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Key connectivity areas in the Llanganates-Sangay Ecological Corridor in Ecuador: A participative multicriteria analysis based on a landscape species

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HIGHLIGHTS

- Native vegetation and small forest patches are critical for Mountain Tapir dispersal.
- Roads and human population density limit the movements of the Mountain Tapir.
- Involving local stakeholders highlighted important areas for Mountain Tapir conservation.
- A participative process doubled the corridor area by including private lands.

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ABSTRACT

Habitat loss and fragmentation are critical threats to biodiversity decline as they decrease the species occurrence and dispersal probability between natural habitats. Thus, promoting habitat connectivity supports species dispersal and accessibility to vital resources within the landscape, and contributes to long term population persistence. However, decision-making in human dominated landscapes challenges the sustainability of conservation-based land management initiatives. The Llanganates – Sangay Ecological Corridor is located on the eastern slopes of the Ecuadorian Andes, harbouring high levels of endemism and biodiversity in a human-dominated landscape between two National Parks. We applied circuit analysis to model the habitat connectivity for the Mountain Tapir. We defined the limits of the corridor based on a Multi-Criteria Decision Analysis and a spatial suitability approach combined with a sub-basin prioritization method. We found that forest and native grasslands contribute the most to the Mountain Tapir's dispersal movements, while roads constrain them the most. Furthermore, natural vegetation remnants between pastures and crops support habitat connectivity as stepping-stones. We identified threats to biodiversity and distance to conservation areas as the most crucial features of spatial suitability. Our study combined scientific information to identify key areas for providing habitat connectivity of a landscape species and the spatial suitability necessary for sustaining wildlife conservation, while supporting the participation of local stakeholders, conservationists, academia, and NGOs.

1. Introduction

Land-use change often leads to habitat loss and fragmentation, triggering a cascade of ecological effects and impacting biodiversity persistence at different spatial and temporal scales (Salafsky et al., 2008; Pereira, Navarro, & Martins, 2012). As such, securing the linkage between habitat patches to support the flow of organisms, materials, energy, and information across landscapes (i.e., habitat connectivity) helps

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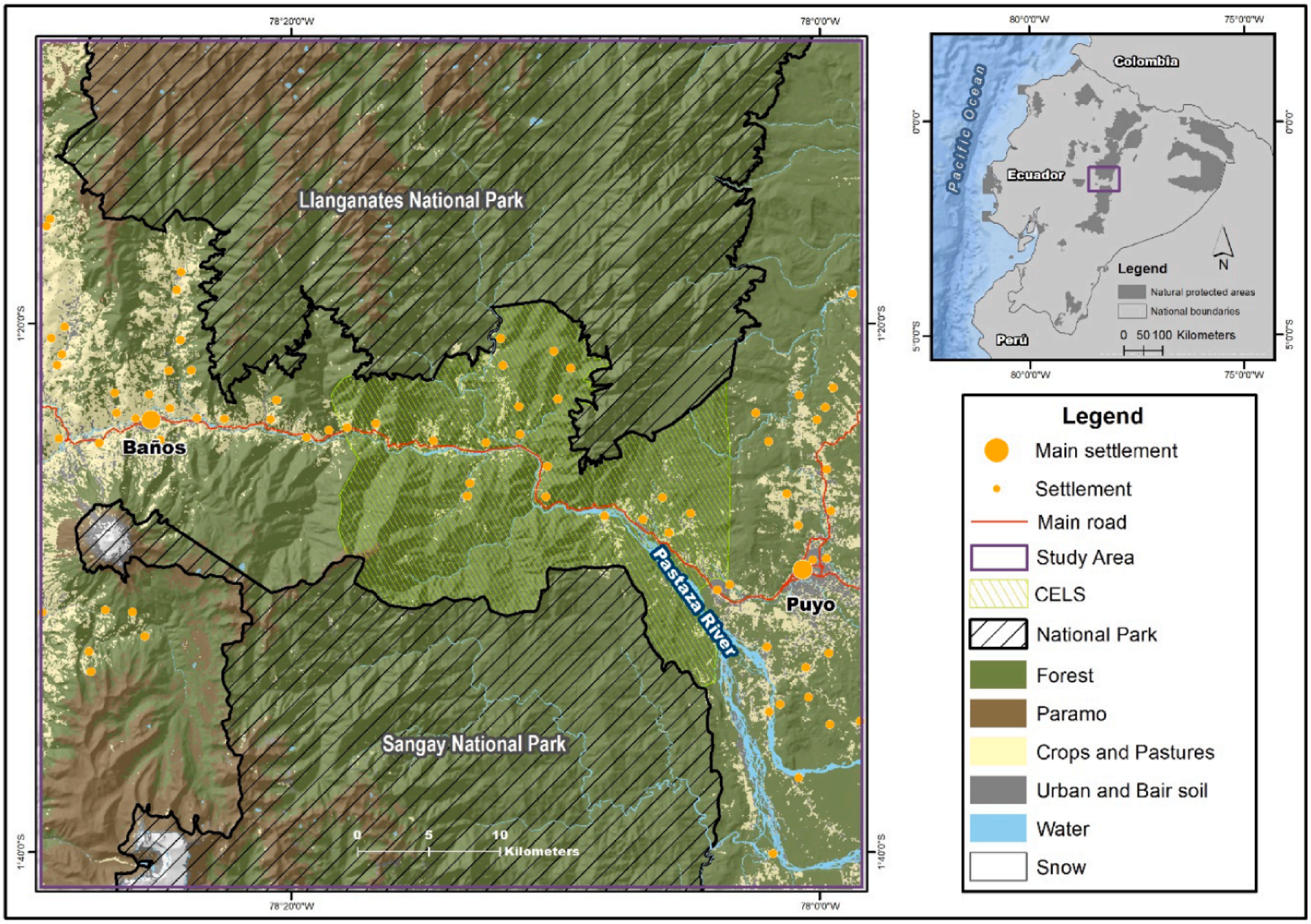

Fig. 1. Location of the Llanganates – Sangay Ecological Corridor (CELS).

reduce habitat isolation, favours population dynamics and reduces the risk of species extinction (Beier & Noss, 1998). In many cases, protected areas are not sufficient to conserve species within their distribution and home ranges (Williams, Rondinini, & Tilman, 2022). Thus, linking protected areas with natural habitat remnants supports interpatch species dispersal and accessibility to vital resources within the landscape as a function of both the temporal and spatial context (Caro, Jones, & Davenport, 2009; Saura, Bodin, Fortin, & Frair, 2014).

In general, there are two main components making up connectivity analyses. The structural component, which deals with the composition and arrangement of the physical elements in the target area (i.e., structural connectivity). And secondly, the ecological component, namely the natural processes or the resulting species-specific responses to the structural elements in the landscape (i.e., functional connectivity) (Tischendorf & Fahrig, 2000). Consequently, there are different techniques for assessing habitat connectivity. For instance, structural connectivity focuses on the spatial arrangement of the habitat patches regardless of any ecological requirement. Whereas functional connectivity deals with the species movement responses according to the spatial features (Tischendorf & Fahrig, 2000; Cushman et al., 2013; Keeley, Beier, & Jenness, 2021). Similarly, the spatial composition and structure of the landscape are site-specific and vary according to human influences. Therefore, assessing the habitat connectivity depends upon the spatial features derived from land-use change and the target species' response (Cushman et al., 2013). One common approach is assessing the movement resistance caused by the arrangement of heterogeneous spatial features within the landscape (McRae, 2006). In the present study, core areas, connectivity corridors, and buffer zones are of greatest importance, as they facilitate ecological processes and wildlife dispersal across the matrix (Beier & Noss, 1998; Cushman et al., 2013; Arroyo-Rodríguez et al., 2020). Combining spatial analysis with potential wildlife dispersal paths is therefore very useful in prioritizing valuable areas when designing connectivity corridors (Caro et al., 2009; Cushman et al., 2018). However, this alone is not sufficient for establishing corridor boundaries (Arroyo-Rodríguez et al., 2020). Success in defining borders depends on physical barriers that allow discrete spatial designation, such as watersheds. Watersheds are excellent hydrogeological features that promote spatial-based conservation solutions. They help maintain ecological integrity within their boundaries and establish natural limits for land management (Theberge, 1989).

