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Integrated cloud computing and cost effective modelling to delineate the ecological corridors for Spectacled bears (*Tremarctos ornatus*) in the rural territories of the Peruvian Amazon

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ABSTRACT

Spectacled bears (SB) (Tremarctos ornatus) are the only bear species native to South America. This particular bear is the single species of its genus, and it is listed as vulnerable according to the IUCN red list. A critical SB conservation habitat is in the rural territories of the Peruvian Amazon, where anthropogenic land-use changes and landscape fragmentation threaten SB habitats. The following questions arise in this context: How much has land-use changed? How to design the establishment of ecological corridors (ECs) to support the conservation of SB?. We investigated the temporal land use and land cover changes for last 30 years (1990–2020) for a better projection of the ECs and to quantify the temporal landscape metrics. Furthermore, we integrated cloud computing, machine learning models with cost-effective techniques to delineate the ECs for SB within the rural territories. Ensemble Random Forest model associated with Google Earth Engine (GEE) was used to develop four land use and land cover (LULC) maps (for the years 1990, 2000, 2010 and 2020). The least cost path (LCP) model based on Dijkstra's shortest path algorithm was assembled based on six variables (altitude; slope; distance to roads; distance to population centers; land use map; inventory map of SB). Then, we calculated the ECs based on the multidirectional origin-destination points, we found that forest patches increased by 57%

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between 1990 and 2020. Results showed statistically significant agreement ($R^2 = 0.47$; $p < 0.05$) between cost/ha* and percentage of forest cover. We observed that the higher the forest cover, the better the connectivity and the lower the cost of mobilization in the ECs. Our study outcomes validated through the images obtained from trap cameras that confirms that delineated routs for SB movements. The proposed model can be adopted for other parts of the global forest including other species of interest. To formulate a sustainable conservation action plan, we provided five recommendations that will support conservation practices, design cost-effective ECs for policy makers.

1. Introduction

Habitat fragmentation in the Peruvian Amazon imposing a serious threat for its rich biodiversity, wildlife, and conservation approaches (Cotrina Sánchez et al., 2021, 2020; Paiva et al., 2020). Due to deforestation, aggressive modern human economic invasion, the Peruvian Amazon is falling into pieces separated by roads, dams, settlements and step cultivations (Laurance et al., 2011; Morrell et al., 2021). According to a recent report by IPBES (The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services) estimated that in last 40 years the habitat fragmentation process largely picked up resulting more than 1 million species are currently under facing extinction and threat (IPBES, 2019). Such fragmentation in the Amazonian landscape rapidly eroding the rich species biodiversity including the spectacled bears (SB), or Andean bear (*Tremarctos ornatus*), the only Latin American representative from the family *Ursidae* (Peyton, 1980).

SB is already listed as "vulnerable" according to the IUCN Red List of Threatened Species[1] and it also comes under CITES Appendix I of Peru representing threatened species of the Amazon due to habitat fragmentation, poaching, and illegal trade (Meza et al., 2020; Rodriguez et al., 2003; Rojas et al., 2019; SERFOR, 2018). The unique *T. ornatus* species or SB mostly found in the widespread mountainous regions (~200–4750 m a.s.l.) of Peru, Venezuela to Colombia, Ecuador, western Bolivia and northwestern Argentina within the tropical rainforest and dry forest regions (Cuesta et al., 2003; Meza et al., 2020). However, increasing fragmentation in the Peruvian Amazon imposing serious threat to the existence of SB because of three reasons: (1) forest fragmentation exposing SB for illegal hunting and killing due to open accessibility; (2) transformation of the Amazonian landscape eradicate the density of the forest cover which is necessary for their presence and sustainability; (3) as the SB are comparatively small in size, isolated in population, it's become easy target for illegal poaching. Such reasons reduce the gene flow within declining SB populations and increase their risk of extinction (Vandermeer and Lin, 2008; Zemanova et al., 2017). Therefore, the conservation of SB is necessary at this moment to ensure the presence of its genus in Latin America which is highly necessary for the conservation of diverse ecosystems of the Amazon. A conceptual framework addressing the risk for SB calculated through the integration of deforestation, land-use change, and exposer is presented in Fig. 1.

Literature related to SB have discussed their history and conservation action plans (García-Rangel, 2012; Peyton, 1999); current and future potential distribution (Meza et al., 2020); distribution and food habits (Peyton, 1980); livestock and human conflicts (Figueroa Pizarro, 2015; Goldstein et al., 2006); existence (Kattan et al., 2004), and the habitat potential in Panama and Ecuador (Cuesta et al., 2003; Goldstein et al., 2008); and so on. However, the conservation efforts of SB have been less addressed. Conservation of SB in the Peruvian Amazon has mainly focused on the Natural Protected Areas (NPA) reported by existing studies (Meza et al., 2020). However, there is a lack of research about its connectivity or corridor development for free movement where only 30 SB are left as per the reported by SERFOR (2018) (Gray et al., 2016; Watson et al., 2014). To effectively connect the NPA, the implementation and development of ecological corridors (ECs) is highly recommended by various studies and reports (Heller and Zavaleta, 2009; Peng et al., 2017; Saura et al., 2019). ECs allow to increases the connectivity of the landscape, increase the free and uninterrupted movement of habitat species including SB (Hong et al., 2017; Peng et al., 2018, 2017) and maintains the compositional and functional biodiversity of ecosystems (Samways and Pryke, 2016). Moreover, ECs supports the processes of population dynamics, naturalization, evolution and community responses to climate change (Kool et al., 2013). In order to effectively meet the conservation goals, the NPA must be connected through ECs which will support the SB and other threatened species (Magris et al., 2018; Saura et al., 2019). Due to poor and unplanned development of ECs, the SB in the isolated NPA may suffer the risks of inbreeding, extinction and unable to adopt the climate change scenarios (DeFries et al., 2005; Heller and Zavaleta, 2009; Krosby et al., 2010; Saura et al., 2019). Moreover, the presence of the SB is mostly found in the rural territories of the NPA compared to the other parts of the Peruvian Amazon.

We studied we are mainly interested about the development of ECs within the rural territories of the NPA. Specifically, we delivered a novel approach to delineate the ECs for SB through the implementation of machine learning based algorithms, cloud computing and cost-effective approaches using spatial and earth observation data.

Remote sensing and Earth observation based approaches together with machine learning (ML) models and cloud computing are acknowledged as most efficient, useful, real-time and accurate solution that can provide significant support to develop spatially explicit models for ECs (Cisneros-Araujo et al., 2021; Jeong et al., 2018). In this study we executed random forest (RF) machine learning modelling in Google Earth Engine (GEE) cloud computing platform to detect the changes in land-use and land-cover (LULC) change of the rural territories of NPA's for the period of last 30 years (1990–2020). Furthermore, the least cost path algorithm (LCP)

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[1] https://www.iucnredlist.org/species/22066/123792952

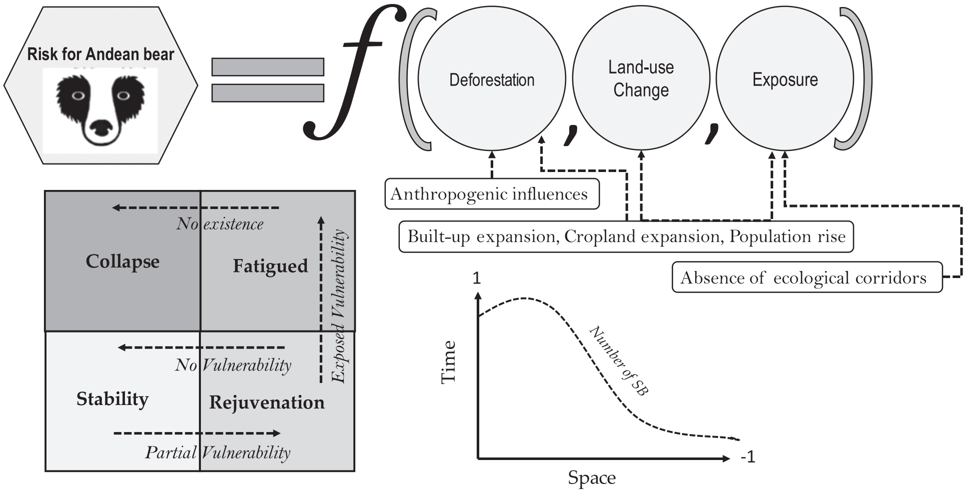

Fig. 1. Conceptual framework to assess the risk of the spectacled bear (*Tremarctos ornatus*).

technique was implemented to identify the ECs within the landscape. LCP allows to identify the optimal flow paths between multiple points on a resistance matrix, allowing decision makers to determine how to connect spaces of territory (dos Santos et al., 2020; Peng et al., 2018; Santos et al., 2018), based on geographic information (Adriaensen et al., 2003; Driezen et al., 2007; Kaszta et al., 2020; Tilker et al., 2020; Yang et al., 2017).

