



## Original research article

# Connecting the fragmented habitat of endangered mammals in the landscape of Riau–Jambi–Sumatera Barat (RIMBA), central Sumatra, Indonesia (connecting the fragmented habitat due to road development)



Barano Siswa Sulistyawan<sup>a,b,e,\*</sup>, Bradley A. Eichelberger<sup>c</sup>, Pita Verweij<sup>a</sup>,  
Rene' G.A. Boot<sup>a</sup>, Oki Hardian<sup>b</sup>, Gemasakti Adzan<sup>b</sup>, Wisnu Sukmantoro<sup>d</sup>

<sup>a</sup> Copernicus Institute of Sustainable Development, Faculty of Geosciences, Utrecht University, Netherlands

<sup>b</sup> WWF Indonesia, Gedung Graha Simatupang, Tower 2 unit C Lt. 7 – 11, Jl. Letjen. TB. Simatupang, Jakarta Selatan, Indonesia

<sup>c</sup> Department of Lands and Natural Resources, Division of Fish and Wildlife, Commonwealth of the Northern Mariana Islands, P.O. Box 10007, Saipan, MP 96950, Northern Mariana Islands

<sup>d</sup> WWF Indonesia, Riau Office, Indonesia

<sup>e</sup> Sustainable Rural & Regional Development - Forum Indonesia, Indonesia

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## ABSTRACT

The trend of wildlife habitat fragmentation worldwide continues as a result of anthropogenic activities on development of a linear infrastructure and land use changes, which is often implemented as part of spatial planning policies. In this paper we expand upon an existing approach to design wildlife corridors through habitat quality assessment. We used models of Habitat Quality of Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) and Corridor Design tools. The habitat quality model of InVEST provides a rapid approach to assess status and change of biodiversity, and can contribute to enhanced corridor design of fragmented wildlife habitat. We conducted an assessment of habitat quality of the RIMBA corridor landscape, which is part of Riau, Jambi and West Sumatra provinces of central Sumatra Island. The result of the habitat quality model was used as the main input to evaluate habitat connectivity and assess the target segment of roads that cross the modelled corridor. We found 20 wildland blocks, the total area of the corridor modelled including wildland blocks was calculated as about 0.77 million hectares. We have obtained accurate quantitative measurement of the length of roads crossing the corridor, with a total of 417.78 km (artery 10.31 km; collector 19.52 km; and local 1987.9 km roads). This method can be replicated as an approach in valuing the quality of habitat as part of the implementation of the presidential decree of Sumatra Island Spatial Planning. This may also be applied to the spatial planning of other major islands in Indonesia and elsewhere.

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\* Correspondence to: Graha Simatupang, Tower 2 Unit C, 7th–11th Floor, Jalan Letjen T.B. Simatupang, Jakarta - 12540, Indonesia. Copernicus Institute of Sustainable Development, Faculty of Geosciences, Utrecht University, Willem C. van Nunnikgebouw, Heidelberglaan 2, Room 910, 3584 CS UTRECHT, The Netherlands.

E-mail addresses: [b.s.sulistyawan@uu.nl](mailto:b.s.sulistyawan@uu.nl), [tbarano@wwf.id](mailto:tbarano@wwf.id) (B.S. Sulistyawan).

## 1. Introduction

The impact of anthropogenic activities on land use worldwide includes accelerated deforestation and habitat fragmentation caused by conversion for other land use purposes and infrastructure development, further contributing to declining local biodiversity (Newbold et al., 2015). A global study on road impact showed that considering the location of human and environmental systems such as agricultural areas and natural forest when developing roads can help to avoid environmental costs of habitat fragmentation and maximize the human benefit from roads, especially in the case of agriculture (Laurance et al., 2014). However, further effort is required to conduct these types of analyses at the national and sub-national level—especially in high biodiversity areas like Indonesia and Madagascar. This will help define optimal strategies for road zone development, including improving cost effectiveness of road design and networks for countries, provinces and districts (Laurance et al., 2014; Mustapha et al., 2012).

Efforts to rehabilitate the connectivity of habitats are strategically conducted from region to local levels. Habitat connectivity maintains the home range of viable populations, and provides the opportunity for enhanced genetic flow of plants and wildlife. Reviews of habitat connectivity from different regions (such as Europe, Latin America, Asia, the Pacific, and Africa) conclude that conservation planning approaches improve preservation of biodiversity at the level of ecosystem, eco-region, and landscape. Moreover, the habitat connectivity approach can be integrated into regional development plans; this would change the paradigm from current protected areas “as islands” to analysing connectivity as a network system and a part of local, national, regional and international systems (Bennett and Mulongoy, 2006). Furthermore, several studies have used this lens to emphasize the impact of construction – including roads, railways, and other linear infrastructure—at the local level on wildlife habitat, such as birds and large mammals, including deer in California and Arizona (Beier et al., 2006), jaguars in Mexico (Colchero et al., 2011) and pandas in China (Wang et al., 2014). According to the existing literature, several ways exist to restore fragmented habitats, including forest restoration (Bhagabati et al., 2014) and by creating artificial connectivity (Liu et al., 2005), such as animal bridges or eco-road construction. The idea of eco-roads is to replace conventional road construction, which includes tactics like cut off mountains and filling valleys. Eco-roads involve adopting the ecological principle of connectivity—in essence, the road is not a barrier, but it can allow movement of animals from one side to the other without an accident and minimize human disturbance (Morelli et al., 2014; Wang et al., 2014; Corlatti et al., 2009; Beier et al., 2006).

The main challenge of biodiversity conservation efforts is maintaining habitat quality and connectivity in the face of anthropogenic disturbance (Wang et al., 2014). Road development can be a main factor in triggering a snowball effect of habitat degradation. Several studies have demonstrated the negative impact of roads, such as habitat loss due to conversion, increased human disturbance including encroachment due to ease of access, mortality caused by traffic accidents, and roads acting as barriers to species movement) (Morelli et al., 2014; Basille et al., 2013; Gaveau et al., 2009). Therefore, crossings for animals are required to reduce accidents, including ecoducts (wildlife bridges) and tunnels (Beben, 2012; Bennett and Mulongoy, 2006). Although road network density in Indonesia is low compared to China, India, Malaysia, Thailand and the Philippines, the investment for road development is still growing, which is expected to continue in the future. The total of the current road network (km) distribution in Indonesia is 60% in Sumatra and Java Islands. Sumatra has the highest road network density compared with major island groups in Indonesia (Java-Bali, Kalimantan, Sulawesi, Maluku, Papua and Nusa Tenggara) (Mustapha et al., 2012).

In Indonesia, many conservation areas are inclined to be discrete locations, and there is poor access to connect one location to another due to linear infrastructure, mainly roads development. Although there are efforts to avoid deforestation and fragmentation, these are not sufficient to prevent the tendency towards isolated protected areas in a matrix of road networks. Furthermore, local strategies to determine scenarios for sustainable land use and eco-friendly infrastructure development for preserving biodiversity and connectivity of wildlife habitat are unclear. A comprehensive study on forest cover loss mapping in Indonesia estimated 6 million ha (hectare) of primary forest loss from 2010 to 2012, and in Sumatra about 2.86 million ha (Margono et al., 2014). One consequence of this deforestation is that species dispersal ability can be disturbed, which negatively affects gene flow (Leblond et al., 2013; Proctor et al., 2012).