Concerning human-populated landscapes, ecological networks (i.e., where human-use areas and natural areas coexist in balance) support conservation by promoting connectivity corridors and low-impact human activities (Arroyo-Rodríguez et al., 2020). Nonetheless, the feasibility of these networks depends on the local peoples' commitment and participation in the decision-making process (Kunjuraman, 2021). To insure the process' sustainability over time, it is important to include contrasting criteria that provide a classification of the main objectives according to stakeholder priorities (Saaty, 1990; Guaita Martínez, de Castro-Pardo, Pérez-Rodríguez, & Martín Martín, 2019). Multi-Criteria Decision Analysis (MCDA) has been a valuable tool for promoting agreement on the management of natural resources and protected areas (Castro-Pardo & Urios, 2016; Cegan, Filion, Keisler, & Linkov, 2017). This analysis allows stakeholders to participate and reach consensus through quantitatively ranking decision-relevant criteria, promoting agreement among all parties involved (Guaita Martínez et al., 2019). Similarly, spatial suitability approaches have been used to support effective decision-making in land management. These approaches maximize benefits from both land-use change and conservation initiatives (Polasky et al., 2008), as well as promote policy-making that encourages sustainable development in urban and rural areas (Yang et al., 2008).

The main threats to biodiversity conservation are the disruption of natural ecosystems caused by roads, infrastructure, deforestation, mining, oil extraction, crops, and cattle ranching (Ortega-Andrade et al., 2021). These factors have played a significant role in the loss of habitat for the critically threatened Mountain Tapir (*Tapirus pinchaque*). In general, protected areas alone cannot sustain large terrestrial mammals due to the limited resources available (Williams et al., 2022). Connectivity approaches targeting endangered species have promoted land management that improves habitat permeability across the landscape, as well as policymaking through supporting economic activities in line with conservation (Silveira, Sollmann, Jácomo, Diniz Filho, & Tôrres, 2014; Ceballos et al., 2021; Tortato et al., 2021).

Herein, we combined ecological connectivity modelling, spatial analysis, and a multi-disciplinary participative process in order to, 1) identify the spatial attributes that contribute to the habitat connectivity of our target species, the Mountain Tapir (*Tapirus pinchaque*); 2) redefine the limits of a global diversity hotspot based on the spatial context for assessing the feasibility and sustainability of a corridor for Mountain Tapirs; and 3) assess the feasibility of involving local stakeholders and organizations in conservation planning.

2. Methods

2.1. Study area

The Llanganates – Sangay Ecological Corridor (CELS) is part of the Tropical Andes, one of the largest and richest global biodiversity hotspots (Myers, Mittermeier, Mittermeier, da Fonseca, & Kent, 2000). It is located on the eastern slopes of the Ecuadorian Andes, in a human-dominated landscape between Llanganates National Park (219,707 ha) to the north and Sangay National Park (502,105 ha) to the south. The elevation of CELS ranges from 760 to 3,812 m encompassing a gradient of climatic conditions within a major ecotone between the Ecuadorian highlands and the upper Amazon (Haynie & Brant, 2006). Its geographical location and geological history favour a high endemism and diversity of ecosystems and species throughout (Palminteri, Powell, & Naranjo, 2001; Jost, 2004; Cuesta, Peralvo, & Valarezo, 2009; Lessmann, Muñoz, & Bonaccorso, 2014; Cuesta et al., 2017) (Fig. 1). These factors led to the declaration of CELS as a priority area for conservation in the Northern Andes (Palminteri et al., 2001). In 2002 it was acknowledged as a "Gift to the Earth" by the World Wildlife Fund (WWF) due to its high level of biodiversity, importance as a climate change refuge, and potential habitat connectivity linkage between protected areas (Ríos-Alvear & Reyes-Puig, 2015). Consequently, in 2023 CELS was formally declared as a Connectivity Corridor by the Ecuadorian Ministry of the Environment, Water, and Ecological Transition (Ministerial agreement 2022-138).

The CELS precipitation regime exhibits bimodal annual rainfalls from April to June and October to December, which can exceed 5,000 mm annually in places (Ilbay-Yupa, Lavado-Casimiro, Rau, Zubieta, & Castillón, 2021). The region encompasses montane forest, grassland, and different land-use classes, but natural vegetation covers around 90 % of its total extent (Ministerio del Ambiente del Ecuador, 2013). CELS is located in the Pastaza and the Napo River basins, encompassing 81 % and 19 % of the corridor's area, respectively. Previous studies indicate that the Pastaza River acts a biogeographical barrier for small-sized vertebrates, like amphibians, reptiles, and medium to small-sized mammals (Jost, 2004; Haynie & Brant, 2006; Reyes-Puig, Reyes-Puig, Franco-Mena, Jost, & Yánez-Muñoz, 2022). However, the river is interrupted by two hydroelectric dams (Agoyán and San Francisco), causing a substantial reduction in flow along sections of up to 6 km in length. Therefore, the passage of large mammals across the river is possible in these places.

Although CELS was conceived in 2002, it was not officially recognized for many more years due to shortcomings in the sustained involvement of local communities and the lack of a legal framework to direct the management of corridors in Ecuador (Ríos-Alvear & Reyes-Puig, 2015).

In the present study, we reviewed 3,417 km^2 of land area in CELS. The study region included the areas south of the Llanganates National Park and north of the Sangay National Park. It is represented by the Patate and Baños de Agua Santa counties from the Tungurahua province, Mera and Puyo counties from the Pastaza province, and a portion of the Penipe, Julio Arosemena Tola, and Palora counties from the Chimborazo, Napo, and Morona Santiago provinces, respectively.

2.2. Target species

The Mountain Tapir (*Tapirus pinchaque*) is one of four extant tapir species. It is distributed throughout the montane cloud forests, riverine habitats, and native grasslands (hereafter referred to as páramos) in the Tropical Andes of Colombia, Ecuador, and northern Peru, from 1,400 to 4,500 m in elevation (Cavelier, Lizcano, Yerena, & Downer, 2011; Lizcano, Amanzo, Castellanos, Tapia, & López-Malaga, 2016). The species occurs in well-preserved and moderately disturbed habitats adjacent to forests (Cavelier et al., 2011). Mountain Tapirs use their sense of smell to orientate while walking and foraging, whereas their sight is thought to be somewhat limited (Downer, 1996). Mountain Tapirs are frequently observed along steep mountain ridges, landslides, and in flat terrain, where they establish numerous overlapping trails associated with their foraging areas. The montane forest serves as a source of food, shelter, and concealment, while the riverine areas facilitate movements between mountains and provide access to mineral salt licks. As a result, Mountain Tapir tracks are commonly found along rivers and around deep pools below waterfalls (Downer, 1996; Cavelier et al., 2011; Reyes-Puig & Ríos-Alvear, 2013). The mature Mountain Tapir maintains a home range of approximately 8.8 km^2, which may overlap with the territory of other individuals. However, human disturbances often lead to shifts in home range (Downer, 2002; Cavelier et al., 2011). The Mountain Tapir plays a critical ecological role as a seed disperser, and due to its association with water sources, it is considered a landscape species (Downer, 2002; Cavelier et al., 2011).

Habitat degradation, hunting, and cattle ranching are the main causes of the species' population decline. It is estimated that around 2,500 Mountain Tapirs remain in the wild today (Downer, 1996; Downer, 2002; Cavelier et al., 2011; Lizcano et al., 2016). Furthermore, land use alteration and climate change threaten the presence and conservation of the species outside protected areas (Ortega-Andrade, Prieto-Torres, Gómez-Lora, & Lizcano, 2015; Mena et al., 2020). Currently, less than one-third (29 %) of the habitat available for Mountain Tapirs remains within protected areas (Cavelier et al., 2011). In Ecuador, climate change could decrease up to 38 % of the possible distribution of the species by the year 2050 (Ortega-Andrade et al., 2015).

Previous studies have revealed that the Sangay and Llanganates National Parks harbour significant populations of Mountain Tapirs, but the species faces anthropogenic pressures that must be addressed in order to prevent their extinction (Downer, 1996; Downer, 1997; Cavelier et al., 2011; Lizcano et al., 2016). Moreover, the area encompasses a large part of the well-preserved habitat of outstanding value for the conservation of Mountain Tapirs and other threatened wildlife (Reyes-Puig & Ríos-Alvear, 2013; Ríos-Alvear & Reyes-Puig, 2013; Palacios, Naveda-Rodríguez, & Zapata-Ríos, 2018; Reyes-Puig et al., 2023) which helped garner recognition of the Sangay National Park as a World Heritage Site by UNESCO (UNESCO, 1983). Therefore, we hypothesized that the Llanganates and Sangay National Parks act as core habitats and encompass the principal populations of Mountain Tapirs in the greater region, while CELS provides temporary refuge and routes for dispersal movements between protected areas.