Therefore, to take the advantages of the modern ML based algorithms coupled with GEE and remote sensing data for the delineation of ECs, the objectives of this study are: (1) detect the LULC changes of the rural territories of NPA over last 30 years followed by accuracy assessments and (2) implement and test the LCP based algorithms for optimal and cost-effective route mapping for the development of ECs. This study is the first to analyze and promote the conservation of SB in the rural territory of the Peruvian Amazon through a territorial vision using the development protocols of the ECs. We hypothesized that changes in LULC can be detected in the

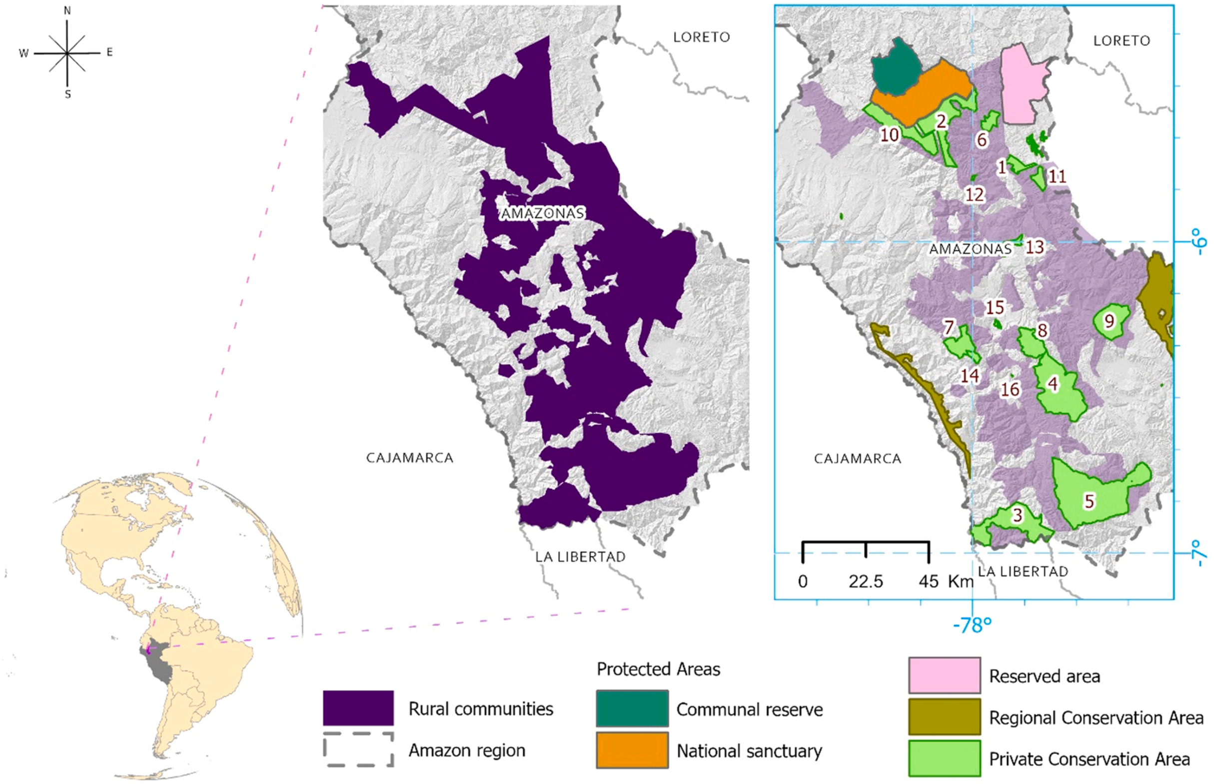

Fig. 2. Location of the Peruvian Amazon and its rural communities in northwestern Peru.

last 30 years and LCP based algorithms can provide optimum solutions for EC development within the rural territories of the NPA. The methodology adopted in this study can be implemented to other regions of the world. We believe the outcome of this study will support the ecological researchers, local and national governments, stockholders, decision support systems and conservation approaches worldwide for sustainable habitat suitability mapping and connectivity modelling.

2. Materials and methods

2.1. Study area

This study was carried out in the 16 territories of the NPA within the part of Peruvian Amazon. The NPA consisted mainly with 14 Private Conservation Areas (PCA) administered by the local rural communities, adjoining 1 National Sanctuary administered by the Government of Peru, and 1 reserved zone (SERNANP, 2021). Fig. 2 shows the geographical location of the NPA and their details are provided in Table 1.

The geographical extent of the study area is located between the parallels of 5°24′00′’ and 7°00′00″ south and the meridians of 77°25′12′’ and 78°54′30′’ west, covered mainly by premontane forests and cloud forests (MINAM, 2014). The experimental sites were characterized by its high floristic and biological diversity. The site was located at an altitudinal gradient ranging from 120 m above sea level in the north and 4900 m above sea level in the south. The temperature ranges from maximum 40 °C in the forest areas at the north, to minimum temperatures of 2 °C in the mountainous ranges at the southern boundary (Vargas, 2010). Additionally a rich socio-cultural diversity from 54 different rural communities were observed in the rural territories of the NPA (IBC, 2016).

The department of Amazonas has the largest number (20) of Private Conservation Areas (PCA) in Peru in an area of 157 123.08 ha (SERNANP, 2021), of which 16 PCA includes our field of study (Table 1). Areas that through ecotourism are self-financed, managed by private owners or rural communities, whose livelihoods depend on agriculture and livestock (Delgado et al., 2021),which increases the vulnerability of anthropic pressure in these spaces (Monteferry, 2019). However, these megadiverse forest territories are the habitat of endemic species of high ecological value such as: *Lagothrix flavicauda, T. ornatus, Aotus miconax, Puma concolor, Lodigesia mirabilis, Xenoglaux loweryi* (Monteferry, 2019; Pederson and Olivera, 2018; SERFOR, 2018). Therefore, it highlights the importance of making an evaluation of the territory in an integrated manner through EC in rural territory of the rural communities of Amazonas in the northwest of Peru (Fig. 2).

2.2. Material and Methods

The methodological framework used in the present study is graphically described in Fig. 3 From the download, processing and analysis of multispectral images, in combination with radar images using cloud computing (Gorelick et al., 2017; Tamiminia et al., 2020), they allowed to identify the multitemporal LULC (1990 – 2020) and landscape metrics in the study area. Likewise, we use physical variables (distance to roads, distance to population centers), Spatial Distribution Model (SDM) of *T. ornatus* (Meza et al., 2020) and the LULC map of the year 2020 to obtain the resistance raster, the latter being a fundamental input prior to the design of ecological corridors. Finally, using the Least-Cost Path plugin in Qgis 3.16, we identified the ecological corridors between the conservation areas (Table 1) in Amazonas department in the northwestern Peru.

2.2.1. Datasets

2.2.1.1. Satellite images. We used satellite images from Landsat 5 TM (L5) and Landsat 8 OLI/TIRS (L8) available in the Google Earth Engine (GEE) platform (https://earthengine.google.com/). We used several images to create a composition of images because one

Table 1
Natural protected areas (NPA) within the scope of the study.