The importance of the island of Sumatra is highlighted by its classification as a priority place of global biodiversity. The 2015 Global Living Planet Report released by World Wildlife Fund (WWF) mentions that infrastructure development is projected to be one of the drivers of future deforestation in Sumatra. Therefore, road development should be designed to properly reduce deforestation risk and the resulting threats to remaining biodiversity areas and habitat connectivity (Taylor et al., 2015). Because Sumatra faces these multiple challenges of deforestation and other forms of anthropogenic disturbance but currently has a primarily isolated protected area network, it is crucial to promote novel approaches for regional development that are effective in minimizing the impacts of road and other linear infrastructure on wildlife habitat quality (Laurance et al., 2014; Leblond et al., 2013; Schuster et al., 2013; Pagnucco et al., 2012). To preserve the remaining Sumatra ecosystem, Indonesia's government has developed island spatial planning regulation and recognized corridor ecosystems as critical for connecting protected areas and homeranges for large mammals (such as tigers and elephants) and birds. The corridor RIMBA (Riau, Jambi and Sumatera Barat provinces) has been designated as one of five such corridors within Presidential Decree No 13/2012 in the Sumatra Island spatial plan (article 48). This study can help inform the adjustment of the RIMBA corridor boundary that has been delineated by the provincial government; the corridor boundary has never been previously evaluated.

In this study, we used three models. First, the habitat quality model of integrated valuation of ecosystem services and trade-offs (InVEST), which is a tool to spatially describe habitat sensitivities and threats of anthropogenic disturbance (land

use practices) towards the wildlife habitat. The habitat quality model is one of a group of models to describe and quantify ecosystem services (such as carbon, water yield, sediment retention, and water purification) (Bhagabati et al., 2014). Second, corridor design is a tool that uses cost-distance and habitat suitability to delineate options for effective cost of corridor width between two points (Beier et al., 2008; Menke, 2008). The last is the maximum entropy method, or Maxent tool (Phillips et al., 2006). The purpose of the tool is to predict species distribution based on species environmental conditions where the species is found (Bellamy et al., 2013; Elith et al., 2011; Phillips et al., 2004). We used the tool to evaluate the corridor design modelled result (called a “protected area network”). The key questions of this study are whether the models used are able to (1) describe anthropogenic spatial disturbance and connectivity, and (2) provide guidance for eco-friendly infrastructure development to provide space for wildlife habitats, given the available data.

This study aims to define the quality and suitability of habitat for wildlife movement based on lower cost from threats within and surrounding the corridor RIMBA landscape, through a quantitative approach. Furthermore, the study results provide insight into infrastructure development, especially related to eco-road construction as a component of implementing spatial planning regulation. The study uses suitable models given the data available and the end goal of providing useful results for spatial planning purposes, including InVEST, Corridor Design and Maxent tools.

The approach for this study was conducted in two main processes. First, we assessed habitat quality using the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) tool for the target species' home range that is influenced by anthropogenic disturbance (i.e. artery roads, collector roads, local roads fires and sensitivity towards human activities such as concessions for agriculture plantation and forestry plantation) (Tallis et al., 2011). Then, the habitat quality result was calibrated with HQ model validation. Subsequently, we used the habitat quality result as a main input to analyse habitat connectivity for species movement, through the corridor design (CD) tool (Beier et al., 2006) and ArcGIS 10.2.2. To determine the quality of the protected area network, it was then evaluated to elephant and tiger distribution modelled by maxent (Phillips et al., 2006). For the second process, the protected area network was used to identify the targeted set of road segments that cross the corridor for possible eco-road construction and vegetation rehabilitation. The chosen methods were expected to achieve the research objectives of assessing habitat quality in light of anthropogenic activities, and using the results to improve habitat connectivity and provide recommendations for target segments of road to be developed through eco-road construction.

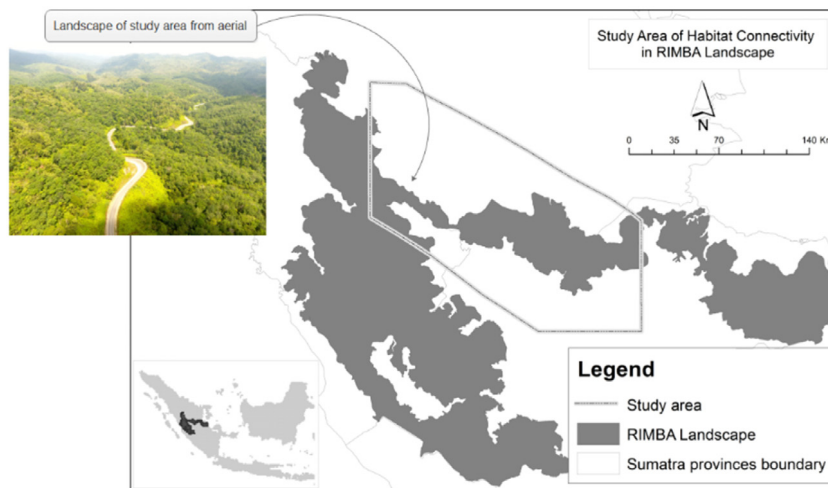
## 2. Methods

### 2.1. Study area

This study was conducted in the central part of Sumatra Island of Indonesia (Fig. 1). The location falls within the borders of three provinces (Riau, Jambi and Sumatra Barat) called Bukit Rimang Baling, Bukit Batabuh and Bukit Tigapuluh of the corridor RIMBA landscape. The shape of corridor RIMBA is delineated by regional planning and development agencies (Badan Perencanaan dan Pembangunan Daerah/ Bappeda) of three provinces, based on a map of Sumatra's spatial planning vision. The vision map was produced by overlaying nine thematic maps at the island level (including 2007 forest cover of Sumatra island, key biodiversity areas, important bird areas, Sumatran rhinos distribution, Sumatran elephants distribution, Sumatran orangutans distribution, Sumatran tigers distribution, Sumatran peat areas distribution and watershed areas) (Roosita et al., 2010; Barano et al., 2008). The width of the study area was about 25,308 km<sup>2</sup>. The climate is part of the tropical wet zone, and the rainfall regime is influenced by the Barisan mountain range. The western side experiences higher rainfall (approximately 6000 mm/year) than the eastern part, which receives about 2500 mm/year. The topography is lowland to undulating. The current land cover and land use is dominated by oil palm plantations, forest plantations and remaining blocks of natural primary and secondary forests. There are two blocks of conservation areas, and one protected forest that is important for large mammal habitat and distribution as inhabitants of the broader RIMBA landscape this includes sumatran elephants (*Elephas maximus* ssp. *sumatranus*) International Union for Conservation of Nature Red List (IUCNRL) - critically endangered, sumatran tigers (*Panthera tigris* ssp. *sumatrae*) IUCNRL - critically endangered, clouded leopards (*Neofelis diardi* ssp. *diardi*) IUCNRL - endangered, tapirs (*Tapirus indicus*) IUCNRL - endangered, malayan sun bears (*Helarctos malayanus*) IUCNRL - vulnerable, sambar deer (*Rusa unicolor*) IUCNRL - vulnerable, pigtailed macaques (*Macaca nemestrina*) IUCNRL - vulnerable, golden cats (*Catopuma temminckii*) IUCNRL - near threatened, barking deer (*Muntiacus muntjak*) IUCNRL - least concern and wild pigs (*Sus scrofa*) IUCNRL - least concern (Sunarto et al., 2012; Wishnu Sukmantoro, 2011) and<sup>1</sup> IUCN red list website.

The condition of the RIMBA landscape is generally fragmented, contributing to isolation of wildlife habitat. The habitat is separated by different levels of anthropogenic disturbances (such as forest conversion and road development). There are several different types of roads in the area, dominated by local, collector and artery roads. The intact forest has mostly been converted into large plantations (such as oil palm, rubber, forest and other agriculture commodities). Land use land cover (LULC) studies have identified the major drivers of deforestation in this region as large scale agriculture, encroachment and small scale agriculture, unsustainable logging, pulp plantations, forest fires and infrastructure (primarily road construction) (Margono et al., 2014; Braimoh et al., 2010).