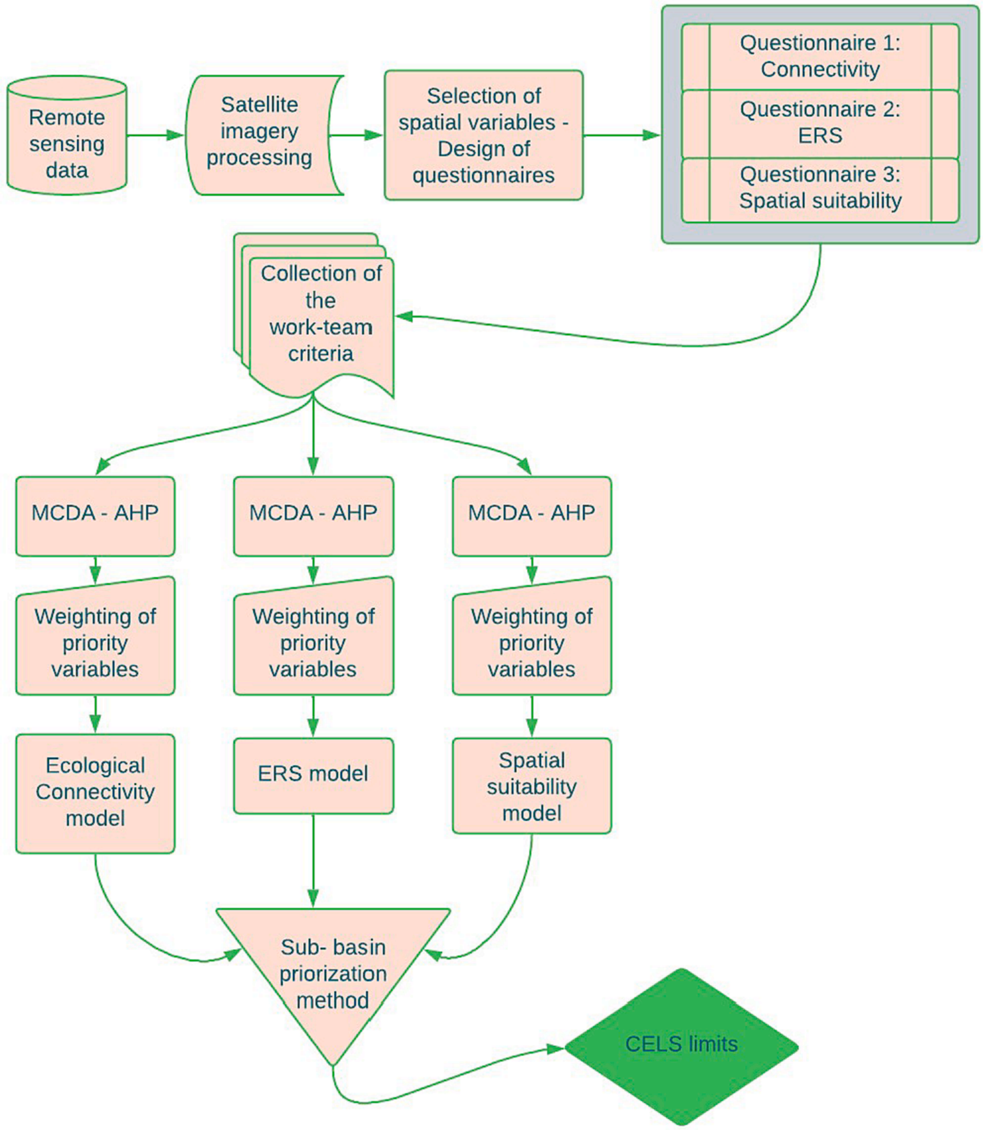

Fig. 2. Workflow and data analysis process for the study (ERS: Environmental Risk Surface, MCDA – AHP: Multi-Criteria Decision Analysis through the Analytical Hierarchy Process).

2.3. Data collection and processing

According to the spatial information available, we selected a set of variables affecting habitat connectivity and terrain suitability for conservation purposes (Keeley et al., 2021). We prioritized the variables following a multi-criteria analysis based on the relative importance value of each variable rated by 14 experts (geographers, sociologists, biologists, and ecologists) and five local conservationists. The team of experts was formed by individuals willing to participate in the survey, including CELS residents and local NGO staff. We developed 1) an ecological connectivity model for the Mountain Tapir, 2) an Environmental Risk Surface (ERS) model, and 3) a spatial suitability model to delineate the corridor (Fig. 2).

We designed three independent questionnaires to collect the expert's criteria for each model (See Supplementary material). Each expert was asked to sort the variables by their relative importance and score their contribution to each model. This procedure was applied separately for the ecological connectivity, ERS, and spatial suitability models.

2.3.1. Prioritization of the variables

To quantitatively assess the relative importance of each variable, we applied the Multi-Criteria Decision Analysis (MCDA) through the Analytical Hierarchy Process (AHP) following the modifications by Goepel (2013) on the responses of the experts (Goepel, 2013). The MCDA allows for consensus formation in decision-making derived from multi-disciplinary information and assembling the criteria of the parties involved (Guaita Martínez et al., 2019). The AHP is an MCDA method that facilitates conflict resolution derived from outputs of the relative importance quantification of variables obtained from the individual criteria (Saaty, 1990). We applied this procedure for each variable in the models assessed (Ecological connectivity, ERS and Spatial suitability models). The experts were asked to rank each variable according to its relative importance for each model. Values ranged from 1 = equal importance to 9 = high importance.

Thus, the relative importance obtained from a pairwise comparison among all the variables and categories (i.e., comparison between the variables, e.g., Energy production vs. Transportation, etc.; and within their categories, e.g., Mining vs. Oil, Primary roads vs. Secondary roads, etc.) generates a vector of normalized weights ranging from 0 to 1 (Saaty, 1990; Goepel, 2013) resulting from (1):

$$AHP = Weighted\ value\ of\ the\ variable * Weighted\ value\ of\ the\ category \quad (1)$$

Table 1
Categories and variables considered for the models assessed: (C) Ecological connectivity, (ERS) Environmental Risk Surface, and (S) Spatial suitability.

Variables	Model assessed	Description of categories
LULC	C	Land-use or land-cover classes identified by the supervised classification of a Sentinel 2 image. We defined six classes of LULC: forest, páramo, pasture/crops, water, areas without vegetation, and snow, however the latter three were not considered for modelling due to their low occurrence in the area.
Primary (PR) and secondary rivers (SR)	C	Spatial information from the Geographic Military Institute of Ecuador on a 1:50,000 scale. Based on the experts' criteria, we set a buffer of 15 m for the PR and 5 m for SR to represent the influence of the river's width perceived by the Mountain Tapir. We set the 5-meter buffer to the portion of the Pastaza River located between the Agoyán hydroelectric dam and the water discharge site (i.e., the confluence of the Pastaza River with the San Francisco creek) to represent low river flow caused by the dam.
Topographic ruggedness index (TRI)	C, S	The TRI represents the terrain heterogeneity based on the difference in elevation of a central cell compared to its surrounding cells (Riley, DeGloria, & Elliot, 1999). For our purposes, a lower TRI supposes greater ease for the dispersal of the Mountain Tapir within CELS (Mena et al., 2020). We generated a TRI based on the SAGA algorithm in QGIS 3.16, using a DEM at a 12.5 m spatial resolution obtained from the ALOS (Advanced Land Observing Satellite) and PALSAR (Phased Array type L-band Synthetic Aperture Radar) sensor of the Japanese Aerospace Exploration Agency (JAXA). We scaled the values according to the AHP, where lower values correspond to pixels with the highest TRI but less favourable for the species' dispersal, whereas higher values represent pixels with the lowest TRI but with greater importance for the species' dispersal.
Human population density (HPD).	C, ERS	We used the HPD model developed from demographic information from the 2010 population and housing census (Ortega-Andrade et al., 2021). For the connectivity analysis, we scaled the raster values from 0 to 2 according to the AHP, where low pixel values reflect high HPD but poor relative importance of the pixel for the Mountain Tapir's dispersal. HPD was used as a factor to represent the species' avoidance of human occupation. For instance, if a forest patch overlaps with an area of high HPD, the effect of the HPD (pixel value = 0) cancels out the positive effect of the forest on the species' dispersal.
Transport (primary, secondary, and tertiary roads)	C, ERS	We used the geographic information from the OpenStreetMap Foundation (OpenStreetMap Foundation) to redefine three classes of roads, 1) primary roads (paved roads and highways connecting primary human settlements), 2) secondary roads (paved or unpaved roads connecting small settlements with primary cities), and 3) tertiary roads (unpaved, minor, public or private roads connecting villages, farms or rural areas). For the connectivity model, we set buffers for each road class to represent barrier effects, as well as the Mountain Tapir's avoidance of human disturbances and vehicular traffic. We assigned a buffer of 125, 75, and 50 m around primary, secondary, and tertiary roads, respectively. A null value was assigned for tunnels due to their importance as potential crossing areas for wildlife. We defined two categories for mortality risk near roads based on human presence, LULC, and according to the observations of Medrano-Vizcaíno and Espinosa (2021). We assumed the segments of primary and secondary roads along human-populated areas, pasture/crops, and 50 m before tunnel entrances were a high mortality risk due to human-associated disturbances (e.g., vehicular traffic, hunting pressure, and presence of domestic dogs) (Suárez et al., 2009; Peck et al., 2010). The remaining segments of roads were considered low-mortality risk areas.
Agriculture	ERS	Perennial crops, annual crops, semi-permanent crops, pastures, agricultural mosaic and livestock, forest plantations, and other agricultural lands. Given our inability to identify different crops, we assumed biodiversity is affected equally regardless of crop class.
Climate change	ERS	Difference in the average annual temperature (Bio 01) between the current (1950–2000) and future climate models up to the year 2050 (RCP 8.5) for the average annual temperature (Bio 01) of WorldClim 2.1.
Deforestation	ERS	This variable refers to non-vegetated areas where the forest has been recently cleared according to the historical map of deforestation in Ecuador.