Natural protected areas (NPA)	N°	Name of the zones	Areal Extension (ha)
Private Conservation Areas (PCA)	1	Copal Cuilungo	2573.07
	2	Monte Puyo	16157.57
	3	San Pedro de Chuquibamba	19560.00
	4	Llamapampa – La Jalca	17502.93
	5	Los Chilchos	46000.00
	6	La Pampa del Burro	2776.96
	7	Huaylla Belén – Colcamar	6339.30
	8	Tilacancha	6800.48
	9	Bosque de Palmeras de la CC.CC Taulía Molinopampa	10920.84
	10	Copallín	11558.74
	11	Hierba Buena – Allpayacu	2282.12
	12	Arroyo Negro	156.42
	13	San Pablo – Catarata Gocta	2603.57
Individual or under family administration	14	Huiquilla	1141.08
	15	San Antonio	357.39
	16	Milpuj – La Heredad	16.57

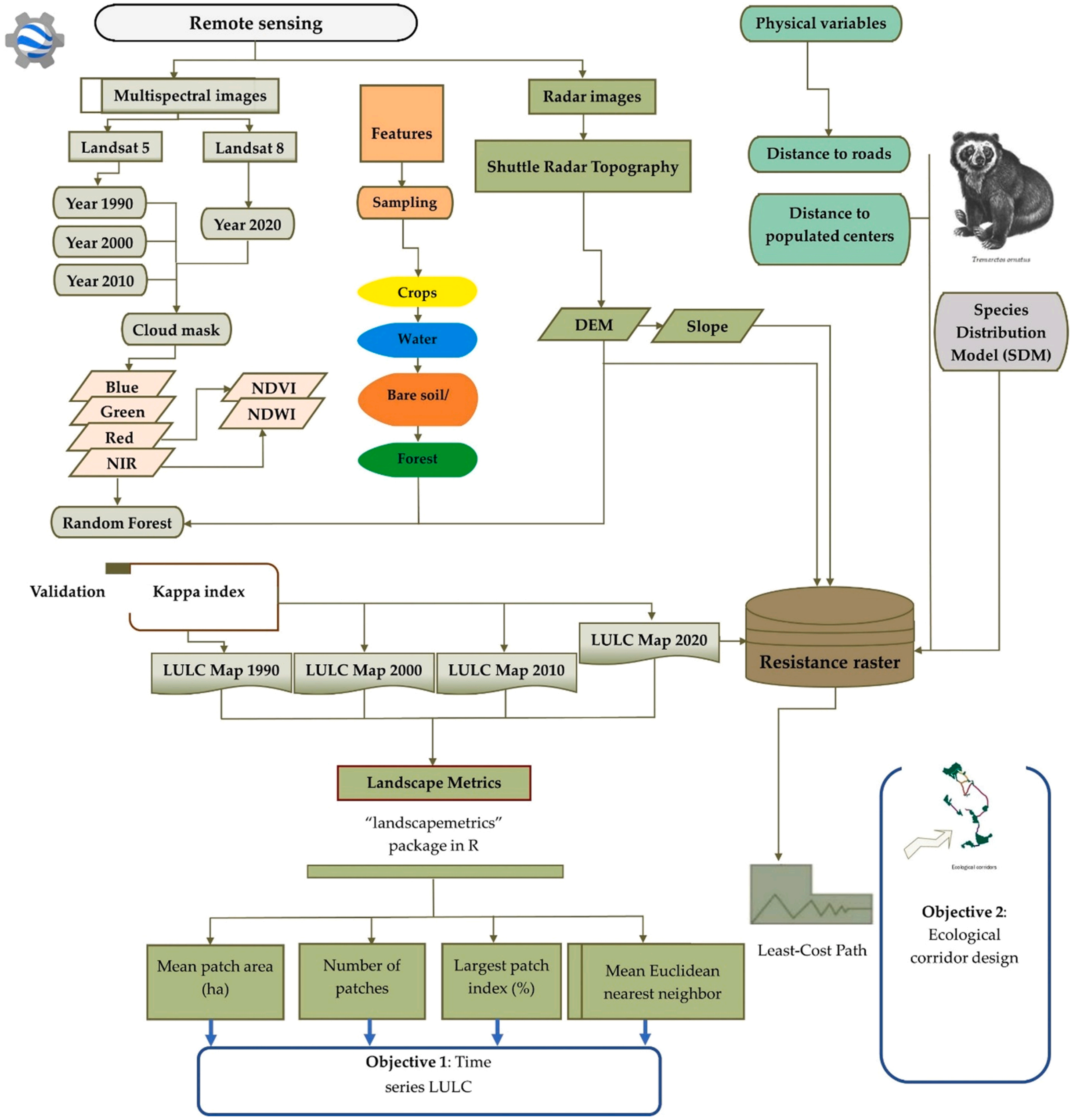

Fig. 3. Methodological scheme adopted in this study.

scene wasn't enough to cover the entire study area. L5 datasets were used for the consecutive years of 1990, 2000 and 2010 (ee. ImageCollection("LANDSAT/LT05/C01/T1"), whereas L8 datasets were used for 2020 (ee.ImageCollection("LANDSAT/LC08/C01/T1_RT_TOA"), considering that our image collections (Landsat) are located between the following path/rows (8/64; 8/65; 9/63; 9/64 y 9/65) covering the entire study area. As our study area is located in the equatorial zone and with tropical forests, cloud cover throughout the year is considered as a serious challenge for the use of optical satellite imageries (Griffiths et al., 2013; White et al., 2014). Therefore, it is necessary to perform cloud free algorithms to facilitate the creation of cloud-free data sets. So, we apply a cloud mask and make compositions of the median of the images, in order to obtain 4 final images with cloud-free pixels (White et al., 2014).

2.2.1.2. SRTM data. From NASA's Shuttle Radar Topographic Mission (SRTM) (Farr et al., 2007), the Digital Elevation Model (DEM) and slope were obtained, both with a spatial resolution of 30 m, a process carried out through the GEE code editor.

2.2.1.3. NPA boundaries. The administrative boundary layers for NPAs were obtained from the database of the National Service of

Natural Areas Protected by the State (SERNANP) (https://geo.sernanp.gob.pe/visorsernanp/; accessed July 10, 2020).

2.2.1.4. Species distribution model. Species Distribution Model (SDM) mapping is a significant part for habitat modelling. It provides accurate, credible, defensible, and repeatable information with which to inform decisions (Feng et al., 2021; Sofaer et al., 2019). Therefore, in this study we adopted the distribution inventory map of SB (T. ornatus) from (Meza et al., 2020). (Meza et al., 2020) considered 92 geo-referenced records of the SB (obtained from GBIF and interviews with local villagers and researchers), 12 environmental variables and the MaxEnt entropy modelling technique over the Peruvian Amazon. They received high accuracy (Area Under Curve = 0.915 ± 0.012) in the mapping of SB. Under the current conditions, 1.99% (836.22 km2), 14.46% (6081.88 km2) and 20.73% (8718.98 km2) area of the Peruvian Amazon illustrated as "high", "moderate" and "low" habitat zones respectively for SB (Meza et al., 2020). The adopted inventory map of SB were further taken into account for LCP modelling.

2.2.2. Methods

2.2.2.1. Ensemble random forest LULC classification in GEE. We quantified the changes in the land-use pattern of the rural communities of the Peruvian Amazon from the last 30 years (1990–2020) using ensemble random forest (RF) classification model in GEE.

The Random Forest (RF) classifier (Eq. 1) is an ensemble of classification methods consisting of several decision tree models as expressed by L. Breiman (2001). The RF classifier enhances the accuracy of LULC mapping as compared to other popular similar algorithms (Bandopadhyay et al., 2021; Zeferino et al., 2020), requires little or no manual intervention (Hatwell et al., 2020) and it generally have a quick processing speed (Schmidt et al., 2019). It also maintains the classification error balance when the class size distribution is unbalanced (Toosi et al., 2019).

〚{D T (x,θ_k)}〛 _(k=1)^T (1)

where x is the input vector, and θk denotes a random vector, which is sampled independently but with the same distribution as the previous θk, …, θk− 1. T bootstrap samples are initially derived from the training data. A k number of samples extracted from the training sample set using bootstrap sampling, and the sample size of each sample, are the same as that of the original training set (Magidi et al., 2021).

We conducted separate classification of LULC for 4 years, 1990, 2000, 2010 and 2020, using satellite imagery from Landsat 5 TM (1990, 2000 and 2010) and Landsat 8 OLI/TIRS (2020). We considered blue, green, red, NIR and SWIR bands from Landsat 5 and Landsat 8, Shuttle Radar Topography Mission (SRTM) 30 m terrain elevation model and the spectral indices like Normalized Difference Vegetation Index (NDVI) (Eq. 2)(Rouse et al., 1973), and Normalized Difference Water Index (NDWI) (Eq. 3) (Mcfeeters, 1996) as RF modelling predictors. We include the elevation as a predictor because it can improve the classification performance (Zeferino et al., 2020). In this study, an average of 350 samples were for each period evaluated, distributed visually in the different coverage classes, 70% (245) training data and 30% (105) validation data was taken into account for RF modelling. The classification was carried out using cloud computing based GEE (Gorelick et al., 2017; Hu et al., 2018; Tamiminia et al., 2020). We define four LULC classes for our classification, level 1 CORINE LULC model for Peru was adapted (MINAM, 2015). It contains 4 classes such as (1) forest, (2) bare soil/urban area, (3) crops (grasses and small farms) and (4) water surfaces.