<sup>1</sup> IUCN website red list: <http://www.iucnredlist.org/> for record the current species status.



**Fig. 1.** The study area in corridor RIMBA landscape, central Sumatra of Indonesia.

**Table 1**

Parameters of threats sources to the wildlife habitat including the maximum distance, weight and decay.

Threat	Max_dist	Weight	Decay
Fire	6	1	Linear
Art	3	0.7	Linear
Clf	1	0.3	Linear
Lcl	5	0.5	Linear

## 2.2. Road classification

Classification of Indonesia's roads system divides roads into three sets of categories, based on a function of the road, administration authority and road capacity. The road functions are generally classified into four levels namely (1) artery, (2) collector, (3) local and (4) neighbourhood/*lingkungan*. In this study we focused on the first three classes (Mustapha et al., 2012).

## 2.3. Assessing habitat quality (HQ) through InVEST tool

The habitat quality model is a function of four factors: each threat's relative impact, the relative sensitivity of each habitat type based on LULC to each threat, the distance between habitat and source of threats, and the degree of land status protection (Tallis et al., 2011). The InVEST Habitat Quality model assesses habitat based on land use and land cover (LULC) data, and relates preferences of species habitat to each class of LULC. Each class of LULC is a proxy for wildlife habitat, and the habitat experiences different levels or intensities of disturbance as a result of anthropogenic activities. An impact of anthropogenic activity on land use is defined as a level of disturbance or threat to the species habitat. The impact of these threats is measured based on values of maximum distances from the source of threats (such as roads, fires, and sensitivity towards human activities such as concessions for agriculture and forestry plantations), weights of the result of the impact, and decays of habitat quality (see Table 1). The table contents were determined based on field observation, experts consultation and literature review (Sunarto et al., 2012; Wishnu Sukmantoro, 2011).

The table threat should be filled properly as a part of the HQ model program requirement and reflect of the context of landscape. For example, the threat column should be given a label with no more than eight characters (such as artery road labelled as Art). The maximum distance (measured in km) over which the habitat is affected by threats is used to calculate the threats influence; the threat impact will reduce gradually to zero at this maximum distance. The value of maximum distance should be bigger than null (0). In this case, we define fire as high for max\_dist, and then local roads, due to intensively used to transport palm oil fruits and timber of forest plantations, followed by artery roads and collector roads. Weightening of threat is the impact of the threat to the habitat quality. The value ranges from 1 (highest impact) to 0 (lowest impact). Fire has a high impact, which we defined with 1, followed by artery roads, local roads and finally collector roads. There are two types of threat decay (i.e. linear and exponential). In this case, we assumed the threat decay is linear. Value 1 indicates linear threat decay, and 0 indicates exponential threat decay (Bhagabati et al., 2014; Tallis et al., 2011).

The level of sensitivity for each habitat to these threats is compiled into a sensitivity table (see Table 2). Each type of disturbance for each habitat type is counted based on references from a large mammal survey report (Tallis et al., 2011).

**Table 2**

The LULC, suitability and sensitivity of wildlife habitat for each type of land use practice in the RIMBA corridor.

No	Name of land use and land cover class	HABITAT suitability	Sensitivity of habitat to threats			
			Forest fire	Artery roads	Collector roads	Local roads
1	Oil palm plantation	0.3	0.5	0	0	0.7
2	Other land use purposes (such as settlement, mining)	0	0	0	0	0.3
3	Pulpwood plantation	0.8	0.7	0	0	0.4
4	Cleared area with some vegetation	0.5	0.2	0	0	0.3
5	Mixed oil palm plantation	0.7	0.5	0	0	0.4
6	Cleared area	0.2	0	0	0	0.9
7	Burnt	0.3	1	0	0	0.5
8	Natural forest	1	1	1	1	0.9
9	Remnant forest	1	1	1	1	0.9
10	Water body	0	0	0	0	0

Habitat preferences were determined by experts and available data from World Wildlife Fund (WWF) Indonesia about the home ranges of umbrella species (such as Sumatran Elephants and Sumatran Tigers).

The parameters of land use and land cover (LULC) classification, suitability and sensitivity (in Table 2) were collected based on spatial data and species information. The first column is the LULC classification. Each LULC class is defined as suitable or not suitable for species habitat due to anthropogenic disturbance. There is a single value of habitat suitability for each LULC class, ranging from 1 (suitable) and 0 (not suitable). In this case, we defined remnant forest and natural forest with high values due to higher suitability for habitat. The remaining LULC values relied on field observation and reports. For example, camera trap reports in the study area provided important insight in terms of where tigers, deers, and pigs are located within different LULC classes, including forest, oil palm, and rubber plantations (Sunarto et al., 2012; Wishnu Sukmanto, 2011). Finally, relative habitat sensitivity of each LULC class to each threat is calculated. Each pixel has a certain sensitivity to each threat, with values ranging from 1 (highest sensitivity) to 0 (lowest sensitivity). Further information on spatial data used is described below.

This study used LULC 2014 data generated from NASA LANDSAT 8 images from 2014, while the LULC map was created by WWF Indonesia. The LULC map consists of ten classes: burned area, cleared area, cleared area with vegetation, mixed oil palm plantation, natural forest, oil palm plantation, other land use purposes (classification for the non-forestry sector e.g. mining, settlement etc.), pulpwood plantation, remnant forest and water body. We classified different distances for road disturbance based on the type of road; for example, artery road causes the highest disturbance compared with collector and local roads (local roads are mostly dirt roads). The road data was collected from the geospatial information agency (previous name is Bakosurtanal). We also collected other data on disturbances to the habitat, such as fires based on hotspots (indicative active fire) data, as well as mining, forest plantation and oil palm concessions. The hotspots data are gathered from MODIS satellite imagery in same period with land cover to check burned scars. The concession maps are produced by the Ministry of Agriculture (for oil palm plantation concessions), the Ministry of Environment and Forestry (for logging and forest plantation concessions), and the Ministry of Energy and Mineral Resources (for mining concession data).

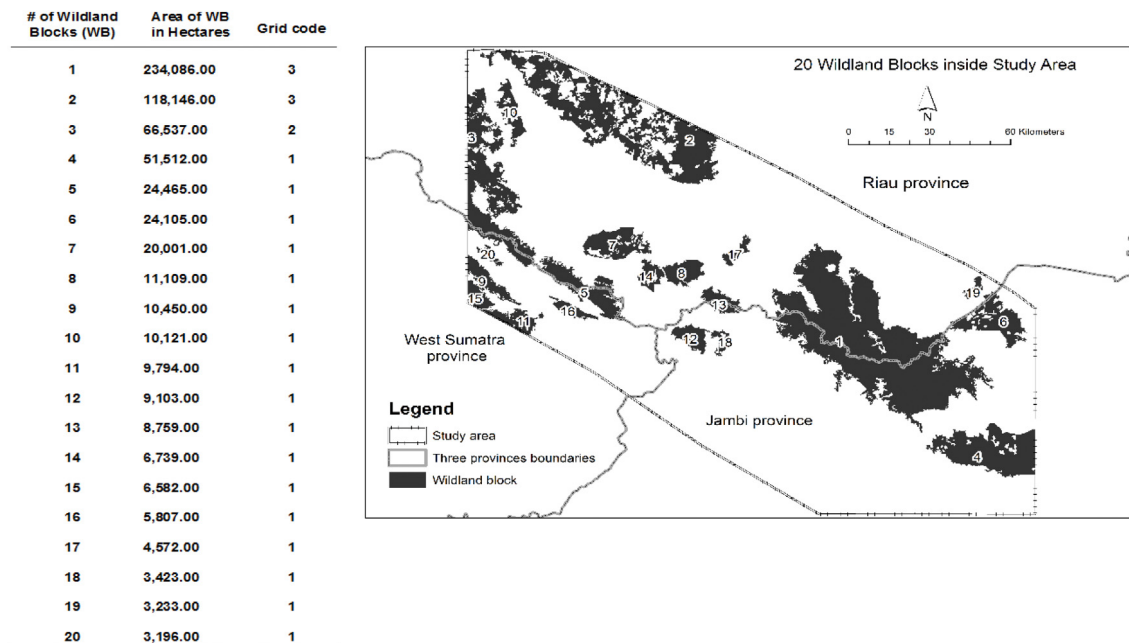
The wildlife habitat preference maps according to types of land use and threats to their habitats were developed from previous species study results on elephants and tigers (Sunarto et al., 2012; Wibisono et al., 2011; Kinnaird et al., 2010; Hedges et al., 2005). We used large mammal as an umbrella species (whose requirements are believed to encapsulate the needs of other species) to indicate representativeness of species home ranges (Lambeck, 1997). The mammal species found in this region have been listed; there were at least 12 large mammal species identified (Sunarto et al., 2012; Wishnu Sukmanto, 2011). Datasets with point observations were only available for Tigers and Elephants.