(continued on next page)

Table 1 (*continued*)

Variables	Model assessed	Description of categories
Stochastic events (ST)	ERS	Model of flood systems and areas influenced by volcanic activity in Ecuador.
Modifications to the natural system (MOD)	ERS	Strategic areas for the development of large-scale projects.
Energy production (EN)	ERS	Important areas for energy production: hydroelectric, mining and oil concessions.
Patch distance to suitable areas for conservation (PED-C)	S	Patch's Euclidean distance (PED) to areas with physical suitability for forestry and conservation or inappropriate for agricultural and grazing activities defined by the Ecuadorian Ministry of Agriculture. This includes páramos, rocky soils, glaciers, bodies of water, and sandbanks of the Tungurahua volcano. It excludes human settlements, infrastructure, and expanding urban areas. We assumed less likelihood of land use change in pixels closer to areas with physical suitability for conservation. Thus, the closer the pixel is to these areas, the more suitable it is for inclusion in the corridor.
Patch distance to areas with physical suitability for agriculture (PED-AG)	S	PED to areas with natural soil suitability for grazing and agriculture, defined by the Ecuadorian Ministry of Agriculture. This includes perennial and semi-perennial crops and pastures. We assumed more likelihood of land use change in pixels closer to these areas and, therefore, less sustainability for the corridor. Thus, the farther the pixel, the more suitable it is for inclusion in the corridor.
Complementary areas for conservation (COMP)	S	PED to complementary areas for conservation outside of the national protected areas (Cuesta et al., 2017). We assumed that the farther the pixel to these areas, the less suitable for the corridor.
Distance to the nearest patch of natural vegetation (PED-NAT)	S	PED to the natural vegetation remnants. We assumed that when the distance between patches is shorter, the greater their value for habitat connectivity, hence their importance for the corridor.
Natural vegetation patch size (PSize)	S	We defined 1 ha as the minimum patch size contributing to habitat connectivity (Wintle et al., 2019). We assumed that smaller patches are prone to be removed from the landscape, are more vulnerable to human disturbances, and contribute poorly as stepping-stones within the landscape.
ERS model output	S	Raster results from the ERS model to assess the threats to biodiversity. We assumed that the more significant the threats to biodiversity, the less suitable the pixel for inclusion in the corridor.
Distance to public and private conservation areas (PED-PPC)	S	PED to public and private protected areas besides the Llanganates and Sangay National Parks. We compiled information on "Bosques y Vegetación Protectora" reserves, private reserves, and forest reserves from private stakeholders in the study area. We validated the data according to the database of local NGOs, the experts, and the Ecuadorian Ministry of the Environment. We assumed that the closer to the conservation areas, the better the habitat conditions and the more suitable the pixel for inclusion in the corridor.
Distance to areas of the Socio Bosque Program (PED-SB)	S	PED to Socio Bosque territories (de Koning et al., 2011). We included the areas with an active agreement to the program only. We assumed Socio Bosque areas contribute to the corridor's feasibility and sustainability.

The Relative Value of the Weighted Hierarchical Analysis (Rel_{AHP}) of the categories and variables, results from (2):

$$Rel_{AHP} = AHP * number\ of\ categories \quad (2)$$

The Final Weight of each category and variable results from (3):

$$Final\ Weight = \frac{Rel_{AHP}\ of\ category}{\Sigma Rel_{AHP}\ of\ all\ categories} * 100 \quad (3)$$

Lastly, we used Intensity (Int_{AHP}) to reflect the relative importance of one variable to others. Intensity is calculated from (4):

$$Int_{AHP} = \frac{Final\ weight}{100} \quad (4)$$

2.3.2. *Parameterization of the variables*

The spatial variables were obtained from remote sensing data, open-source repositories, and the Ecuadorian government's cartography (OpenStreetMap Foundation, n.d.; European Spatial Agency, 2021; Ministerio de Agricultura del Ecuador, 2021) in order to represent the structure and composition of the landscape within CELS. We selected the variables according to their significance for the models assessed and rescaled from 0 to 1 (Table 1).

2.3.3. *Satellite imagery processing*

In order to identify the land use land cover classes, we performed a supervised classification of Sentinel 2 satellite imagery (European Spatial Agency, 2021) via the Random Forest algorithm (Thanh Noi & Kappas, 2018). A time series image composition was created from January 2020 to August 2021 to prevent inconsistencies in the classification process derived from cloud cover (Carrasco, O'Neil, Morton, & Rowland, 2019). We applied the Sentinel-2cloudless package for Python to mask the clouds and shadows in Sentinel imagery (Zupanc, 2017). The classification process was performed in the Google Earth Engine platform.

We used 236 training areas based on high-resolution images and aerial photographs obtained from Google Earth and the Ecuadorian government (Ministerio de Agricultura del Ecuador, 2021), as well as by recognition of spatial features observed in true colour and vegetation identified in false-colour band combinations for the same Sentinel 2 image. We defined six classes of land use and land cover (LULC): forest, páramo, pasture/crops, water, areas without vegetation, and snow, although the latter three were not considered for the models due to their low occurrence in the area. Once the training areas for each class were established, we applied the Random Forest algorithm with 100 interactions as recommended for land cover classification (Cánovas-García, Alonso-Sarría, Gomariz-Castillo, & Oñate-Valdivieso, 2017). We applied a majority filter with a 3 x 3 window to the result obtained in order to eliminate isolated pixels. Finally, the information gaps and poorly classified areas in páramos, where cloud and shadow masking errors occurred, were filled with information from the national land use and cover map at 1:25000 scale (Ministerio de Agricultura del Ecuador, 2021). We used 185 areas for validation via field visits and review of the high-resolution images and photographs. A confusion matrix was applied in order to test the precision in the LULC process according to the Kappa index. The LULC map was used subsequently and weighted with the AHP values according to the requirements during the modelling process. The variables selected were rasterized with a 30 m resolution.

2.4. Modelling process

2.4.1. Ecological connectivity model

We performed a connectivity analysis based on the principle of isolation by resistance, which predicts a positive relationship between genetic differentiation and the resistance distance caused by the matrix features (McRae, 2006). Circuit models convert the landscape into a circuit panel, composed of nodes (i.e., habitat patches) connected by resistors with different conductance (i.e., habitat link) according to their capability to sustain the electrical flow between nodes (i.e., dispersal movements between habitat patches depending on the spatial features) (McRae, Dickson, Keitt, & Shah, 2008). The model states that the effective resistance between a pair of nodes decreases as more connections are added (McRae et al., 2008). That is, the greater the number and the wider the links connecting two patches, the higher the probability of individuals' dispersal movements from one patch to another.

We selected five variables and ten categories according to the spatial information of CELS and their potential for promoting the dispersal of the target species in the Ecological Connectivity model ("C" in Table 1). A quantitative prioritization process was performed for the categories according to the expert criteria of five Mountain Tapir specialists working in the area. Each spatial feature was assigned with the AHP score according to its relative importance for the dispersal of the Mountain Tapir within CELS (Supplementary material A). Additionally, we incorporated ground connections into the circuit (e.g., mortality-risk areas) to represent the energy loss caused by spatial features that may reduce the success of dispersal movement within the landscape. The analysis was performed using Circuitscape version 1.5.3 in the Julia programming language (Anantharaman, Hall, Shah, & Edelman, 2019). We built a map of conductance representing the Mountain Tapir's dispersal probability as a function of the spatial features within the landscape (McRae et al., 2008). The natural vegetation patches were sorted into three size categories according to the spatial structure of CELS: category 1 (patches of < 1 ha), category 2 (patches of 1–53 ha), and category 3 (patches of > 53 ha). We performed a correlation analysis to investigate the relationship between the patch size and the cumulative electric current conducted by each patch size category. We did not explicitly factor in hunting pressure on the Mountain Tapir due to a lack of reports in the CELS over the last 15 years, with the majority being anecdotal and coinciding with habitat degradation activities such as agriculture and cattle ranching (Downer, 1996; TSG, 2010; Lizcano et al., 2016). Additionally, according to the experts' criteria, the Mountain Tapir is perceived as a charismatic and harmless species by local inhabitants throughout the corridor.