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)} \tag{2}$$

$$NDWI = \frac{(NIR - SWIR)}{(NIR + SWIR)} \tag{3}$$

The ground control points (GCPs) of each class were obtained by photointerpretation of high-resolution images available in GEE for the validation purpose. Then, the evaluation of the accuracy of the classified images were evaluated with the Cohen's kappa coefficient (k) (Cohen, 1960). The standard kappa coefficient scale that denotes k = 0.40–0.59 as weak, k = 0.60–0.79 as moderate, k = 0.80–0.90 as strong, and k > 0.90 as perfect was adopted to evaluate the accuracy of the classified LULC maps (McHugh, 2012).

2.2.2.2. Landscape metrics determination. Quantification of the landscape patterns and linking them with ecological process and habitat suitability is one of the central task of ecological modelling. To understand the landscape characteristics that are characterized as discrete patches of different land-cover classes along with the spatial distribution of species and communities, it's important to develop landscape metrics (Hesselbarth et al., 2019). In order to do so, landscape metrics were calculated to quantify changes in spatial patterns experienced by the forest cover class in the study area (Cushman and McGarigal, 2008). The landscape metrics were developed for the period between 1990 and 2020 in this study. The quantification the metrics were performed in the R software version 4.1.0 (R Core Team, 2021) using the package "landscapemetrics" (Hesselbarth et al., 2019). This package was considered as a drop-in replacement for FRAGSTATS (the first software to provide an extensive collection of landscape metrics) and it allows a reproducible workflow for landscape analysis in a single environment (Hesselbarth et al., 2019). The "landscapemetrics" package offers to develop four theoretical metrics of landscape complexity: (1) marginal entropy, (2) conditional entropy, (3) joint entropy, and (4) mutual information (Nowosad and Stepinski, 2019). We categorized and developed the following landscape metrics over the study area: (1) number of patches; (2) mean patch area (ha); (3) largest patch index (landscape percentage covered by the largest patch); and (4) the mean Euclidean nearest neighbor distance (m) for further modelling and simulation in agreement with (Arora et al., 2021; Reynolds et al., 2016; Salazar et al., 2021).

2.2.2.3. Least cost path modelling.

The impact of the landscape matrix and its connectivity between 'origin' and 'destination' to understand the patterns of animal movement was widely recognized by ecologists and conservation practices (Pinto and Keitt, 2009). Least cost path (LCP) approach is the optimal solution that considers the matrix's influence on the length, relative quality, and redundancy of dispersal routes connecting habitat patches. Therefore, in this study we applied LCP modelling approach to delineate the optimal path and develop ECs for SB that can be implemented by the conservation authorities for their sustainable future (Fig. 4). The principle of LCP is based on the fundamental geographic principle of friction of distance, and it states the optimal solution which minimizes the total cost of the route based on the field cost density and local factors.

In this study we used the 'Least Cost Path plugin' from version 3.16 of the QGIS software to delineate the optimal route for SB. The 'Least Cost Path plugin' of QGIS is based on the principle of Dijkstra's shortest path algorithm.[2] The algorithm creates the shortest path from a starting node to a target node in a weighted graph and it also creates a tree of shortest paths from starting point to all other possible points (Shekhar and Xiong, 2008).

For example, a network by a directed weighted graph $G = (V, E, \phi)$, where V is a nonempty set of nodes; E is a set of edges, one for each link; and ϕ is a weight function from E to nonzero positive real numbers. The number of nodes is denoted n, and the number of the directed edges m. The shortest path weight, also called distance, from node u to v, denoted $dist(u, v)$, is the minimum weight of all possible directed paths with origin u and destination v. Let $u \xrightarrow{p} v$ denotes that v is reachable from u through the directed path p. Therefore,

$$dist(u, v) = min\ \{\phi(p) : u \xrightarrow{p} v\} \tag{4}$$

For a source node $s \in V$, the Dijkstra's shortest path algorithm calculates the distance $dist(s, v)$ for all $v \in V$ (adopted from Xu et al., 2007).

Firstly, we developed a resistance raster by integrating six different raster layers: (1) altitude (obtained from SRTM elevation data), (2) slope (calculated from SRTM elevation data), (3) distance to roads (through network analysis), (4) distance to population centers (through network analysis), (5) LULC of the year 2020 and (6) potential distribution model of SB (adopted from (Meza et al., 2020)). Each of these rasters was reclassified into resistance values ranging from 1 to 100, where 1 is the minimum value and 100 is the maximum value. (in agreement with (Graves et al., 2014; Reynolds et al., 2016). The weighted value of each pixel considered as the cost of displacement of the species of interest (*T. ornatus*) (Oliveira-Junior et al., 2020). We assigned the resistance of each raster based on the experts and scientists opinion as well as from existing literatures related to SB such as (Crespo-Gascón and Guerrero-Casado, 2019; Cuesta et al., 2003; García-Rangel, 2012; Meza et al., 2020; SERFOR, 2016; Wallace et al., 2014). Once the reclassified rasters were obtained, they were added together to generate the final resistance raster.

Furthermore, LCP toolbox was implemented to delineate the optimal path in terms of ECs to identify the cost of moving between patches of the habitat. The plugin requires two input files: (1) resistance raster, which indicates the level of disturbance or degree of difficulty that the target species are expected to encounter when moving between patches, (2) vector points, that represents the origin and destination in the NPA area. In this way, the representative points of the NPA were established at the edges of these, with the lowest possible resistance value and preventing them from crossing large rivers and roads.

2.2.2.4. Ecological corridor design and establishment.

After receiving the LCP modelled optimal path for habitat movement, the least expensive routes (lower resistance values) were identified where the ECs could be established. The identified routes were established with 2 km of width recommended as minimum thickness of the corridor (Beier, 2019). Additionally, a buffer of 1.5 km was applied for the establishment of ECs that connects the NPA of the area, considering some of the limits of rural communities are referential (IBC, 2016; SERNANP, 2021). The ECs were established taking as a reference to the distribution of *T. ornatus*, conservation plans, and priority conservation units according to their habitat in the NPA (SERFOR, 2016; Wallace et al., 2014).

In order to understand the degree of resistance in each ECs, we have calculated the cost of teach Ecs. The cost is the sum of the pixel values in the resistance raster, and represents the cost of displacement of the species of interest (*T. ornatus*). Finally, the cost/ha of the ECs, the percentage and area of forest they contain were calculated in order to identify which ECs would be more feasible to establish (in agreement with (Morandi et al., 2020)).

3. Results

3.1. Land use change in rural communities for the period 1990–2020

The results showed NPAs landscape underwent continuous temporal and spatial changes (Fig. 5A). The major transformation was observed with the loss of forest cover and increasing built-up and croplands over the last 30 years. Results showed an increase in the croplands over time, which covered 20.8% (144,867 ha) in 1990 and 30.3% (211,610 ha) in 2020. The rate of increase of this class was 2224 ha/year with an increasing rate of 9.5%. Similarly, bare lands/urban areas also increased over time. Bare lands/urban areas covered 12.8% (89,296 ha) of the study area in 1990 and it was increased to 15.83% (110,521 ha) by 2020. The rate of increase of this

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[2] https://plugins.qgis.org/plugins/LCPNetwork/

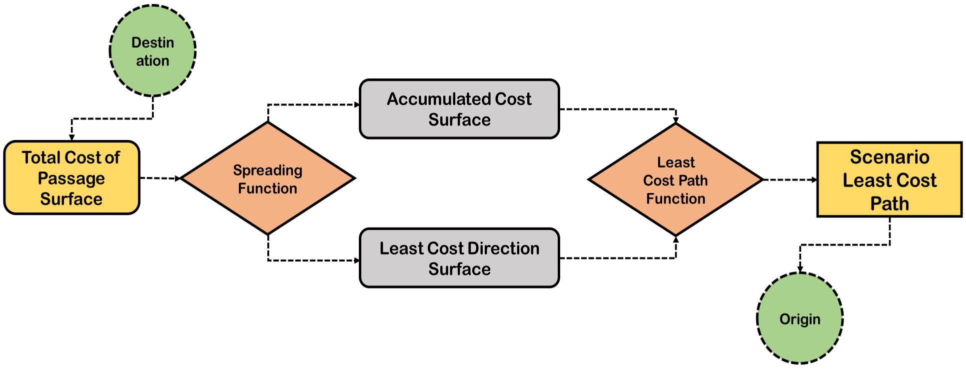

Fig. 4. Flow diagram of LCP concept.

class was 707 ha/year with an increasing rate of 3.03%. However, a significant loss in forest cover was observed over the last 30 years in the NPA of the Peruvian amazon. Forest cover reduced to 53.7% (410,716 ha) in 2020 from 66.2% (460,560 ha) in 1990. This forest cover decreased at a rate of − 12.50% with an area of 1661 ha/year.

