited canopy closure, because its movement is facilitated by forest canopy cover (Hearn et al. 2018; Haidir et al. 2021). In Sumatra, vast areas have been deforested over the last few decades. Driven primarily by agricultural expansion, timber harvesting, and infrastructure development, Sumatra is now the island with the highest deforestation rates in Indonesia (Cochard 2017; Rijal 2019; Kaszta et al. 2024). The reduction of habitat and connectivity caused by these anthropogenic disturbances can affect the genetic diversity and population sizes of Sunda clouded leopards (Macdonald et al. 2018b). Based on the severity of these threats, the Sunda clouded leopard should receive more conservation attention to ensure its sustainability.

The Batutegi Protected Forest in Lampung is home to more than 22 species of mammals, including the endangered Sumatran tiger and the rare Sumatran serow (*Capricornis sumatraensis*) (Huda et al. 2020). This protected forest covers an area of 58.162 ha, with only around 17% of natural forest remaining; the rest is utilized by communities for developing agroforestry and mixed plantations, predominantly coffee, cacao, and pepper (Huda et al. 2018). The remaining natural forest area was gradually fragmented into two isolated areas, which have since become core areas in the protected forest. Despite being core areas, continued deforestation in these areas is inevitable. As a result of higher disturbances in one of the core areas, this area has become much smaller than the other.

A recent study revealed that Sunda clouded leopards existed in both of Batutegi Protected Forest's core areas (Malik and Hernowo 2023), although their existence is highly threatened in the smaller of the two areas due to persistent habitat loss. With their minimum home range size of 16 km^2 (Hearn et al. 2013), providing connectivity between core areas is the solution that could mitigate the fragmentation impact for this felid. Indeed, this increased connectivity could provide conservation benefits not only for the Sunda clouded leopard but for a variety of other terrestrial species present in the Batutegi Protected Forest and could contribute towards improved biodiversity conservation in general. The Sunda clouded leopard represents a decent indicator species to conduct a forest connectivity analysis because of its semi-arboreal nature and key role as an umbrella species (Cheyne et al. 2016; Macdonald et al. 2018a; Kaszta et al. 2024). In addition to habitat connectivity, the characteristic differences between the core areas make a habitat suitability analysis an important exercise in identifying the key environmental variables that influence the distribution of the Sunda clouded leopard.

To address these needs, we modeled habitat suitability using maximum entropy (MaxEnt) distribution modeling. This modeling approach has been commonly used to predict habitat suitability and distributions of Sunda clouded leopards using presence-only data through camera-trapping surveys (McCarthy et al. 2015; Hearn et al. 2016; Haidir et al. 2020; Mohd-Azlan et al. 2023). We then developed the resistance surface based on the habitat suitability model to perform a habitat connectivity analysis using least-cost modeling. This study undertakes the first habitat connectivity analysis of Batutegi Protected Forest and maps the linkages between the core areas. Considering forest utilization by the community, these results provide useful information not only for future biodiversity conservation development but also for sustainable forest utilization strategies by the community in the area.

MATERIALS AND METHODS

Study area

This study was conducted in Batutegi Protected Forest (104º 27' - 104º 54' East, 5º 5' - 5º 22' South), a tropical forest located in Tanggamus District, Lampung Province, Indonesia. Specifically, we surveyed the two remaining core areas of natural forest with the Batutegi Protected Forest area (Figure 1). Way Sekampung is a core area located in the northern part of the Protected Forest comprising a mix of lowland (0-300 m asl) and upland (300-800 m asl) forests. This core zone serves as a water catchment for the Batutegi Dam. The other core area is Batulima, located in the southern part of the Protected Forest, characterized by a sub-montane (800-1900 m asl) forest. Batulima is a smaller core zone compared to Way Sekampung.