2.4.2. Environmental Risk Surface (ERS) model

We prioritized threats to biodiversity with a standard classification according to the Conservation Measures Partnership of the IUCN following Salafsky et al. (2008). Eight threats were defined as model variables and 18 categories within CELS ("ERS" in Table 1, Supplementary Material B). We set the maximum ranges of distance influence, the decay functions of each variable, and category of threats to biodiversity according to the criteria of Ortega-Andrade et al. (2021). We used the "Rescale by function" tool in ArcMap 10.5 to apply the decay functions on the rasterized variables for each threat and subcategory. In addition, the MSSmall transformation function was applied to represent the effect of distance to threats, so that short distances to the threat exhibit maximum intensity values, but sharply decay when moving away from the threat.

We asked the experts to rank the variables according to their relative importance in order to represent threats to biodiversity. Based on the selected geographic information and the weighting of the threats, we applied a spatial analysis to prepare the input variables required for the model. The modelling process included three stages: 1) resistance model by variables and categories based on the value of intensity and distance, 2) re-scaling by a decay function, and 3) summation of the raster models of the variables and categories rescaled with the "Sum Rasters - Any Extent (Folder)" tool of the SDM Toolbox v2.0 package (Brown, Bennett, & French, 2017). The result was a raster with continuous values of 0 (minimum threat) to 1 (maximum threat) at a resolution of 30 m $\times$ 30 m.

2.4.3. Spatial suitability model

A cartographic model was generated based on the relative importance of nine spatial variables within CELS ("S" in Table 1). We asked the experts to rank the variables according to their importance for promoting spatial connectivity and rasterized them given the score obtained from the variables' prioritization. We scaled the pixel values between 0 and 1 to represent the lower and higher contribution of each variable to landscape connectivity (Supplementary Material C).

Sub-basin prioritization process. A prioritization process was performed to redefine the limits of CELS by including key areas to sustain the spatial and ecological sustainability of the corridor in the mid and long term. We used a sub-basin approach to apply watershed management and delineate CELS borders, aligning with Ecuador's government policy for jurisdictional land management and governance areas (Constitución de la República del Ecuador Art. 262, num. 2). We defined the basin's borders using the DEM from the ALOS Project of the Japanese Aerospace Exploration Agency (JAXA) with the Hydrology tool of the Spatial analyst toolbox in ArcMap 10.5. The sinkholes in the DEM were corrected, from which we calculated the direction of water flow and the accumulated water flow. A hierarchical water network was then prepared following the Strahler classification method (Horton, 1945; Strahler, 1957) and according to closure points that fall into the Pastaza and the Anzu Rivers.

We designed a double-entry matrix based on the spatial suitability and ecological connectivity models as inputs. Scores ranging from 1 to 5 were assigned for the spatial suitability importance and half of the value for the average conductance. We considered that greater conductance reflects redundancy in the dispersal paths because of the unsuitability in the surrounding areas, which would reduce the sustainability for CELS. We used zonal statistics to prioritize the inclusion of each sub-basin according to its suitability for sustaining spatial connectivity and the average conductance for the Mountain Tapir's dispersal (i.e., ecological connectivity). The average values of the inputs were classified into geometric intervals and defined five priority levels for landscape

Table 2
Land use classes identified within CELS.

Land cover	Area (Ha)	Percentage in CELS (%)
Forest	83,200	88
Paramo	1,000	1
Pasture/crops	7,300	8
Urban and bare soil	1,700	2
Water	1,100	1

Table 3
Percentage of CELS represented by protected areas.

Protected area category	Area (Ha)	Percentage in CELS (%)
Public	34,565	36.6
Private	8,736	9.3
Socio Bosque	4,210	4.4
Total	47,511	50.3

connectivity (Supplementary Material D). We assigned an inclusion priority to each watershed within CELS, and the weighted values of each raster in the raster calculator were summed in QGIS 3.16.

3. Results

3.1. Prioritization of the variables

The MCDA promoted the involvement of stakeholders and multidisciplinary academics that contributed to a more in-depth assessment of the spatial features in CELS. Their contributions allowed us to quantitatively rank the variables according to their importance for ecological connectivity, threats to biodiversity, and spatial suitability models. They also provided commentary on the involvement of local governments and considerations for delineating the corridor's borders.

The following issues were explicitly discussed with the group of experts: 1) including conflicting training areas for improving the satellite imagery processing and land use classification (e.g., páramo vs herbaceous crops); 2) the contrasting barrier effect on wildlife dispersal along the Pastaza River due to water flow reduction caused by hydroelectric dams; and 3) identification of high mortality risk areas along Highway E30. Additionally, the experts provided up-to-date information on threats to biodiversity within CELS, which created a comprehensive scenario for assessing habitat connectivity and delineating the corridor's borders.

3.2. Satellite imagery processing

The confusion matrix revealed a classification accuracy of 94 % and a Kappa index of 0.89, reflecting a high agreement in the LULC classification (Cohen, 1960). Forest was the dominant LULC class, followed by pasture/crops, comprising 88 % and 8 % of the land area in CELS, respectively (Table 2). In addition, half of the land area in CELS is protected under private and public conservation schemes (Table 3).

3.3. Ecological connectivity model

The AHP showed that forest and páramo are the variables that most highly contribute to the dispersal of the Mountain Tapir within CELS. Conversely, the primary, secondary, and tertiary roads, as well as human population density obtained the lowest weights (Fig. 3A).

The circuit connectivity model revealed that forests and páramos near protected areas favour a generalized dispersion for Mountain Tapirs; that is to say, there are no specific movement routes for species dispersal (Fig. 4A). Similarly, the natural vegetation cover over road tunnels potentially allows the species to cross over Highway E30 (Fig. 4B). Overall, roads constrain the Mountain Tapir's dispersal within CELS. However, we observed that high current density values (i.e., connectivity pinch points) appeared near roads when natural vegetation

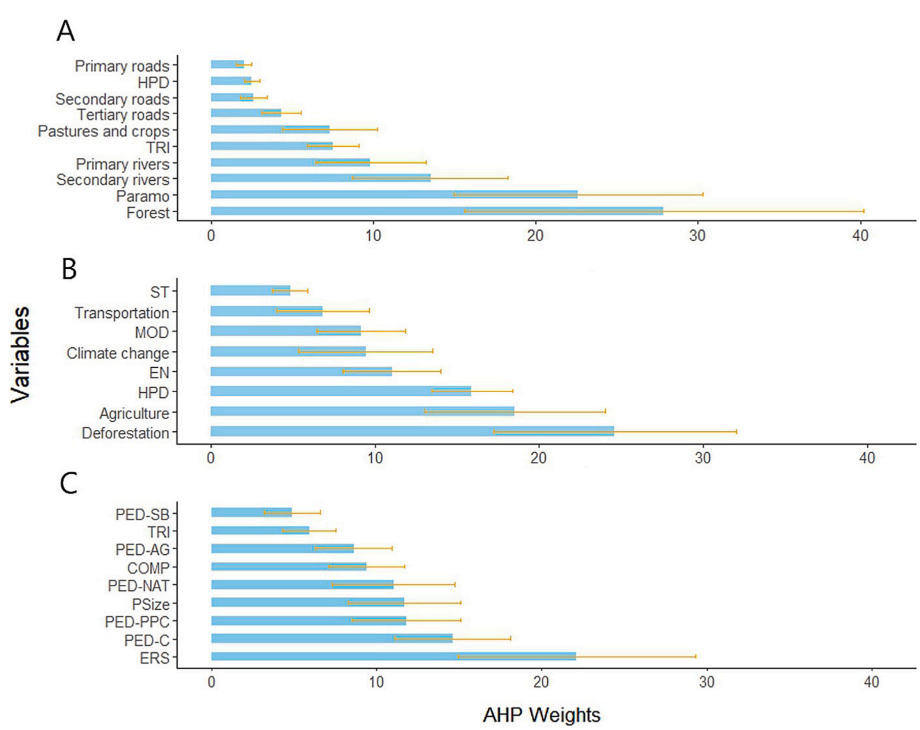

Fig. 3. Relative importance of the variables according to the AHP for each model assessed; A) Ecological Connectivity model; B) Environmental Risk Surface model; and C) Spatial suitability model. HDP: Human population density; TRI: Topographic ruggedness index; ST: Stochastic events; MOD: Modifications to the natural system; EN: Energy production; PED-SB: Patch distance to areas of the Socio Bosque Program; PED-AG: Patch distance to areas with physical suitability for agriculture; COMP: Complementary areas for conservation; PED-NAT: Distance to the nearest patch of natural vegetation; PSize: Natural vegetation patch size; PED-PPC: Distance to public and private conservation areas; PED-C: Patch distance to suitable areas for conservation; ERS: Environmental Risk Model output.