The validation of the LULC maps in reference to the kappa coefficient showed satisfactory values with strong accuracy. We received a kappa coefficient of 0.90, 0.86, 0.85, 0.88 for the years 1990, 2000, 2010, and 2020 respectively.

3.2. Trajectory of LULC change for the period 1990–2020

To understand the habitat loss of SB (*T. ornatus*), we analyzed the trajectory of the LULC changes at the NPA region during 1990–2020. The major transformations in this landscape were paid by forest change and deforestation activities (Fig. 6). The main transformation experienced by the loss of forest cover was replaced by crops and to certain extent by bare soil/urban area. Forest cover replacement by crops were 11.6%, 11.4% and 14.3% for the period between 1990 and 2000, 2000–2010, 2010–2020, respectively. Such transformations were observed in the northwest and in the central area of the NPA. Fig. 6 showed an increase in croplands replacing other LULCs, mainly the forest cover. Similarly, accelerations observed for bare soil/urban areas with the rate of 5.7% and 5.1% between 2010 and 2020 respectively paid by the deforestation activities. However, the forest areas located in the south of the NPA were quite stable and uniform over the period assessed.

3.3. Quantification of landscape metrics

Table 2 and Fig. 7 shows the outcome of the landscape metrics within the forest class analyzed between 1990 and 2020. A significant change was observed for the forest landscape metrics namely number of patches, mean forest patch area (ha), and largest patch index (%). The number of forest patches within the study area increased by 57.7% between 1990 and 2020, from 7997 ha to 12,615 ha, respectively. Whereas, the average size of forest patches decreased by 48.4%, from 57.6 ha (1990) to 29.7 ha (2020). The higher patch index decreased by 35.3% throughout the entire period of study. Finally, the Euclidean distance to the average nearest neighbor remained relatively stable for the entire period.

3.4. Ecological corridors delineation

The variables (i.e. altitude, slope, distance to tracks, distance to population centers, LULC of 2020 and species inventory map) to generate the resistance raster shows wide variability. Fig. 8 shows individual variables including the resistance raster. The altitude that represents the elevation profile of the region, varies between < 1000 m.a.s.l to > 4000 m.a.s.l with the higher concentration between 3000 and 4000 m.a.s.l. Slope level in this region is observed with a wide degree of variability ranging between 0° to $> 30^\circ$. Similarly, distance to road and distance to populated centers are well distributed over the NPA region of the Peruvian Amazon. As per the LULC of 2020, most of the landscape is covered by forest followed by crops and bare soil/urban with limited availability of water bodies. Habitat suitability zones are dispersed in nature and not concentrated in a single part or location.

Finally, the resistance raster shows the variability between the low resistance scale from 63 to highest resistance scale of 460. From the modelled resistance map, highest resistance is observed in the north-eastern part of the NPA whereas lowest resistance is observed in the south. High resistance values are observed along the border line of rural communities in the NPA whereas the border areas of NPA are mostly characterized by low resistance.

We established 13 different route of ECs with their associated cost per hectare (cost/ha*) (Table 3 and Fig. 9). It shows that ECs number 8 is characterized with lowest cost/ha with the value of 2776 followed by ECs number 7, 4, 9, 1 with the value of 2869, 2877, 2951, 2971 respectively. Similarly, ECs number 10 characterized with highest cost/ha with the value of 3845. Additionally, we observed that the percentage of forest cover significantly changes with the cost of ECs. Regarding the percentage of forest cover owned by each of the ECs, corridor number 7 is identified with the highest value, which covers maximum forest of 99.4% (502.3 ha) and corridor number 13 is identified with the lowest value, with the forest cover of 17.4%. ECs number 1, 6, 11 are characterized with

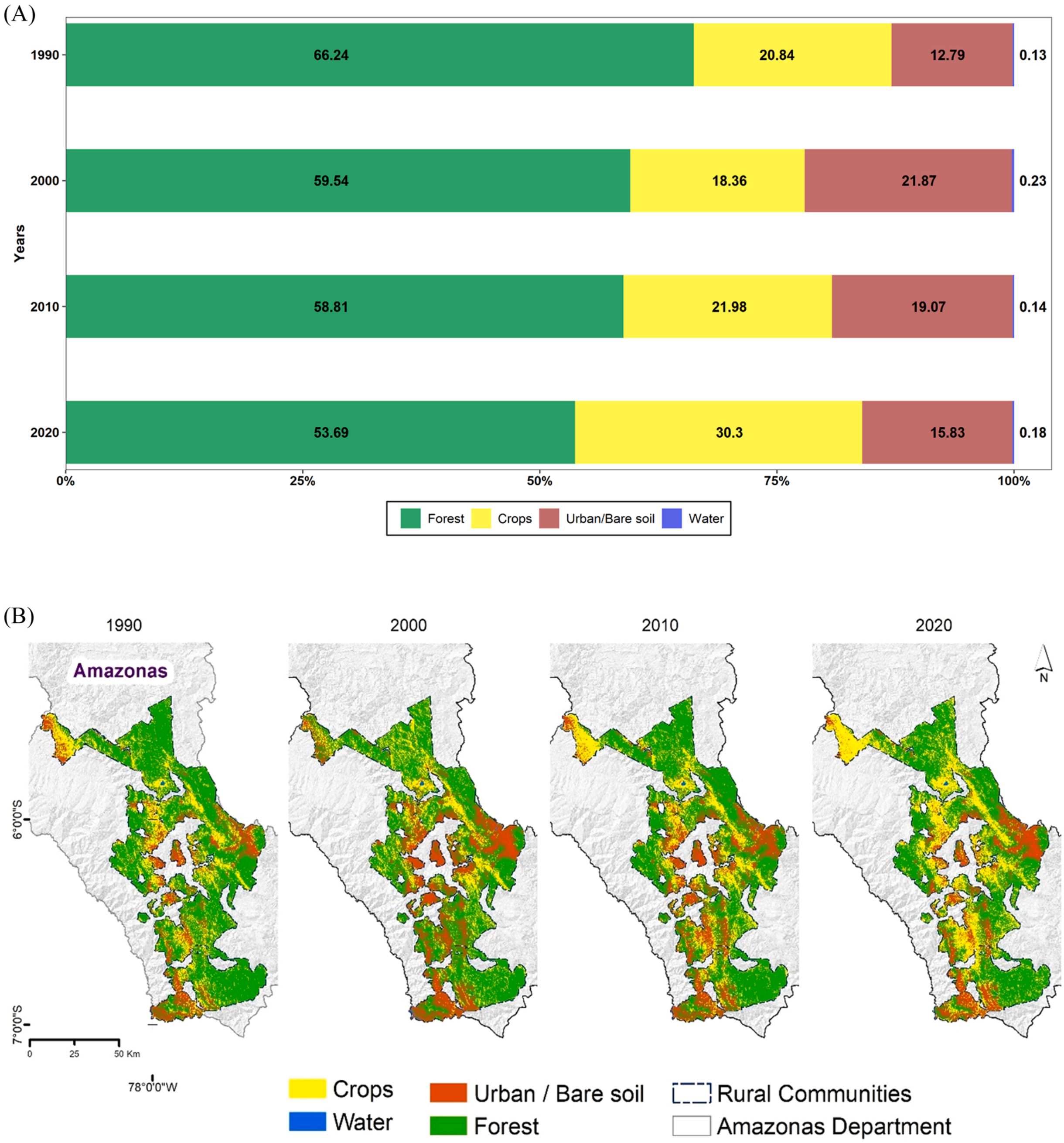

Fig. 5. LULC change in the territory of rural communities between 1990 and 2020. (A) the relative composition of LULC between 1990, 2000, 2010 and 2020; (B) LULC maps for the years 1990, 2000, 2010 and 2020.

similar cost and percentage of forest cover (Fig. 10).