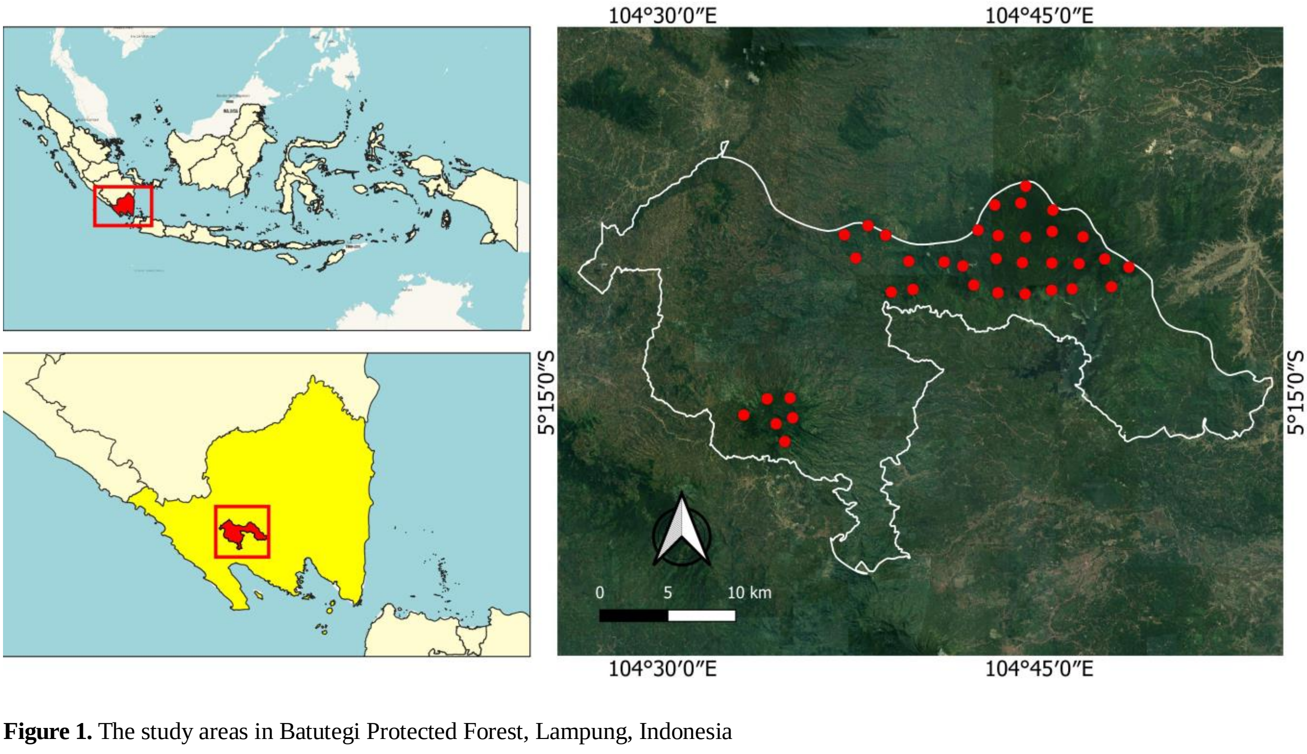

Figure 1. The study areas in Batutegi Protected Forest, Lampung, Indonesia

The environmental diversity of the Batutegi Protected Forest sustains complex animal communities, as demonstrated by the presence of more than 22 mammal species (Huda et al. 2020). The potential competitors to the Sunda clouded leopard, the sun bear (*Helarctos malayanus*) and the Asiatic golden cat (*Catopuma temminckii*) are widespread in both core areas, whereas other sympatric felid species, such as the Sumatran tiger, the marbled cat (*Pardofelis marmorata*) and the leopard cat (*Prionailurus bengalensis*) are present in certain areas. Considering potential prey species, the wild ungulate community includes six species, the wild boar (*Sus scrofa*) and the barking deer (*Muntiacus muntjak*) are the most abundant, followed by the sambar (*Rusa unicolor*) and the greater mouse-deer (*Tragulus napu*), whereas the Sumatran serow and the Malay tapir (*Tapirus indicus*) are the rarest. Moreover, the protected forest hosts a widespread community of small mammal species from Sciuridae, Muridae, Soricidae, and Tupaiidae families.

Data collection

Over an 11-month period from February 2022 to January 2023, covering both dry and wet seasons, we monitored Sunda clouded leopard presence using camera-trapping surveys. We used 36 camera traps (Bushnell Trophy Cam Model 119678C) in both Way Sekampung (n=30) and Batulima (n=6). Cameras were set in an existing 2 × 2 km grid formation designed for the Sumatran tiger camera-trapping survey with approximately equal distances between trap locations (1.5-2 km). Cameras were placed in covered forested areas with varied canopy closure levels using a stratified sampling design. Positions of the camera were determined by the most common path taken by animals (approximately 1.5 m) based on animal tracks found in the vicinity of the placement location. Each camera was secured to a tree trunk at a height of 50 cm so that the camera would be triggered by medium-sized mammals such as the Sunda clouded leopard. We set each camera to take three burst shots when triggered, followed by a period of ten seconds before the next trigger. Cameras were regularly checked every two months for battery and memory card replacement.