#### 2.4. Habitat quality (HQ) model validation

The map of Habitat Quality result was validated using Tigers and Elephants field observation data (source: WWF Indonesia) and sensitivity, specificity, true skill statistic (TSS), and area under the receiver operating characteristic curve (AUC) were used to evaluate model performance. Sensitivity is the rate of true positives or correctly classified true presences at a given HQ score. Specificity is the rate of true negatives or correctly classified known absences at a given HQ score. TSS is a measure of model agreement with the evaluation dataset and ranges from 1.0 (perfect agreement) to −1.0 (complete disagreement) (Allouche et al., 2006). AUC represents the probability that a classifier will assign a higher score to a random positive sample than a randomly chosen negative sample, or randomly chosen pseudo-absence. AUC ranges from 0.0 to 1.0, with a score of 1.0 indicating a perfect model, and scores lower than 0.5 indicating a model worse than expected by chance/random. Models with AUC values between 0.9 and 1.0 are considered as excellent, 0.8–0.9 as good, 0.7–0.8 as fair, 0.6–0.7 as poor, and below 0.6 as failed attempts (Swets, 2016).

The analysis of validation used the tool ArcGIS 10.2.2 to extract the pixel value of HQ raster data and then calibrated with HQ model validation (Eichelberger, 2013). Survey results were used to extract the raster values of habitat quality at the same resolution of the habitat quality raster, and known presence points (Tigers  $n = 77,021$ ; Elephants  $n = 475,686$ ) and known





**Fig. 2.** Wildland blocks sizes and grid codes (habitat patch sizes are given numeric codes). Grid code 3 is a potential population patch, 2 is a potential breeding patch and 1 is smaller than a potential breeding patch according to [Majka et al. \(2006\)](#).

absence points (Tigers  $n = 1,328,694$ , Elephants  $n = 2,054,232$ ) were used to calculate the accuracy of the models. The formula to validate habitat quality described in formula (1).

$$TSS = \frac{((TP \times TN) - ((\text{total presences} - TP) \times (\text{total absences} - TN)))}{(\text{total presences} \times \text{total absences})} \quad (1)$$

TP = true positives TN = true negatives total presences = total number of presence points from model input total absences = total number of absence points or pseudo-absences from model input.

## 2.5. Defining habitat connectivity through corridor design tool

The next analysis within this study used the habitat quality results as a layer input to define habitat connectivity based on the corridor design (CD) tool. The corridor design tool requires three steps. First is scoping the target landscape to be connected. The second is developing the habitat suitability model (the value of suitability is between zero and one hundred). The last is defining slices (corridor width) of wildlife pathway to connect one wild block (land expected to remain in a relatively natural condition) to another wild block, to influence species movement or migration ([Vega et al., 2014](#); [Beben, 2012](#); [Beier et al., 2008](#)).

In this study, we start from the second step used the result of habitat quality of InVEST to produce habitat suitability in CD model. Species habitat preference in habitat quality resulted in a range of values: for highest threats or lowest habitat quality the value was zero, and for lowest threats or highest quality for species habitat the value was a one. We normalized the habitat quality value from 0–1 to 0 (bad)–100 (good), to fit the requirements of the CD model. In addition, we assessed the habitat patches to identify wild habitats blocks to be connected to a main habitat block. We selected areas sized above 3000 ha as main wildland blocks to be connected.

The corridor design for habitat connectivity is based on cost distance for each pixel and suitability for species movement. We followed a step by step process to assess habitat suitability, defining the start and end of habitat to be connected and the least cost layer calculation. First, the model calculates the path size based on parameter input. The result of this step is average habitat suitability model using Rectangle  $3 \times 3$  cell neighbourhood. The second process is to find start patch and cores within the wild block 1, and calculate the minimum area for breeding and population size. A similar process is carried out for wild block 2. The next step calculates cost distance (a distance between points that reflects the difficulty of moving between them). The last develops different width of corridor slice from 0.1%, 1%, 2%, 3%, 4%, 5%, 6%, 7%, 8%, 9% and 10%. The percent numbers means the most permeable area of landscape contained in the corridor slice ([Majka et al., 2006](#)). The basic principle of the corridor is to design it to be as large as possible; this is beneficial for wildlife but may create a trade off with available budget for managing the corridor ([Beier et al., 2006](#)). To create a habitat path, we used the suitable home range for elephant habitat for a group (estimated 180 population) of elephants, which is about 54,100–69,400 ha ([Hedges et al.,](#)

2005). Other study mentioned the minimum of range-wide for elephant in Asia countries compared with human population 8300 hectare in Vietnam (Fernando and Pastorini, 2011). However, the elephant habitat is a mix of dense forest, shrub and grass land. We found the wildland block (WB) covered by natural forest and secondary forest is relatively intact above 3000 ha (Fig. 2). We assumed the remaining forest in wildland block can be used by elephant mosaic with non-forest land in the protected area network can be increased the area up to 10,000 ha. Hence, the minimum size of a wildland block with natural forest was selected as 3000 ha. The total amount of wildland blocks was twenty, and then we selected twelve of these wildland blocks of these as a starting point and end point to connect the habitat based on slice corridor design. We used wildland block 1 as a centre to connect with other wildland blocks (such as wildland block 2, 3, 4, and 6) and then followed with wildland block 5 to 12, WB 7 to 8, WB 8 to 4, WB 9 to 11, WB 12 to 4 and WB 12 to 8.

The range of wildland block size was from 3196 Ha up to 234,086 Ha (see Fig. 2). The wildland block was generated from habitat quality (HQ) data; the normalized HQ result was used as an input to create a habitat path map. Since no specific rule is available to define width of wildland blocks, we used a proxy of minimum breeding area for elephants. We used 54,100 ha for minimum breeding area and 69,400 ha for viable population (Hedges et al., 2005). The minimum of range-wide for elephants compared with total human population in Sumatra is 240,000 ha (Fernando and Pastorini, 2011). Hence, we defined the wildland block result (see Fig. 2) based on minimum threshold of breeding and population path into three grid codes. Grid # 3 (above 100,000 ha) is suitable for a viable population. Grid # 2 is suitable for habitat path (above 54,000–100,000 Ha), and Grid # 1 (below 54,000 ha) is suitable for a smaller habitat path. Habitat path means the area represents pixels that are good enough, large enough and close enough together to support breeding for a particular species (Beier et al., 2006). The biggest wildland block (Fig. 2 number 1) is Bukit 30 National Park, which is a core area for breeding and maintaining a viable wildlife population of elephants, tigers, tapir and other species.