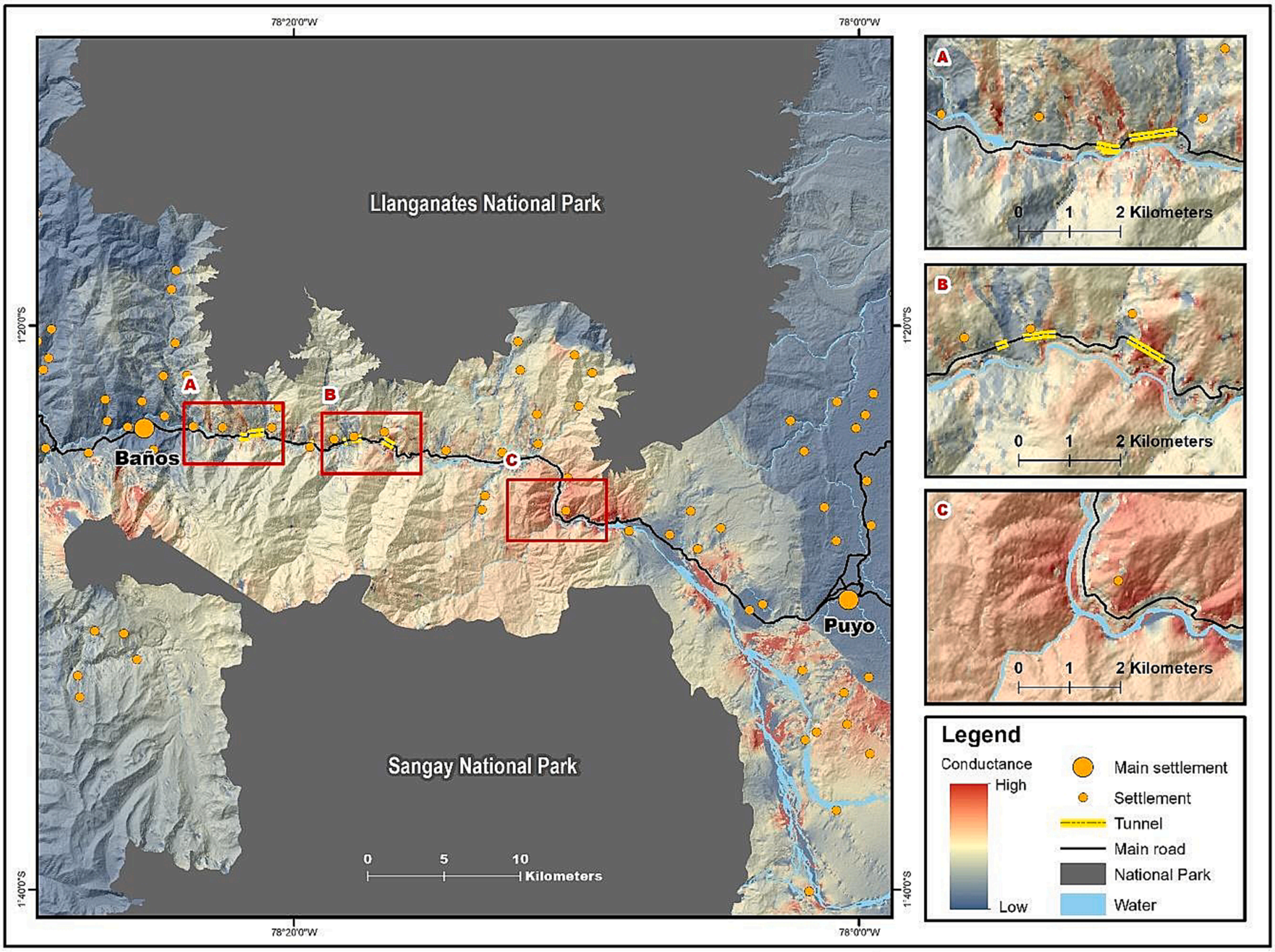

Fig. 4. Circuit connectivity model for the Mountain Tapir within CELS. Warm colours show greater conductance, reflecting high dispersal probability paths and connectivity routes of high redundancy (i.e., connectivity pinch points) for the species' movement.

remnants occur between pastures and crops (Fig. 4C). This allows the Mountain Tapir to move from protected areas to the surroundings of Highway E30, but it also creates potential paths for movement across the highway.

The barrier effect of primary rivers depends on the presence of patches of natural vegetation. When natural vegetation is present, primary rivers reduce the probability of dispersal by half, but if there are no patches, the effect increases. On the contrary, secondary rivers facilitate the dispersal of tapirs. The connectivity analysis showed a positive correlation ($r2 = 0.66$; $p < 0.001$) between the current density of forest and páramo patch size. However, small patches of natural vegetation (from <1–53 ha) contributed to high levels of current density within CELS (Supplementary Material E).

3.4. Biological and landscape suitability approach

3.4.1. Environmental risk surface model

The AHP revealed that deforestation, habitat modification derived from agriculture, and human population density are the most critical variables for the ERS model (Fig. 3B). As a result, the ERS showed that the more threatened areas within CELS occur near human settlements that are close to deforested areas and along primary roads (max = 0.61) (Fig. 5).

3.4.2. Spatial suitability model

According to the AHP, the most important spatial features that condition landscape connectivity were ERS output (i.e., threats to biodiversity), distance to areas with physical suitability for conservation, distance to public and private conservation areas, natural vegetation patch size, and distance to the nearest patch of natural vegetation (Fig. 3C). These areas are mainly distributed along Highway E30 (Fig. 6).

3.4.2.1. Sub-basin prioritization method. We identified 86 sub-basins within CELS, which were used to redefine the new limits for the corridor (Fig. 7). The total area proposed encompasses 94,362.24 ha. We included all the sub-basins of very high and high priority, which are located primarily in the central, northeast, and southeast portions of the study area. In addition, we included specific mid and low priority areas along the east and west borders of the corridor based on effective land-management criteria and participative discussions with the group of experts.

4. Discussion

The present study produced the necessary information for the proposal of an up-to-date delineation of CELS' limits. The proposal was based on the involvement of residents, conservationists, academia, and NGOs, considering technical criteria, spatial conditions, and the

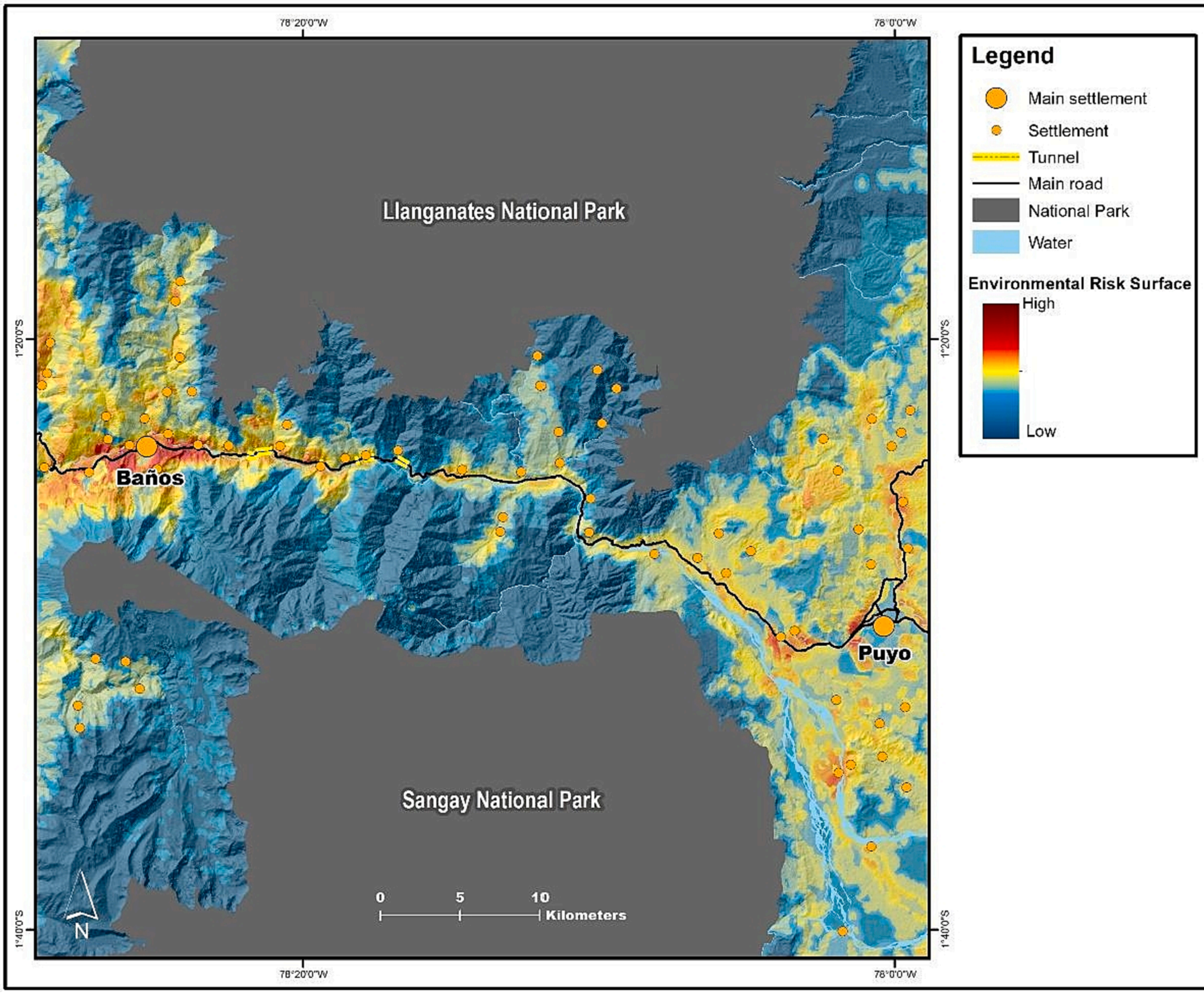

Fig. 5. Environmental Risk Surface Model (ERS) based on the AHP of threats to biodiversity in the study area.