Data analysis

Habitat suitability analysis

The habitat suitability analysis was conducted using occurrence coordinates (presence data only) of Sunda clouded leopards, which were pooled and overlain with GIS layers comprising environmental variables to assess habitat preference. Based on previous studies related to habitat suitability analysis of the Sunda clouded leopard, we identified eight candidate environmental variables to be used as GIS layers for the habitat suitability analysis. The primary variables were elevation, slope, land cover, distance to forest edge, distance to nearest water source, and percent forest cover (McCarthy et al. 2015). To account for anthropogenic impacts, we included distance to the nearest settlement (Haidir et al. 2020) and forest fragmentation (Macdonald et al. 2018a). We used Landsat 8 imagery as the data source to generate land cover data which was downloaded from http://earthexplorer.usgs.gov with the acquisition date of July 2022. The elevation data were obtained from a digitalized elevation model (DEM) with 5 meters resolution and data records for rivers were obtained from Indonesia's Terrain Database RBI (*Rupa Bumi Indonesia*). Both DEM and RBI were downloaded from http://tanahair.indonesia.go.id.

We performed the environmental variable processing in ArcMap 10.8. Land cover data were obtained from supervised classification on Landsat 8 imagery. We divided land cover into five categories (forest, non-forest vegetation, bare land, settlement, and waterbody). For the variables distance to the forest edge and distance to the nearest settlement, we used Euclidean Distance Tool on forest and settlement classes from land cover data. For the variable distance to a water source, waterbody class from land cover data and rivers data from RBI were merged before measuring Euclidean distance. The variable elevation, which had been obtained from reclassifying DEM data, was then used for determining the variable of slope using the Slope Tool. We calculated a landscape metric Mean Patch Size (MPS) on land cover data as an approach to determine forest fragmentation using Spatial Statistic from Patch Analyst, an extension for ArcGIS. For the variable percent forest cover, we used the Forest Density Canopy (FCD) algorithm (Rikimaru et al. 2002), on Landsat 8 imagery.

To test for correlation among variables, multicollinearity test was performed using band collection statistics tool, we eliminated the pair from the data set when a pair of variables had a correlation value >0.5 (McCarthy et al. 2015). This resulted in a final data set consisting of six variables without variables of land cover and percent of forest cover. We modeled habitat suitability for Sunda clouded leopards using MaxEnt 3.4.4. The sample input consisted of Sunda clouded leopard detection records, and the environmental layers consisted of all environmental variables, as well as a spatial mask layer that restricted the analyses to Batutegi Protected Forest. All environmental variables were continuous. We chose the logistic format for the output and checked "auto features" for the program run. This output format is easier to interpret than other output formats, it can be interpreted as estimating a species probability of presence, conditioned on environmental variables (Phillips and Dudik 2008). For settings, we set the random test at 25%, replicates at 50, iterations at 5000, and chose a subsample for the replicated run type. We calculated the relative contribution and permutation importance of environmental variables to determine important variables for the model, this calculation was an average of over 50 replicates.

Habitat connectivity analysis

We modeled connectivity between the core areas currently occupied by Sunda clouded leopards in Batutegi Protected Forest using least-cost modeling. Least-cost modeling has the objective of predicting movement between locations while considering the influence of the landscape. In that case, the landscape is represented as a cost surface, where a high cost is considered highly resistant to movement (Marrotte and Bowman 2017). We performed least-cost modeling in Linkage Mapper, an ArcGIS extension tool designed to support regional analyses of wildlife habitat connectivity (McRae and Kavanagh 2011). The input data required by Linkage Mapper are maps of core habitat patches and resistance surface raster layers used to identify and map linkages between core habitat patches. For maps of core habitat patches, we used forest class from land cover data, which represented the core areas in the protected forest. Due to the different sizes between core areas, we divided the larger core area into six smaller areas based on the presence of Sunda clouded leopards so that alternative corridors could be generated.