## 2.6. Protected area network (corridor design result) evaluation

The available data of both tigers and elephants was used before for validating the HQ model. Furthermore, the species data was also used for evaluating the protected area network using Maxent. The model Marxan is often used to define prioritization of conservation areas (Watts et al., 2009). To evaluate the modelled corridor result, we used habitat modelling of Maxent to understand the species distribution based on environmental space variables (Pearson, 2010).

The maxent approach divided into two windows. First, the coordinate location of tigers and elephant found in field was tabulated with Excel (the file in csv format). The second window for environmental parameters (such as elevation, distance from roads (artery, collector and local), Index vegetation (NDVI), slope and aspect). All parameter (files in ASCII format) will use to determine the distribution pattern of tigers and elephants in the landscape. The result of this analysis overlaid with protected area network to evaluate the corridor model.

## 2.7. Identify target segment of roads crossing the protected area network

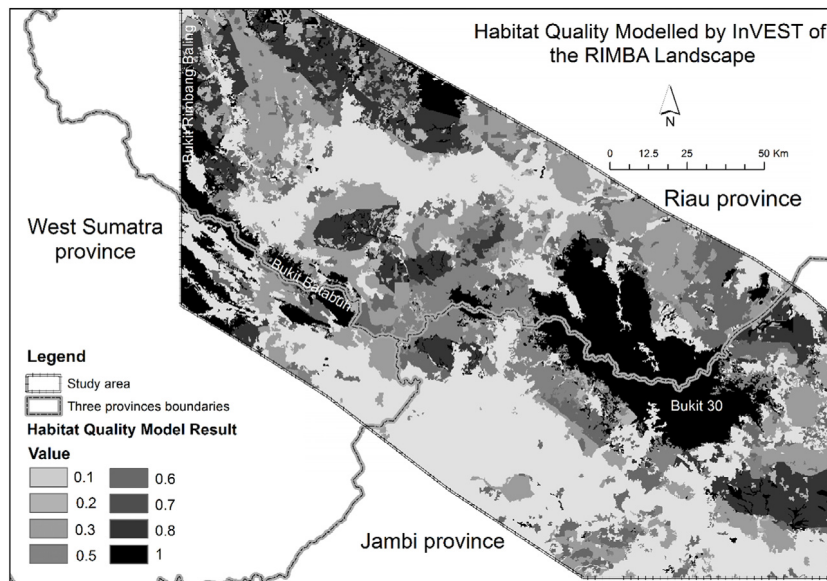
The last process of this study, to identify the target segment of road that critically reduce the habitat quality due to the roads crossing the protected area network as a barrier of species movement in corridor RIMBA. We used the Geo-processing tool in ArcGIS 10.2.2 to identify and measure the length of roads. We overlaid the road layer with protected area network used clip function of the Geo-processing tool. The identification result of segment of roads as a recommendation to decision maker to consider for developing eco-road construction.

# 3. Results

## 3.1. The habitat quality model and validation

The InVEST Habitat Quality model result shows the pixel values range from 0.1 (lower quality) to 1 (higher quality) for wildlife habitat (see Fig. 3). The map result represents the current condition based on LULC 2014 data. The good quality habitat (dark colour) was mostly in protected areas, followed by secondary forest/remnant forest, forest plantations, opens areas with some vegetation, oil palm plantations, and formerly burned area. The intact dark area Bukit 30 on the border of Riau and Jambi provinces is a part of the corridor RIMBA landscape, around the Bukit 30 moderate dark to light grey to towards pixel values of 0.1 to outside the corridor. However, the quality of habitat inside and surrounding of the RIMBA corridor was not intact dark, but represents a scattered pattern. Some areas near Bukit Batabuh showed more black and mosaic, with other brighter to white colours as well. The bright area was influenced by high density of local roads and land use patterns for other land use purposes (e.g. settlements, intensive agriculture and urban areas). Furthermore, dark black areas were influenced by good forest conditions and less road access. The land use status for dark black (Bukit 30, Bukit Batabuh and Bukit Rimbang Baling) is mostly protection, either as conservation area or protected forest for maintaining hydrologic systems.

The model validation was conducted based on pixel values of habitat quality and field survey data for tigers and elephants. A habitat quality score of 0.4 yielded the highest combination of sensitivity, specificity, and true skill statistic scores for both tigers in appendices (Figure S.6A) and elephants (Figure S.6B) and can be used as a threshold for determining habitat. The area under curve (AUC) metric suggests the overall model performance was excellent for tigers (AUC = 0.91) and fair for elephants (AUC = 0.74). Overall, the models performed well when validated with field observation data.



**Fig. 3.** The result of habitat quality model in study area, dark colour means high quality (indicated the value 1), the light grey means lower quality (indicated with value 0.1).

**Table 3**

Wildland blocks, slices selected and selected target segment of roads.

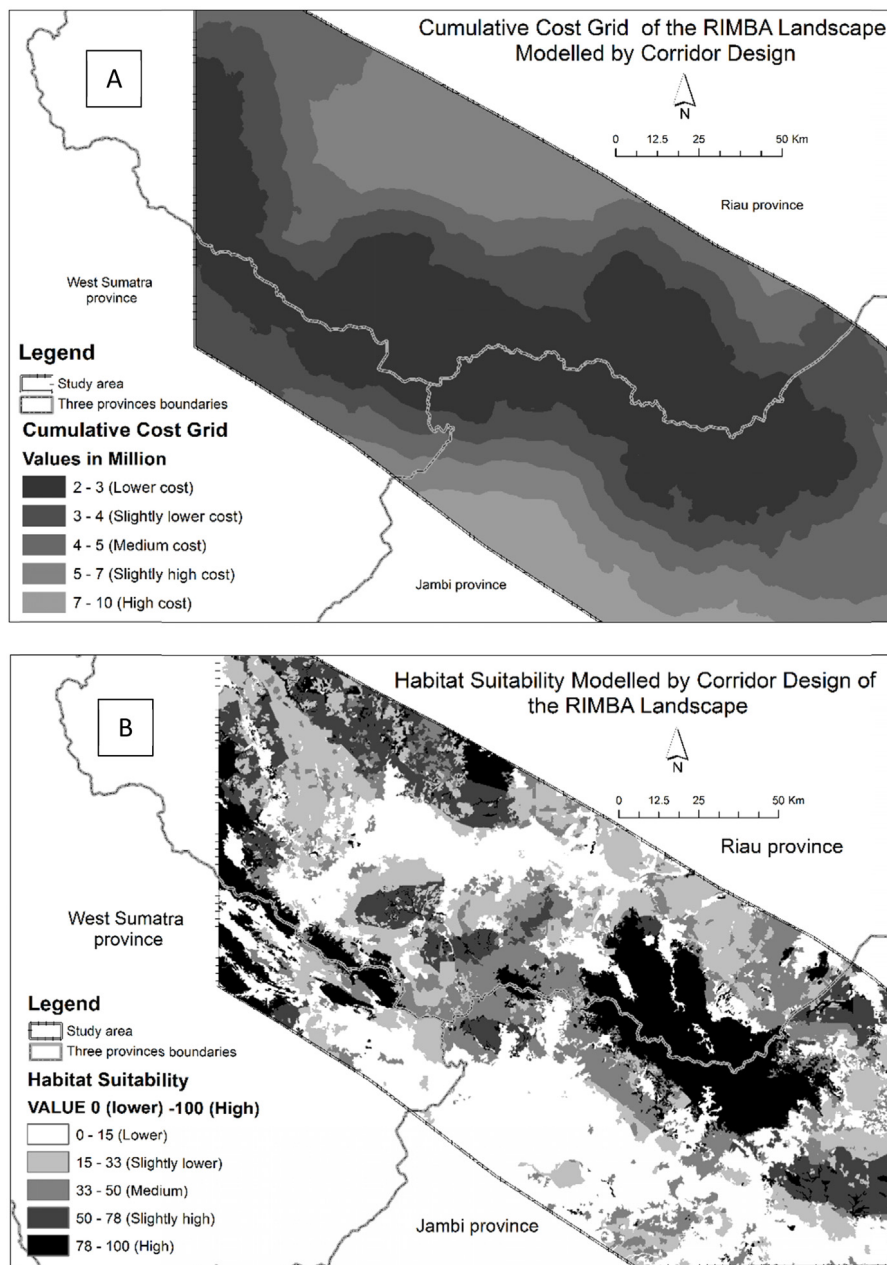
No	The wildland block connected	Slices selected %	Roads code	Selected target roads	Length of roads (km)
1	Block 1 to Block 4	1	14	Local roads	24.12
2	Block 1 to Block 6	1	16	Artery roads	1.86
3	Block 1 to Block 3 (B1–B13; B13–B8; B14–B5; B3–B5)	10		Collector roads and local roads	
3.1	Block 1 to Block 13	10	113	Local (Dirt) roads	94.52
3.2	Block 14 to Block 5	10	145	Local roads	44.12
3.3	Block 13 to Block 8	10	813	Local roads	87.06
3.4	Block 5 to Block 3	10	35	Collector roads	9.85
4	Block 12 to Block 13	3	1213	Local roads	59.30
5	Block 18 to Block 13	3	1813	Local roads	28.31
6	Block 5 to Block 12	3	512	Local roads	50.51
7	Block 3 to Block 2	7	32	Collector	8.37
8	Block 3 to Block 10	7	310	Collector	1.30
9	Block 9 to Block 11	1	911	Artery roads	0.78
10	Block 9 to Block 15	1	915	Artery roads	3.10