4. Discussion

We delineated the ECs for threatened SB over the NPA region of the Peruvian Amazon for the firs time through the integration of cloud computing and machine learning models. Moreover, we also quantitatively estimated and updated the temporal LULC change over the last 30 years which was never studied before. The uniqueness of our study was that we integrated the spatio-temporal LULC change and designed the ECs in a cost-effective approach that will immensely support the development of ECs in real grounds. (Rosenthal et al., 2012) emphasized and only discussed the strategies to develop mosaic-based conservation corridors in southeastern Peru. However, no such model grounded design of ECs with cost-effective solutions for the SB at the NPA region was not delivered.

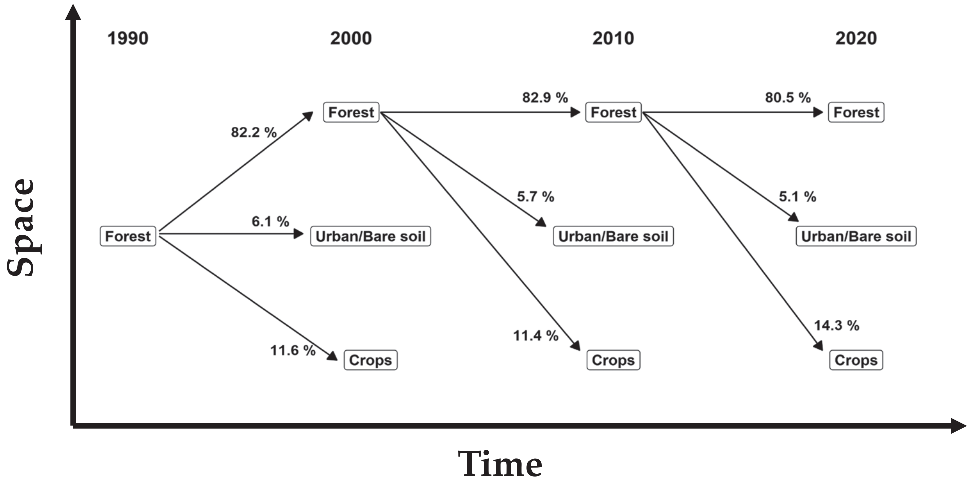

Fig. 6. Space-time trajectory of LULC change for the period 1990–2020.

Table 2
Changes in the forest landscape pattern indices for the forest in the study area in 1990, 2000, 2010, and 2020.

Landscape metrics	1990	2000	2010	2020	% change (1990–2020)
Number of patches	7997	12,992	10,062	12,615	+ 57.7%
Mean forest patch area (ha)	57.6	32.0	40.8	29.7	-48.4%
Largest patch index (%)	45.8	17.7	12.5	10.5	-35.3%
Mean Euclidean nearest neighbor distance (m)	118.9	107.7	123.1	118.8	-0.1%

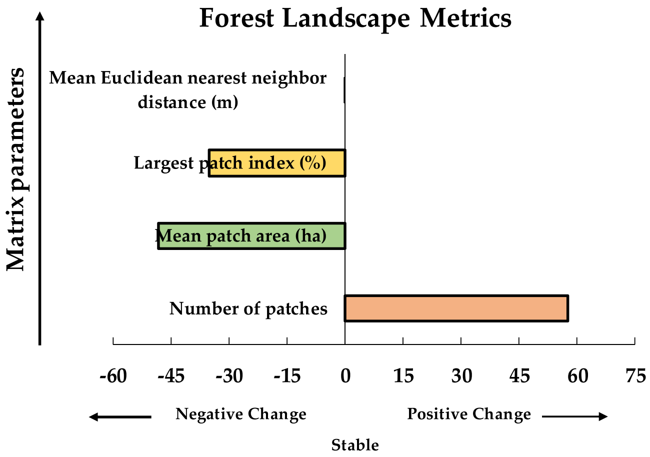

Fig. 7. Forest landscape change matrix during the period 1990–2020.

Furthermore, the present landscape scenario of the NPA and its temporal transformations over a long decade was not studied by them. Similarly, during the 1990 s Niman et al. (1993) only studied the role of riparian corridors in maintaining regional biodiversity that mainly focused the fluvial corridors over the Peruvian Amazon in line of argument with McClain and Cossío (2003). Aikman (2010); Cotrina Sánchez et al. (2021); Sánchez-Cuervo et al. (2020) also limited their research on LULC transformations and did not discuss the development of ECs.

4.1. LULC change and forest fragmentation

The scientific evidences obtained from this study supports our hypothesis that considerable transformations of the LULC occurred over the rural communities as well as in the NPA. Our study showed a decrease in forest cover, generated mainly by the increase in agricultural activities and colonization of human populations. This behavior responds to the colonization by people from other regions who arrived with few economic resources and cut down trees to extract wood and plant crops to survive (Schjellerup et al., 2003). In

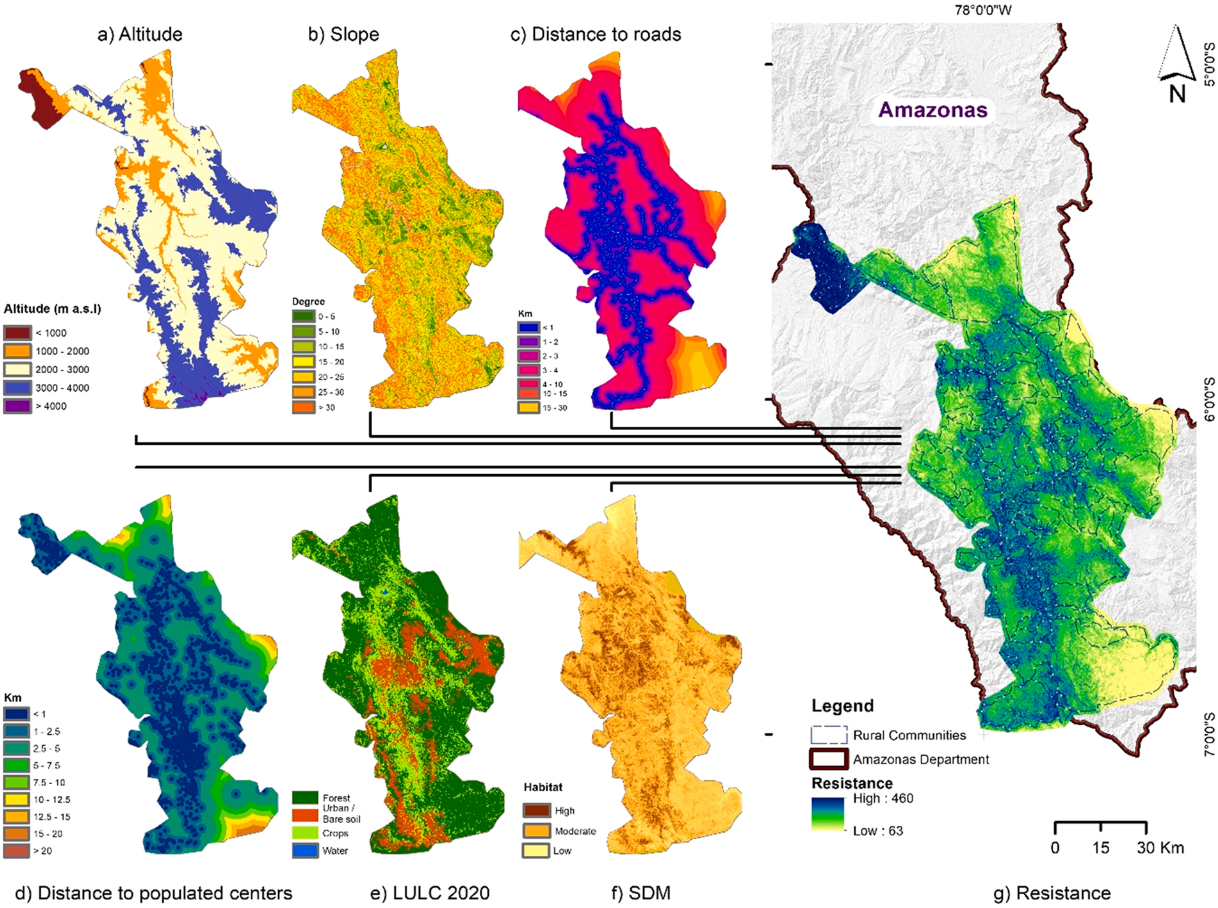

Fig. 8. Variables used to model the resistance layer along with the modelled resistance raster map. (a) Altitude; (b) Slope; (c) Distance to roads; (d) Distance to populated centers; (e) LULC of 2020; (f) Species inventory; (g) Modelled resistance raster.