To develop the resistance surface layer, we used habitat suitability model because habitat suitability models have proven to be useful alternative data to parameterize resistance maps for wildlife habitat connectivity analyses (Stevenson-Holt et al. 2014; Liu et al. 2018; Torretta et al. 2020). We reclassified the habitat suitability map using its 10th percentile training presence logistic threshold value as the minimum value for moderate resistance, higher values from the threshold would be categorized as lower resistance, and vice versa. This change was conducted because the 10th percentile training presence logistic threshold could be used to distinguish unsuitable (high resistance) from suitable (low resistance) areas (Urbani et al. 2015). We calculated the least-cost path using cost-weighted and Euclidean network adjacency methods and the nearest neighbor measurement unit in Euclidean distance and trimmed the network to four connected nearest neighbor core areas.

RESULTS AND DISCUSSION

Habitat suitability

A total of 36 different camera locations were used within the protected forest's core areas over the sampling period, and cameras were deployed for 7256 trap nights. This resulted in 16 photographic events of Sunda clouded leopards (0.22 photo events/100 trap nights). The model showed an excellent performance in predicting habitat suitability for Sunda clouded leopard (AUC = 0.902). To better understand the difference in results between core areas, we reclassified the final model into unsuitable, low, moderate, and high suitability of habitat. The prediction map revealed that the most suitable area for Sunda clouded leopard proportionally was located in Batulima with a 35.7% high suitability area, higher than the high suitability area percentage in Way Sekampung with 15.3% (Figure 2). Overall, the results indicated a moderate potential that large parts of the two core areas could support the occurrence of Sunda clouded leopards. The relative contribution and permutation importance of environmental variables showed that distance to forest edge, elevation, and slope were consecutively the first, second, and third most important explanatory variables to the Sunda clouded leopard habitat suitability model (Table 1).

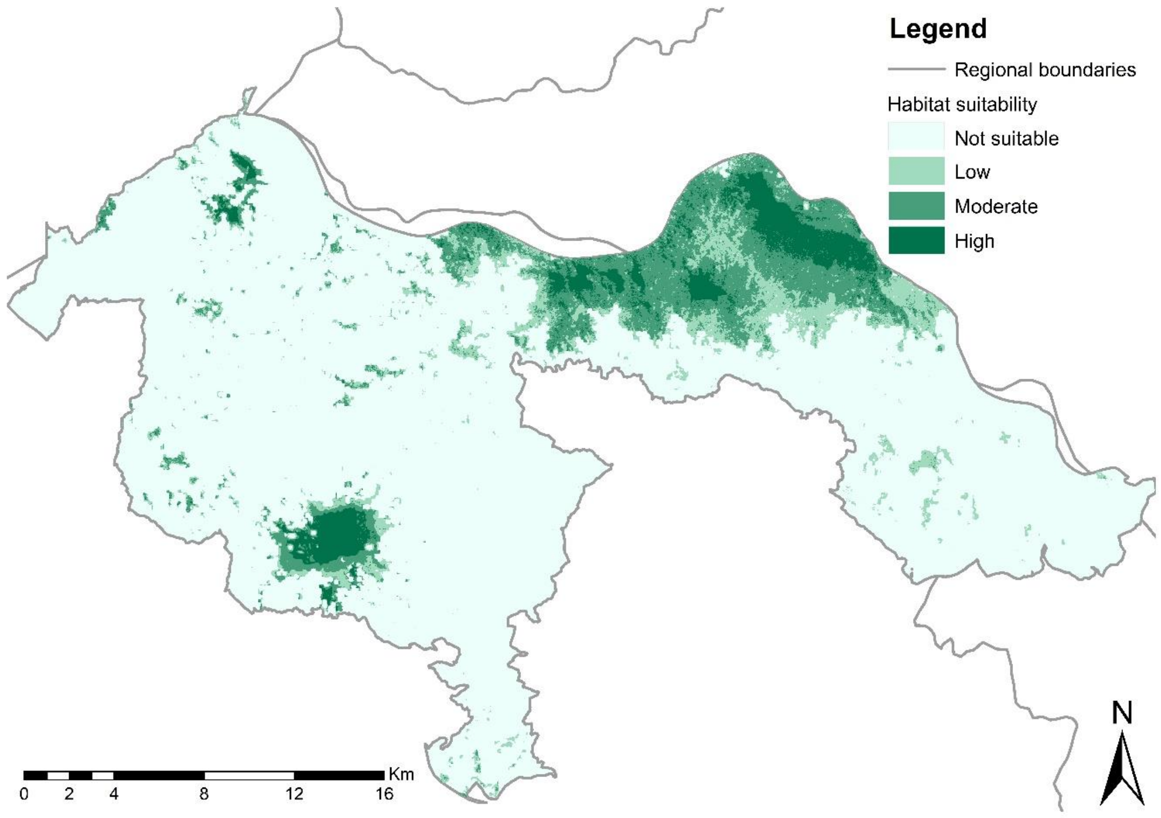

Figure 1. Predicted habitat suitability map for the Sunda clouded leopard in Batutegi Protected Forest, Lampung, Indonesia