### 3.2. Corridor design and protected area network evaluation

Fig. 4(A) shows the cumulative cost grid. The cost (*or resistance*) represents the difficulty of particular species moving from one place to another (Beier et al., 2006). Light grey signifies areas with high cost pixels. These are areas which face high potential for human-wildlife conflict. The map of average habitat suitability suggests the best pathway among wildland blocks and the eligible area for establishing habitat connectivity (Fig. 4(B)). The dark black signifies high suitability with values of one hundred (100), and the white colour signifies lower suitability for habitat connectivity, with pixel raster values of zero (0). The raster layers of cost grid and average habitat suitability are used as main inputs to produce slices of necessary “corridor width” for the wildlife corridor (Beier et al., 2006).

Cost distance and averages of habitat suitability were used as main inputs for materializing wildland blocks and slices corridor. The slices of corridor design from wildland block (WB) 1 to wildland blocks (WB) 2nd & 3rd were two of ten connected for defining best corridor width options (see Fig. 5(A)). We choose 10% corridor width to represent several WB 1–WB13–WB8–WB14–WB5–WB3–WB2. Furthermore, to connect remaining wildland blocks, we created a new corridor slice for connecting from WB 1–WB4 and we selected corridor width 1%. Further, started from WB 1 and end to WB 6 we selected corridor width 1%. Next process, started from WB 5 and end to WB 12 we selected corridor width 3% and started from WB 7 and end to WB 8 we selected corridor width 0.1%. Next, from WB 8 to WB 4 we selected corridor width 7%; from WB 9 to WB 11 we selected corridor width 1%; from WB 12 to WB 4 we selected corridor width 10% and the last from WB 12 to WB 8 we selected corridor width 3%. The detail of each slice of corridor design is provided in the appendices (Fig. S.7).

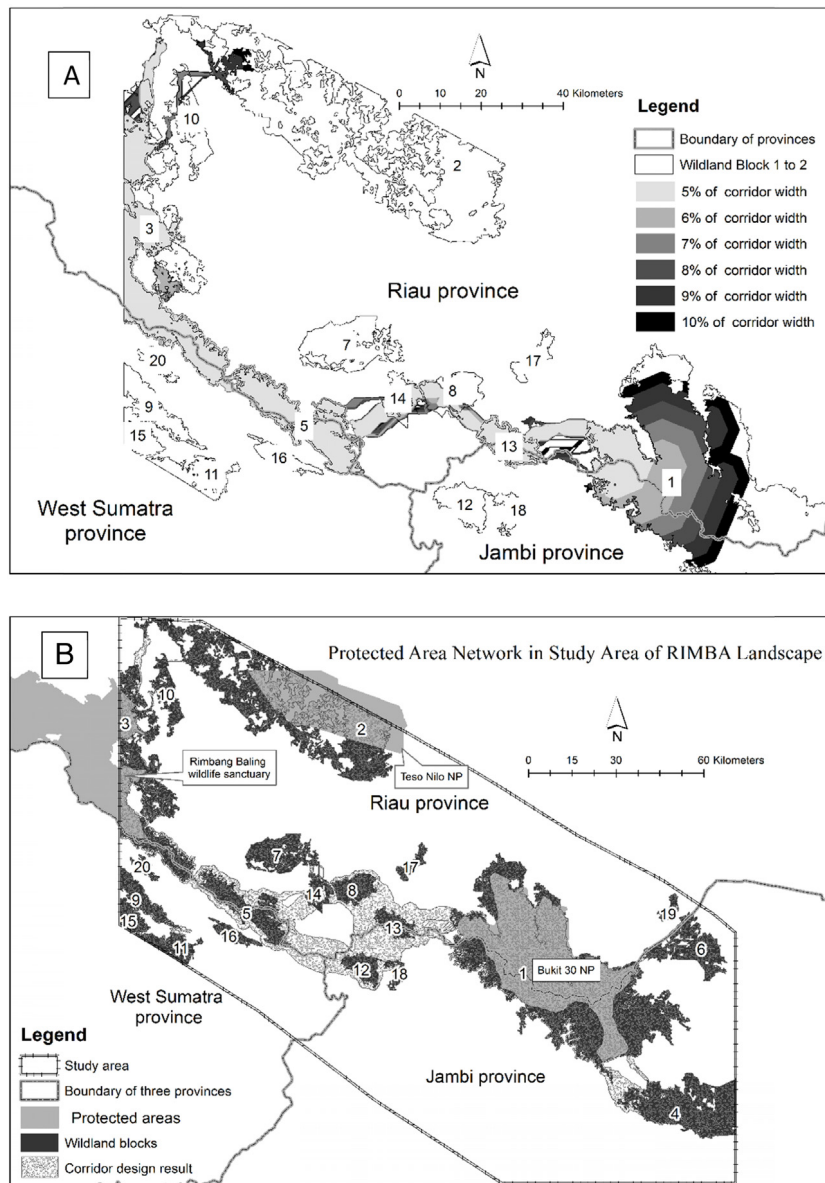




**Fig. 4.** (A) Cumulative cost grid and (B) habitat suitability of corridor design model.

Fig. 5(B) shows the final corridor design result. The corridor was merged from 10 slices (see Table 3). Slices were constructed from connecting wildland blocks 1, 2, 3, 4, 5, 6, 7, 8, 9, 11 and 12. The other wildland blocks do not need to be connected, because they can be nested in existing slices. For example, wildland block 10 can be connected to wildland block 2 and wildland block 3. The path result from wildland block 10 is nested in slice path from wildland block 1 to 2. The merged result of slices corridor then produced the protected area network.

To evaluate the delineation of the protected area network, it was overlaid with elephant and tiger distribution modelled by Maxent in Bukit 30 National Park (Figs. 6(A)&(B)–7(A)&(B)). The light white colour indicates the highest probability 0.8 for elephants distribution and 0.9 for tigers distribution—and light grey indicates medium probability of presence; dark indicates the lowest probability of presence. Based on these overlays, the corridor design has captured the core area of elephant and tiger distribution found in the Maxent model. The evaluation result showed that the Maxent modelling gives more a detailed probability of tigers and elephants distribution inside the modelled corridor.