Table 3
Characterization of potential corridors connecting conservation areas in rural territory.

EC	Length (km)	Area (ha)	Total cost	Cost/ha	Forest Area (ha)	Forest (%)
1	8.8	1989	5,912,332	2971	1708	86.0
2	11.5	2540	8,222,019	3237	1932	76.1
3	12.2	2653	9,475,867	3571	1379	52.0
4	6.7	1607	4,626,347	2877	1530	95.2
5	25.6	5178	19,037,776	3676	2567	49.6
6	27.3	5593	17,448,637	3119	4552	81.3
7	1.0	505	1,450,944	2869	502	99.4
8	56.4	11,343	31,490,470	2776	6425	56.8
9	19.3	4090	12,069,949	2951	3918	95.5
10	6.3	1545	5,941,049	3845	777	50.1
11	18.6	4012	12,484,910	3112	3827	95.3
12	15.9	3429	11,179,702	3260	2345	68.4
13	7.1	1698	5,911,703	3480	294	17.4

other cases, forests were cut down to create grasslands, and paramos and puna were burned to provide new spaces for livestock. It reduced the food supply of bromeliads and ericaceae that make up an important part of the SB diet (Amanzo, 2008; Figueroa and Stucchi, 2009; Peyton, 1999). So, it is important to consider that historical threats remain in the NPA region where deforestation, forest fragmentation, built-up encroachments, soil degradation, and increasing number of step-cultivation mainly remain the drivers of LULC change.

As a result of the increased development of anthropic activities in the study area during the period 1990–2020, forest fragmentation accelerated with 57% increase in the number of patches. Additionally, the average patch size was reduced by 48.4%, from 57.6 ha in 1990 to 29.7 ha in 2020. This pattern follows the global trend, where large areas have been degraded to multiple patches that are

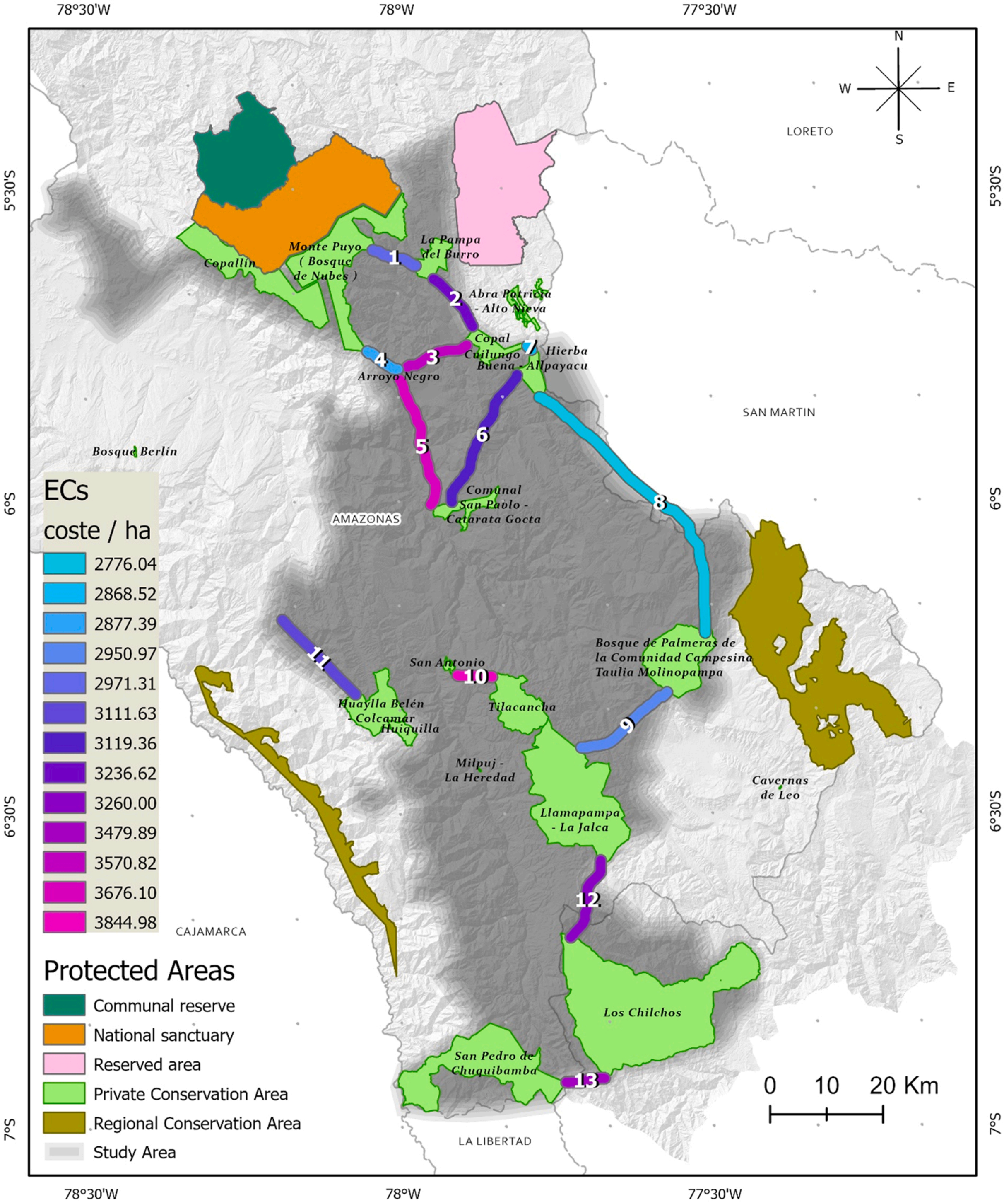

Fig. 9. Identification of ECs connecting the conservation areas of SB in the NPA of the Peruvian amazon. The cost is the sum of the pixel values in the resistance raster and represents the cost of displacement of the species of interest (*T. ornatus*).

smaller and disconnected and put the survival of the species at risk (Fahrig, 2003; Wu et al., 2021). These trends have also been reported in other Latin American countries, such as Chile (Hernández et al., 2016; Schulz et al., 2010) and Brazil (Salazar et al., 2021). The accelerated rate of forest fragmentation in the NPA region forced the SB to retreat from there, avoiding contact within the community, increasing the overlap zones between human economic activities and SB (Rojas et al., 2019).

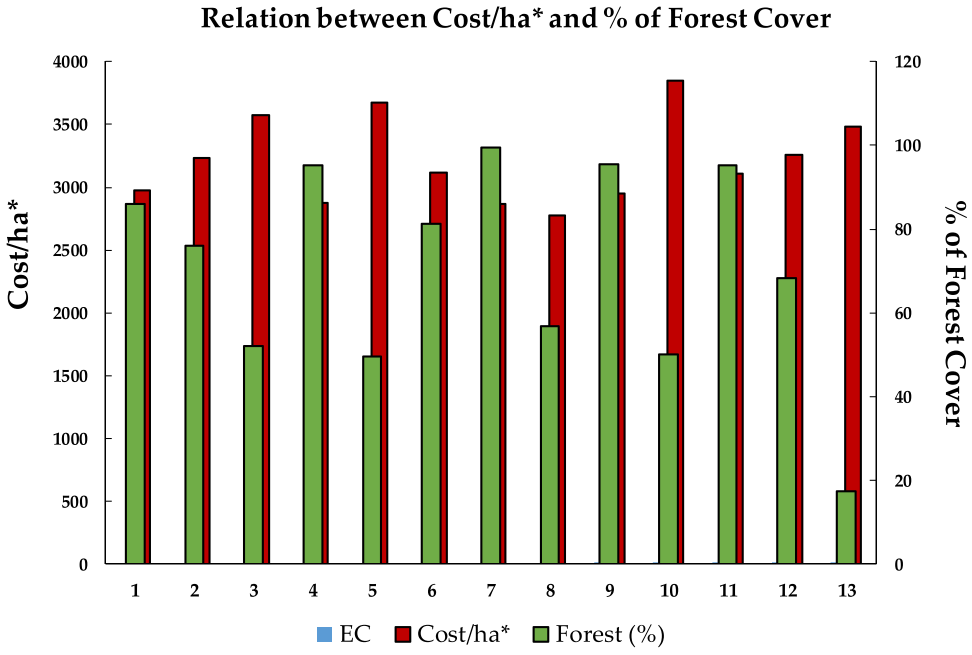

Fig. 10. Relationship between cost/ha and percentage of forest cover at every EC.