The Sunda clouded leopard appears to inhabit deeper areas of the forest, which was indicated by the increased occurrence probability calculated at greater distances from the forest edge. Elevation and slope were variables with positive effects on the probability of the occurrence of Sunda clouded leopard. This is in line with other studies, which reported that the Sunda clouded leopard has a positive association with forested landscapes and higher elevation ridgeline areas (Pusparini et al. 2014; McCarthy et al. 2015; Hearn et al. 2016; Mohd-Azlan et al. 2023). Due to its relatively large home range, the Sunda clouded leopard also prefers larger areas of forest and avoids fragmented forest patches (Macdonald et al. 2018b). Our data showed that this felid's occurrence probability was negatively affected by forest fragmentation. As an elusive species, the Sunda clouded leopard avoids anthropogenic disturbance (Macdonald et al. 2018a) and this was corroborated by the increased occurrence probability yielded with greater distances from settlements and water sources. The main water source in Batutegi was the reservoir, which is a key resource used regularly by the community and may be why the Sunda clouded leopard avoids this area.

We assumed that the habitat use of the Sunda clouded leopard was affected by the presence of the Sumatran tiger, specifically in Way Sekampung, where this apex predator exists (Huda et al. 2018; Huda et al. 2020). Indeed, based on evidence from our camera-trapping survey, the occurrence probability of the Sunda clouded leopard in Way Sekampung was less than the occurrence probability in Batulima. While the Sumatran tiger has a preference for lower elevation landscapes and areas near lakes or rivers (Priatna 2020; Sulistiyono et al. 2021; Pudyatmoko et al. 2023), smaller felids such as the Sunda clouded leopard, typically inhabit forests at higher elevations and areas with greater distances from lakes or rivers. The presence of a larger predator could force a smaller predator to become more arboreal and hence less frequently camera-trapped (Singh and Macdonald 2017). We were unable to address any details of spatial and temporal differences between these two species since the Sumatran tiger was not our focal species. However, considering that these pantherine felids occupy a habitat sympatrically, they will ecologically use different niches specifically in their foraging.

Habitat connectivity

The map of predicted corridors was produced by calculating the least-cost path based on the resistance surfaces obtained from the habitat suitability map. The results showed a gradient of connecting paths between the two core areas in Batutegi Protected Forest (Figure 2). The corridor's suitability was based on the cost-weighted distance (Table 2), where the most suitable corridor for connecting the Sunda clouded leopard habitat is the corridor with the lowest cost-weighted distance (dark green). This corridor ran between the two core areas and connected both by crossing forest patches and mixed plantations, and on occasion monoculture plantations. The second most suitable corridor (light green) also connected core areas, but this one crossed more areas of monoculture plantations. The two other corridors (orange and red) connected core areas by sharing the main path with the most suitable corridor.

Besides the cost-weighted distance, the length of the corridors was another important dimension used to identify the most supportive corridor for animal movements (Brodie et al. 2015). Among the four potential corridors, the most suitable corridor was the second shortest corridor in length, whereas the second most suitable corridor was the shortest corridor. However, the differences in length between the two corridors were insignificant and so the most suitable corridor for the Sunda clouded leopard remained unchanged. Based on these results, the second most suitable corridor identified could also be considered as an alternative option in the strategy of habitat connectivity development.