**Fig. 5.** (A) Slices of corridor design and percents of corridor width, (B) proposed the protected area network of RIMBA landscape to maintain viable large mammals population migration and movement within their home range. The grey area as a protected area network was proposed to connect wildland block 1 is Bukit 30 national park (NP)–Rimbang Baling wildlife sanctuary–Teso Nilo national park.

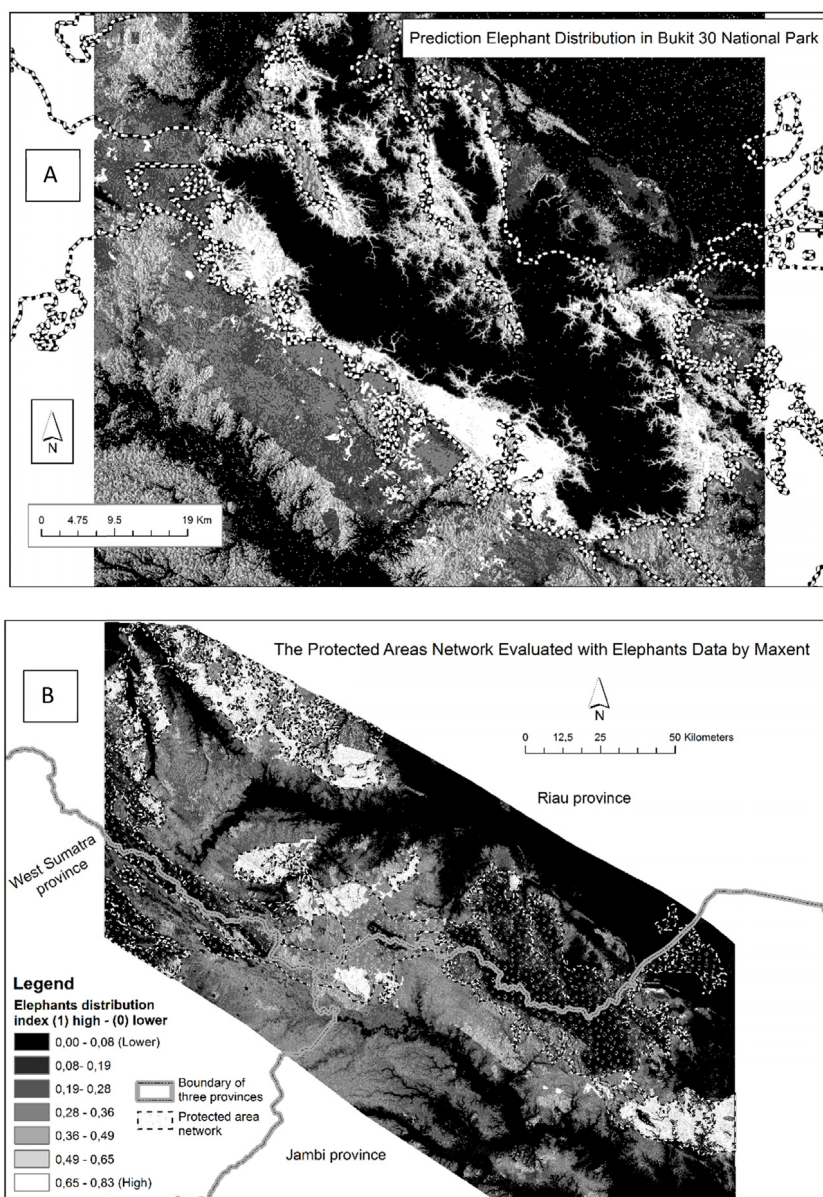
### 3.3. Target segment of roads

Total length of roads crossing the protected area network was about 417.78 km. Length of local roads was 187.94 km (longer than both artery (10.31 km) and collector (19.52 km) roads); each class and the length of roads is presented in Table 3.

## 4. Discussion

The summary of overall approaches in this study included an assessment of the quality of habitat from anthropogenic disturbance using InVEST and validated with species data; further, design of wildlife habitat connectivity by corridor model and evaluated with Maxent model; and finally, identification of a target segment of roads.

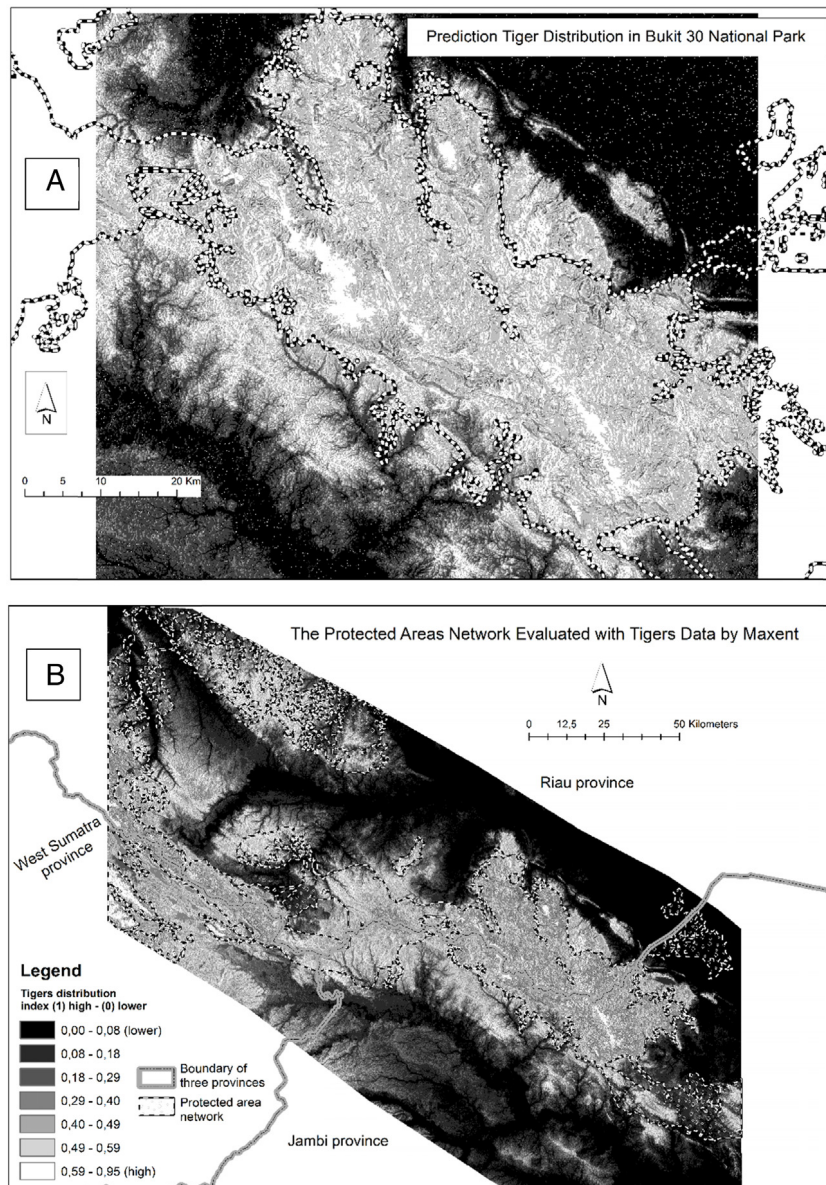
The model of Habitat Quality of InVEST can assess the anthropogenic disturbance to the wildlife habitat. The result of Habitat Quality was validated with distribution data of tigers and elephants, which showed that the AUC for tigers was 0.91