participation of stakeholders committed to wildlife conservation. We combined multidisciplinary expert criteria, biodiversity threats and spatial analysis to delineate an effective connectivity corridor between two protected areas in a human-dominated landscape (Castro-Pardo & Urios, 2016; Cegan et al., 2017; Guaita Martínez et al., 2019). This allowed for an objective assessment of priority areas for habitat connectivity within CELS and in turn, encouraged the organization of stakeholders to participate in subsequent land management and promote activities in favour of wildlife conservation.

Corridor delineation based on wide-ranging species allowed for spatial assessments at large scales, identifying suitable habitat available and latent threats for wildlife conservation (Beier & Noss, 1998; Silveira et al., 2014; Cushman et al., 2018; Ceballos et al., 2021). Moreover, by focusing on threatened species, land management strategies can be developed to benefit the conservation of other sympatric wildlife (Silveira et al., 2014; Ceballos et al., 2021). Similarly, involving stakeholders and governments will hopefully lead to agreements in land management and planning of alternative conservation programs that consider both people's interests and wildlife's needs (Ceballos et al., 2021). This approach helps mitigate the effects of human disturbance by identifying priority areas for conservation and the strengths and weaknesses involved in their management (Cushman et al., 2018; Ceballos et al., 2021).

Our approach constitutes the first comprehensive attempt to identify potential dispersal paths for the Mountain Tapir in one of its last remaining strongholds in Ecuador (Downer, 1996; Downer, 1997; Cavelier et al., 2011). The AHP allowed us to perform a quantitative evaluation of the models' inputs according to the biological information collected by local conservationists, which we hope will contribute to raising awareness and promoting the involvement of third parties in the cooperative management of the corridor (Ríos-Alvear & Reyes-Puig, 2015). Moreover, we are confident our findings will contribute significantly to the conservation of the Mountain Tapir in the region.

Our findings revealed that forests and páramos near protected areas allow the unrestrictive dispersal of Mountain Tapirs. Thus, due to the wide range and broad altitudinal gradient where the Mountain Tapir occurs, promoting its habitat connectivity contributes to the conservation of: 1) sympatric threatened and rare mammal species inhabiting the mountain forest and páramo (Downer, 1996; Reyes-Puig et al., 2023), highly diverse species of amphibians and reptiles (Reyes-Puig et al., 2022), fish species occurring at mid and low elevations (Rodríguez-Galarza et al., 2017), and endemic species of orchids (Jost, 2004; Jost & Shepard, 2017); 2) habitats threatened by climate change and human disturbance (López de Vargas-Machuca et al., 2015); 3) key areas for the provision of ecosystem services (Gaglio et al., 2017); and 4) areas of high endemism (Jost, 2004; Haynie & Brant, 2006; Reyes-Puig et al., 2022).

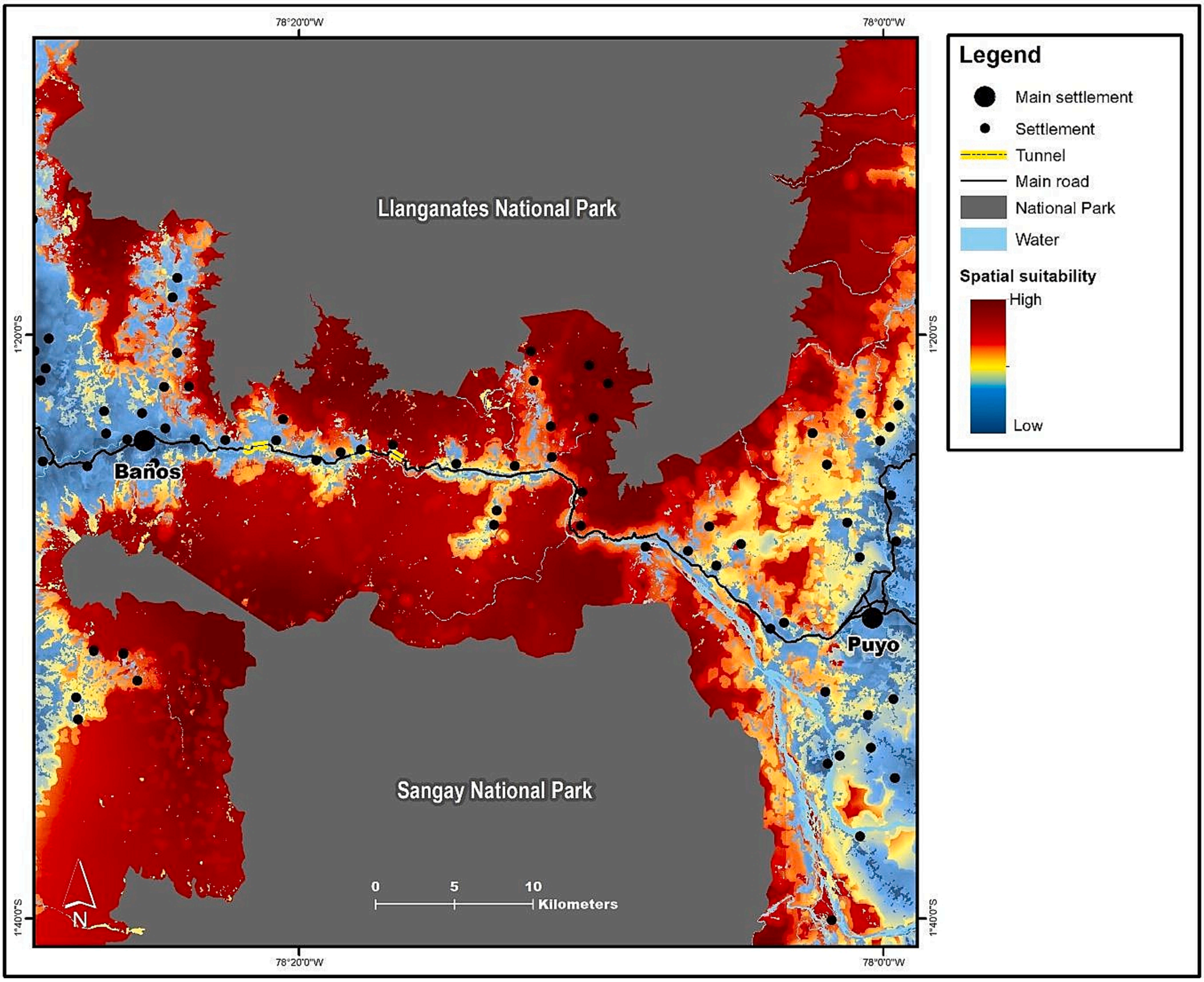

Fig. 6. Spatial representation of the sum of the nine spatial features used in the landscape suitability model. Cold to warm colours represent low to high suitability values for conservation.

In addition, the current redefinition of CELS limits encompasses the distribution range of two species of tapirs, namely the Mountain Tapir (*Tapirus pinchaque*) and the Lowland Tapir (*T. terrestris*), whose overlapping occurrence has not been fully understood yet. As such, supporting the connectivity of Mountain Tapir habitat in CELS contributes to the conservation of half of the world's tapir species (Cavelier et al., 2011). The remaining patches of natural vegetation found over the tunnels, along secondary rivers, and between pastures and crops close to roads act as stepping-stones to strengthen the habitat connectivity. This allows for dispersal movements towards larger areas throughout the corridor (Saura et al., 2014; Diniz et al., 2021). However, promoting wildlife dispersal in human areas can increase poaching, invasive species, and pathogen spread (Beier & Noss, 1998). Therefore, to ensure effective connectivity and reduce human disturbances on wildlife, it is essential to involve policy-makers, private and public landowners, and local inhabitants in order to ensure responsible corridor management and law enforcement (Ceballos et al., 2021).