Our goal was to assess the relative effectiveness of different connectivity scenarios in facilitating the movement of the Sunda clouded leopard between two core habitats. Landscape cost for this felid was closely linked to forest cover as the forest became the most important explanatory variable to model its habitat suitability. The Sunda clouded leopard's movement is facilitated by forest cover, including areas of disturbed forest, as long as there is high canopy closure (Hearn et al. 2018). This may be closely related to the foraging behavior of the Sunda clouded leopard, which is generally carried out on trees. Thus, this felid is very dependent on the existence of natural forests in its search for prey. In our study area, we identified the low canopy closure areas. These areas became the highest resistance for the Sunda clouded leopard and consisted of the monoculture plantations with coffee as the main crop. The mixed plantations provided higher canopy closure due to the presence of overstory tree species such as tiger's claw tree or *dadap* (*Erythrina variegata*), *kapok* tree (*Ceiba pentandra*), and Siamese cassia or *johar* (*Senna siamea*) which were growing among the agricultural crops (Putraditama et al. 2021). This condition was similar to the disturbed forest described by Hearn et al. (2018), whereby even a highly disturbed forest could still facilitate the movement of the Sunda clouded leopard despite having open canopy cover.

Table 1. The relative contribution (RC) and permutation importance (PI) of each environmental variable for Sunda clouded leopard habitat suitability model

Environmental variable	RC	PI
Distance to forest edge	53.6	72.9
Forest fragmentation	27.5	1.7
Elevation	10.4	13.7
Distance to water source	5.4	2.4
Slope	2.6	9.2
Distance to settlement	0.5	0.1

Table 2. The cost-weighted distance (CWD) and corridor length of each potential corridor to connect the habitat of Sunda clouded leopard

Corridor suitability	CWD	Length (km)
High	5392	10
Moderate	5565	9.8
Low	5600	10.5
Very low	5698	10.7

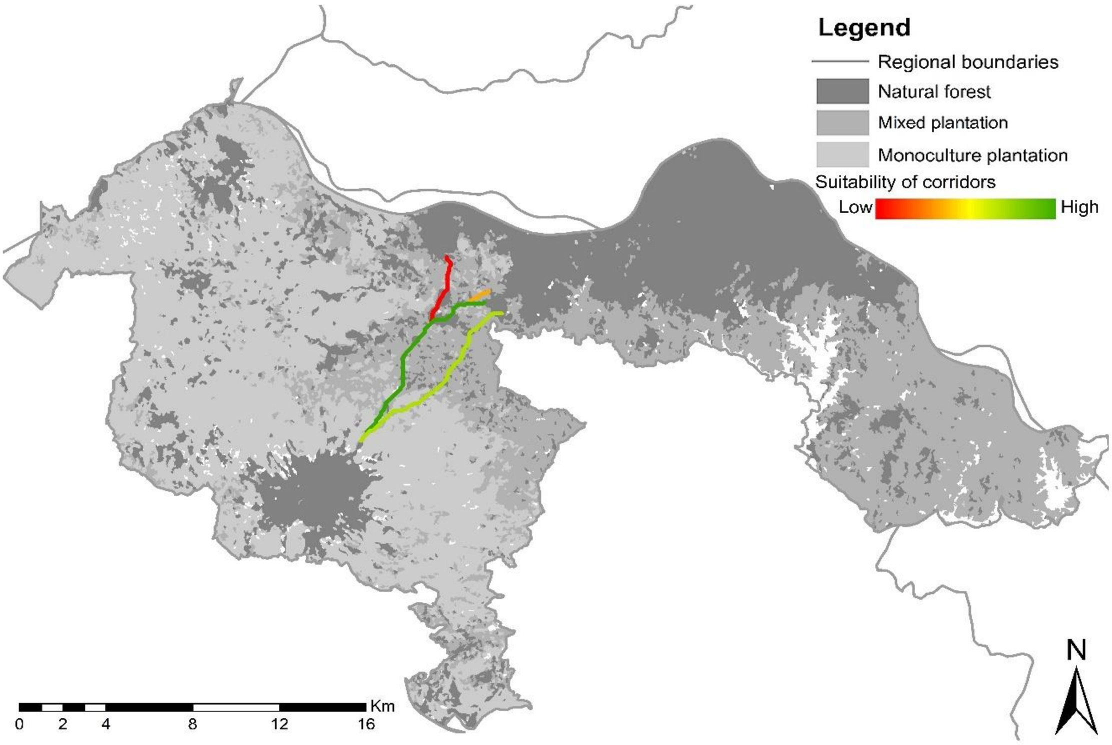

Figure 2. Predicted corridors to connect the habitat of the Sunda clouded leopard in Batutegi Protected Forest, Lampung, Indonesia