**Fig. 6.** (A) White colours show areas with better predicted of elephants in Bukit 30 and as training area. The Elephant homerange white colour index (0.53–0.82) is predicted high distribution and dark colour 0–0.15 is lower distribution prediction. The grey area (0.44–0.59) is moderate; (B) this was a projection of the elephants distribution in study area based on environmental parameters of elephants and its occurrence.

and elephants 0.74, indicating that the HQ model result was adequate to develop wildland blocks and design for habitat connectivity. The corridor we modelled might be evaluated by Maxent to further explore the distribution pattern of species inside the corridor. The design of the corridor could be used to identify the existing road segments in the landscape. The local roads were more dense and longer, since some roads were developed by companies as concession roads. Although local roads are generally dirt roads, further study is required to evaluate the impact of these roads. A previous study stated that dirt roads may allow wildlife greater ability to cross, compared with artery and collector roads (Schwab and Zandbergen, 2011). However, other findings conflict with this, stating that dirt roads in the Southern Rockies Wildlands Network, US can only support wildlife movement if they are used for recreation (e.g. mountain biking) and not for heavy vehicles (Bennett and Mulongoy, 2006). Highways (such as collector and artery roads) have a significant negative impact, if the frequency and intensity of vehicles is high, which can cause disturbances for species habitat such as in the US (Leblond et al., 2013). However, the environmental road impact varies in different contexts, and there is a need to integrate information on local conditions regarding the intensity and level of traffic (Laurance et al., 2014). Artery and collector road disturbance for wildlife is quite





**Fig. 7.** (A) white colours show areas with better predicted of tigers in Bukit 30 and as training area. Tiger homerange white colour (0,53–0,95) is predicted high distribution and dark colour 0–0,11 is predicted lower distribution and grey area 0,41–0,53 is moderate; (B) this was a projection of the tigers distribution in study area based on environmental parameters of tigers and its occurrence.

complex; in addition to the physical barrier, impacts include chemical, thermal, acoustic, and light emissions, as well as water flow and traffic accidents (Beben, 2012). Furthermore, the roads can generate indirect impact disturbance for wildlife habitat within the corridor landscape, such as encroachment and land clearing including potential risk of forest fire.

The white colour to the grey areas (Figs. 6(A)&(B) and 7(A)&(B)) are preferred for safer species migration. However, this does not mean that white colour areas are free from poaching, snaring and potential encroachment (such as illegal logging and oil palm agriculture by small holders). This depends on land use practices and management of each land use class, including conservation areas. In this model, we did not account for these disturbances, as previously mentioned.

The total size of the modelled habitat connectivity from the analysis, including the wildland blocks, was about 0.77 million ha, and the total length of the connectivity was about 180 km. This corridor connected the habitat blocks from the eastern part to western part of central Sumatra. In this study we used elephants and tiger as umbrella species. The area size for umbrella species such as elephants requires enough space for their home range. Other studies have stated that suitable home range for Sumatran elephants habitat is about 54,100–69,400 ha (Hedges et al., 2005). Another monitoring study on elephant movement in India found that it could reach 8 km per day within 8000 ha area and 27 km per day within 39,000 ha

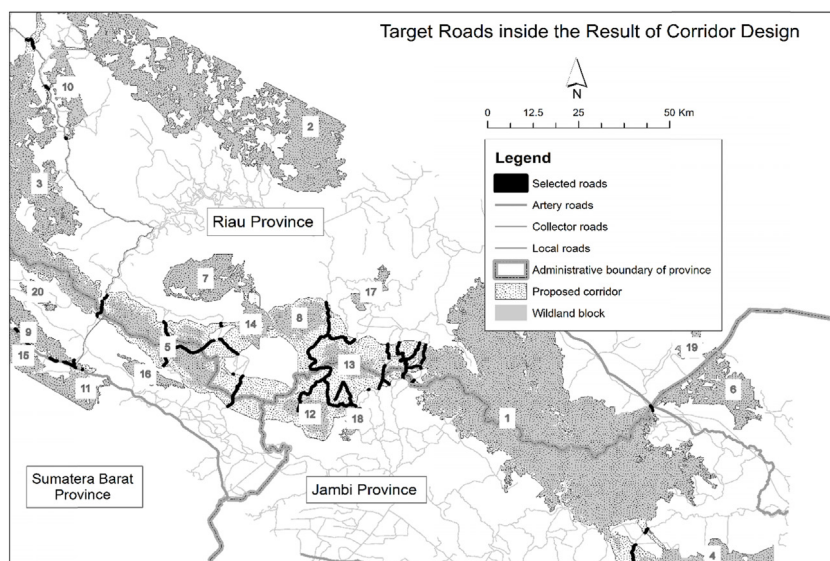


Fig. 8. Priority segments of roads inside protected area network.

(Joshi et al., 2009). The future habitat quality of large mammals such as elephants is influenced by human attitudes towards sharing the same landscape. The present human/elephant distribution estimated for Asian elephants is about 70,000 people per elephant across the range (Fernando and Pastorini, 2011). Therefore, central Sumatra is very important to maintain the remaining habitat of large mammals in this island. (See Fig. 8.)

The approach taken here in the RIMBA corridor of central Sumatra can be used for four other corridors in the whole of Sumatra, and also other regions in Indonesia. This model can be leveraged to improve habitat connectivity and reduce the impact of roads on the Borneo tropical rainforest, tropical rainforests in Papua and Sulawesi, as well as the tropical monsoon forest in Nusa Tenggara including the Maluku rain forest. The general approach of connecting habitat is not new in Asia; for example, in 1995, the ecological network was adopted in South Korea and Japan. Government conservation agencies and Conservation organizations (such as Conservation International, The Nature Conservancy, and WWF) through eco-regional and hot spot approaches have been promoting the corridor landscape approach in several Asian countries since 1997, such as the Terai Arc landscape in Nepal and India (125,693 hectares), the corridor initiative in Xiaoheishan Nature Reserve, China (11,550 hectares), and the Arakawa river ecological network, Japan (50 hectares) (Bennett and Mulongoy, 2006). However, in Indonesia several challenges remain for establishing habitat connectivity, and this approach may help to improve the conventional practice of road development due to the information it provides on habitat quality, connectivity, identification of relevant road segments, and potential for habitat nexus areas.

This model can be useful for several key stakeholders, such as road developers and policy makers in regards to infrastructure development; NGOs in relation to conservation objectives; spatial planning and regional development planning agencies; and natural resources sectors i.e. forestry, mining and agriculture. The approach can be replicated for other islands in Indonesia, to describe disturbances of human activities on land use, to design connectivity of habitat, and to define the target segments of road which are barriers to connectivity of protected areas and wildlife habitat. However, the approach cannot evaluate the impact on species crossing of the target segment of roads, including disturbances (such as snaring and poaching). This requires further research, for example an impact assessment, to define the location conditions and to optimize a function of corridor design as homerange of wildlife movement that has been fragmented, and measure additional impacts of disturbance.

Furthermore, the study approach can be applied in conservation planning to strengthen the protected area network at the landscape level. The method to delineate wildland blocks based on InVEST can be replicated and used as a reference to validate other landscapes, though the target landscape is insufficient the species data survey. Importantly, the results are useful as a material to communicate and advocate the integration of wildlife conservation into the regional development plan. However, the approach is limited in its ability to describe in detail the species niche (such as habitat modelling based on species occurrence and its environmental condition).

The model also can be applied to support eco-road construction. For example, the target segment roads in artery and collector classes were more appropriate to develop; potential methods could include eco-ducs (artificial wildlife bridge), tunnels, flyovers (such as a bridge above the wildlife pathway), and canopy bridges. For local roads, improvements include connecting the trees' canopy, planting vegetation along the road, and limiting vehicles to reduce the frequency and intensity of the road.



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