4.2. *Cost effective design of ECs*

Our study reports and evidences the design of cost-effective ECs and their interconnectivity (Fig. 9) that connects the different parts of the NPA within the rural territories for better accessibility of the SB. This will help to develop an interconnected NPA network that could prevent ecosystem destruction and species isolation, and reduce the risk of wildlife extinction (Gutiérrez-Chacón et al., 2020; Kaszta et al., 2020; Travis Belote et al., 2016). According to the cost/ha and the percentage of forest that the ECs possess (Table 3), corridors 4 and 7 would be the most feasible to establish, while corridors 3, 5, 10 and 13 would be less feasible. According (Beier, 2019), the corridors need to be developed with a width of 2 km without disturbing the forest cover and increasing feasibility. Similarly, if the landscape are full with barriers that prevent the ECs from having a width of 2 km (as could be the case of corridors 3, 5, 10 and 13), the width of the corridor can be reduced and thus increase the feasibility of establishing them in such landscape (Gregory and Beier, 2014).

We found a statistically significant and a negative agreement between the cost of ECs and percentage of forest cover (Fig. 11). It shows that the cost of ECs are increasing with a decreasing rate of forest cover and vice-versa which is in agreement with the arguments of Salazar et al. (2021). It means that the higher the forest cover, the better the connectivity and the lower the cost of mobilization in the ECs. Thus deeper and dense forest covers will support the SB community interactions, safe mobilization and movement of services.

The ECs located in the northern part of the study area is the one that allows a greater connection to NPA from rural conservation and national administration perspectives (Fig. 9). In addition, during the study, information collected from the camera traps in the "Copallin" conservation area (indirectly connected by the ECs 1 and 4), evidenced the presence of the SB (Fig. 12). Similarly, in the Hierba Buena-Allpayacu private conservation area (connected by the ECs 6, 7 and 8) along the Corosha River bank confirmed the presence of currently unique golden SB as reported by (Rojas et al., 2019; Yunkawasi, 2021). Such highlights breakthrough the importance of ECs, which increases the interconnectivity of SB populations, which was reduced by 53.61% from its historical records (Wallace et al., 2014). The reported ECs may be the functional units for SB that need to be monitored over time. Our study will support such initiatives and allow the development of more sustainable ECs that could act as functional units for SB as well as for other species of the Peruvian amazon. Moreover, development of ECs in these areas will compensate for the loss of forest experienced since 1990 in the territory of rural communities of the Peruvian Amazon.

Alternatively, to the establishment of ECs, there are various conservation interventions that can be used to achieve the goal of increasing connectivity, such as steppingstones, expanding NPA, and managing the entire matrix for permeability. Most of the routes identified for the establishment of the ECs have a forest area greater than 50%, so it is possible to guide forest preservation or restoration strategies (Arroyo-Rodríguez et al., 2020). In addition to the above, the economic, social and political aspects that are also crucial when deciding whether to protect, where and how much should be protected must be considered (Cushman et al., 2018).

Furthermore, the cost-effective ECs design developed in this study for a heterogeneous forest land like Peruvian Amazon, could be implemented and adopted for other parts of the global forest areas with required modifications of the variables. Our study opens new avenues that combine modern geospatial simulations along with cost-effective solutions for affordable, sustainable ECs development procedures in the forest regions. This study provides key information for the national plan and future conservation initiatives through

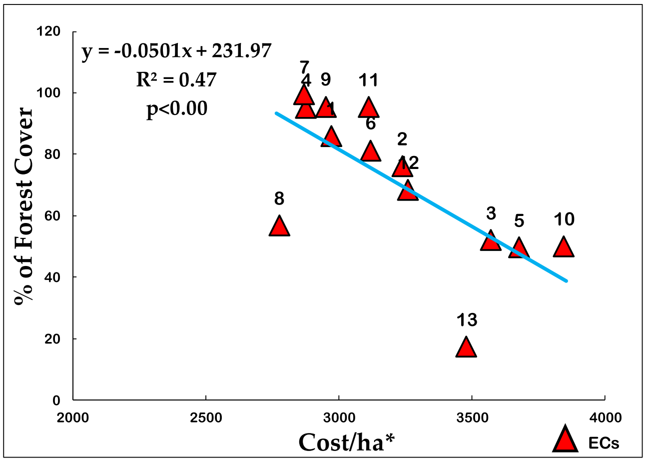

Fig. 11. Agreement between cost/ha* and percentage (%) of forest covers. Numbers in triangles represent the ECs.

Fig. 12. SB captured from the camera traps in the "Copallin" conservation area (indirectly connected by the ECs 1 and 4).

the development of ECs.

5. Conclusion and Recommendation

This study shows the cost-effective design of ECs that can be developed and implemented in the NPA region of the Peruvian Amazon in support of cloud-computing and geospatial technology. We observed that increasing forest cover creates better connectivity and lowers the cost of mobilization in ECs and vice-versa, which was never examined before for this ecological relevant territory. Additionally, identifying the LULC changes over time can serve as an excellent indicator to target vulnerable ecosystem zones and implement immediate biodiversity conservation actions in the study region (Figueroa Pizarro, 2015; Meza et al., 2020; Rojas et al., 2019; SERFOR, 2018). Finally, our study outcomes were validated through the images obtained from trap cameras that confirms our delineated routes for habitat movement.

The proposed method can be adopted for other species too in this region. Therefore, scientific observations obtained from this study helps us to formulate sustainable recommendations that will support the conservation practices for the Peruvian Amazon and as well as other global habitat zones.

(1) Establishment and promotion of Forest Association/Cooperation structures to rejuvenate, monitor and develop new ECs to support the mobilization of the SB. According to the same, cost-effective design of the ECs presented in this study needs to be adopted those accounts for higher connectivity with low cost and less harm to the forest cover. Furthermore, model projected distribution sites will be considered with maximum interest.

(2) Projected ECs model in climate change scenarios could help more in this task, because even if there are changes in the distribution of the species, the model also changes. Therefore, under the scenario of climate change, the conservation authorities, local governmental organizations, stockholders and policy makers need to be attentive to modify the variables of the ECs model throughout the development process. This will support the functional habitat mobility even under the rising temperature or during climatic anomalies.

(3) Key concentration need to provide for the regions with significant LULC change in the last 30 years to protect the local ecosystem and identify the threatened species within the forest area. Engagement of adequate technology (such as UAV) and AI

driven (such as machine learning models) modelling approaches need to be adopted time-to-time to monitor real-time LULC changes. Special focus needs to provide in the critical zones.

(4) Engagement of the local rural and tribal communities are highly necessary for sustainable and cost-effective ECs development. Therefore, promotion and capacity building of the rural communities for forest mobilization and motivation for sustainable management through training opportunities, information campaigns and events need to be adopted.

(5) Moreover, a synergetic strategic involvement including regional and multinational commitments are highly necessary to protect one of the distinct species of the Peruvian amazon.

In Peru, the National Plan for the Conservation of the SB was implemented for the period 2016–2026 (Meza et al., 2020; SERFOR, 2016). Involvement of technology driven scientific studies and their recommendations need to be incorporated significantly with the final management policies and conservation plans adopted by the government in the near future. Additionally, more biogeographic simulations and climate concern diversity modelling studies need to support by the conservation stockholders and policy-makers for sustainable conservation of SB and other species under climate change scenarios.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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