Conservation implications

The results of this study have important implications for the conservation of Sunda clouded leopards in Batutegi Protected Forest. Protection of both suitable areas and movement-facilitating corridors comprise typical conservation measures for medium-sized carnivores (Khosravi et al. 2018; Torretta et al. 2020). Fragmented and shrinking habitats increase species vulnerability, which might result in local extinctions and a decrease in the global population. Accordingly, the Sunda clouded leopard conservation in Batutegi Protected Forest should focus on both conserving the core areas and ensuring that cultivated areas become increasingly heterogeneous to provide more permeable corridors. Such heterogeneously vegetated landscapes could strengthen the effectiveness of the existing ecological networks and create new colonization routes (Dondina et al. 2018).

Cultivated areas in Batutegi Protected Forest are located in the utilization area and managed by community-based forest schemes that allow the community to cultivate the land for economic benefit. All of the land cultivation, therefore, should be based on an agroforestry system to ensure that the area can still provide a range of different ecosystem services. In fact, some cultivation practices have still not adopted the agroforestry system and have become monoculture plantations instead, specifically for coffee cultivation. One potential reason for the need for more adoption of the agroforestry system by some farmers is that the common hardwood timber and overstory trees in the area are believed to decrease coffee productivity (Putraditama et al. 2021). We suggest using other overstory species that not only provide shade for the coffee but can provide another benefit for the community. Other studies have reported that certain tree species can be successfully grown along with coffee crops. Tree species such as silk tree or sengon (*Albizia chinensis*), acacia (*Acacia* sp.), white lead tree or lamtoro (*Leucaena leucocephala*), calliandra (*Calliandra calothyrsus*), and rubber tree (*Hevea brasiliensis*) are commonly used shade trees for coffee plants in agroforestry systems due to their capacity to increase soil fertility and improve nutrient cycles and their ability to increase coffee cherry productivity (Worku et al. 2015; Wu et al. 2016; Lisnawati et al. 2017). The proper implementation of a coffee agroforestry system could provide additional economic benefits and create wildlife refuges at the same time (Campera et al. 2021; Imron et al. 2022). The sustainable land utilization of the community in Batutegi would also help to preserve the overall health and condition of the land. Ultimately, the adoption of a decent agroforestry system in Batutegi would lead to the improvement of a Protected Forest's primary function, including the protection of water resources and the reduction of the risks of floods and erosion impacts, which would be the main concern for the management authority.

The implications of this study extend beyond single-species conservation. Due to the Sunda clouded leopard's semi-arboreal nature and relatively large home range, the prediction models used in this study that were parameterized specifically to this species are also likely to be relevant to other medium-sized forest dependent carnivores such as the sun bear (*Helarctos malayanus*) (Macdonald et al. 2018b), small carnivores such as banded palm civet (*Hemigalus derbyanus*) (Brodie et al. 2015), and smaller sympatric felids that may have similar dispersal distances and habitat associations. In addition to medium and small-sized carnivores, primates may also have relevance to this ecological-based study because felids and primates essentially face the same threats and may benefit from many of the same solutions (Macdonald et al. 2013).

Batutegi Protected Forest is a habitat for many species of primates such as siamang gibbon (*Symphalangus syndactylus*), pig-tailed macaque (*Macaca nemestrina*), long-tailed macaque (*Macaca fascicularis*), southern mitered langur (*Presbytis mitrata*), greater slow loris (*Nycticebus coucang*) and silvery lutung (*Trachypithecus cristatus*) (Huda et al. 2020). This site has also been used as a release site for slow lorises rescued from the pet trade (Moore et al. 2014). Therefore, it is important to conserve this habitat and its biodiversity. We hope that our study can become a reference for initiating habitat improvement efforts that can broaden the suitable core areas to facilitate species movements and fulfill the release site requirements for slow lorises and other species.

The most important conservation message from this study is that clouded leopards are associated with forested landscapes and higher elevations and are negatively impacted by forest fragmentation and plantation areas. In short, deforestation and subsequent conversion to plantations are major threats to this felid. The protection of the remaining core areas with high forest cover should be the priority simultaneously, with a focus on improving the quality of connectivity corridors between core areas. Accordingly, the conservation in Batutegi Protected Forest should focus on both conserving natural areas and making cultivated areas more heterogeneous to originate alternative permeable paths to strengthen the effectiveness of the existing ecological corridors.

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