We found that small patches (<53 ha) contributed significantly to the connectivity within the fragmented portion of the landscape. Therefore, to promote the Mountain Tapir's dispersal it is critical not only to avoid the removal of small patches of natural habitat, but to strengthen the linkage between them and larger patches, thus working towards the consolidation of a connectivity network for the species (Downer, 1996; Cavelier et al., 2011; Saura et al., 2014; Lizcano et al., 2016; Diniz et al., 2021). Furthermore, if managed correctly, the conservation of the Mountain Tapir and its habitats can be used as a conservation target to boost ecotourism. This will benefit many people's livelihoods within CELS (Downer, 1996; Lizcano et al., 2016; Gaglio et al., 2017), and consequently may reduce pressures on the natural resources by promoting the local population's well-being (Tortato et al., 2021).

The present work contributes to improving territorial management according to principles of wildlife conservation by allowing the identification of critical areas for the Mountain Tapir's habitat connectivity. As such, the connectivity model showed sensitive areas whose removal endangers the connectivity within the entire area (i.e., connectivity pinch points). But moreover, it allowed us to visually identify habitat remnants that could be linked by habitat restoration (e.g., forest patches between pastures and crops, and non-vegetated areas over tunnels). This information will allow policymakers to properly inform their decisions about the potential impacts of land-use planning on habitat connectivity. Consequently, this may facilitate the allocation of sustainable-use plans and conservation initiatives to favour wildlife conditions based on ecological and geographical data. For instance, in Ecuador, private

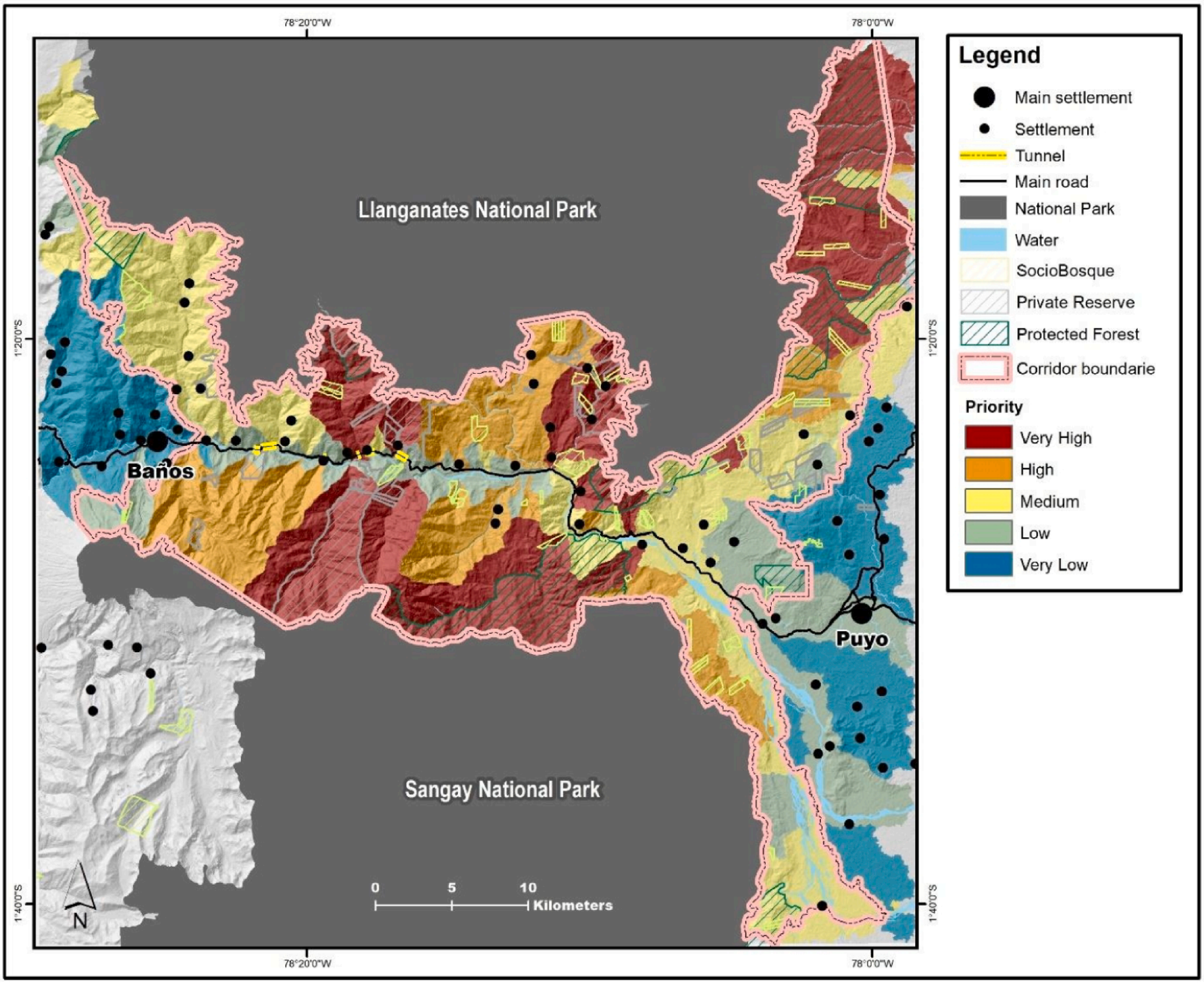

Fig. 7. Proposal of new limits for CELS according to the sub-basin prioritization criteria.

landowners who protect forests may access monetary or tax incentives from the national and local governments (de Koning et al., 2011). We consider that in addition to the ecological and charismatic value of the Mountain Tapir, its conservation supports the conservation of the ecological integrity within the landscape as a whole (i.e., co-occurring species, habitats, and ecosystem services) (Downer, 1996; Sanderson et al., 2002; Breckheimer et al., 2014). Likewise, due to the endangered status of the Mountain Tapir, our analysis will allow conservationists to address effective actions for the conservation of this species (Lizcano et al., 2016).

The ERS model revealed that anthropogenic disturbances are the most pervasive threats, suggesting potential constraints in the effective management of the corridor, particularly close to large cities (i.e., Baños, Puyo, and Shell. Fig. 3). However, the lack of up-to-date demographic information (i.e., the last national census was in 2010) limited the identification of the total number of people living in these high-density populated areas. In addition, the cloud coverage and availability of high-resolution satellite imagery prevent the timely detection of deforested areas and land-use changes (e.g., open areas for pastures and crops) (Zupanc, 2017). Thus, according to the variables prioritized in the AHP, we expect a higher number of areas that threaten biodiversity within CELS.

Conversely, the spatial suitability model showed that the best localities to design spatial connectivity depend upon physical characteristics favouring conservation initiatives (i.e., areas whose topographic and edaphic characteristics make them unsuitable to promote agriculture and cattle ranching activities), distance to protected areas, patch size, and distance between patches of natural vegetation. These areas are distributed along Highway E30, coinciding with the east-central portion of the Llanganates National Park, where a large and continuous extent of natural forest has remained well preserved under the management of public and private protected areas (e.g., Cerro Candelaria, Río Verde, Machay, Zuñag, Sumak Kawsay In Situ, EXISTE Reserves). Consequently, these areas exhibit lower levels of threat to biodiversity in contrast with the extreme western and eastern areas within CELS, which are more densely populated and host major productive activities. The sub-basin prioritization method resulted in more than doubling the previous size of CELS, increasing the corridor area from 41,517 to 94,362.24 ha. We found that the MCDA and AHP provided an objective view of the land-management expectations of stakeholders and represented their commitment to wildlife conservation. Nevertheless, we hold that effective land management actions within CELS demand the involvement of decision-makers in local governments. We hope that the analyses herein presented will be an effective catalyst in closing the gap between scientific knowledge and conservation action, as well as in persuading local governments to endorse and officially recognize CELS. As a result, we have observed the active involvement of conservationists, private landowners, and residents in forming a group of representatives to promote the management of the corridor. We hope our findings will promote further research of the habitat connectivity for other wildlife species in CELS, providing for integrative conservation actions, and supporting local governments with spatially explicit information on the important areas for landscape connectivity within the corridor.

CRediT authorship contribution statement

Gorky Ríos-Alvear: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Pablo Meneses:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **H. Mauricio Ortega-Andrade:** Conceptualization, Methodology, Formal analyis, Writing – review & editing. **Cinthya Santos:** Writing – review & editing, Conceptualization. **Aymé Muzo:** Writing – review & editing, Conceptualization. **Karima G. López:** Writing – review & editing, Methodology. **Alexander Griffin Bentley:** Writing – review & editing. **Francisco Villamarín:** Writing – review & editing, Investigation, Conceptualization.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2024.105039.

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