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Assessing the impacts of gold mining deforestation on the giant otter (Pteronura brasiliensis) in Madre de Dios, Peru

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ABSTRACT

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Gold mining activity is highly prevalent in the Madre de Dios region, Peru. This activity poses large environmental impacts including deforestation, sedimentation of rivers, and pollution from mercury used during extraction. Mining activity is a major threat to the endangered giant otter as it destroys its preferred riverine habitat. Moreover, mercury used during gold extraction bio-accumulates in fish, which constitutes the entirety of their diet. In order to conserve the giant otter, it is necessary to identify conservation priority areas. In a reactive conservation planning approach, the objective of this work was to prioritize areas suitable as giant otter habitat and vulnerable to mining activity. This study utilizes a habitat suitability model (Maxent) and a connectivity model (Circuitscape) to identify suitable habitats for giant otter. Vulnerable areas were identified through the combination of vulnerability to mining from a land change model (Terrset-LCM) and current protection status information. Highly suitable giant otter habitat was concentrated on the eastern portion of Madre de Dios, and was largely unprotected with over 69% of highly suitable habitat outside of protected and conservation areas. Movement pathway models identified low connectivity between protected areas. Areas of highest connectivity were concentrated along the Madre de Dios and Inambari rivers between the Tambopata National Reserve, Manu National Park, and Los Amigos

Conservation Concession, which was also found vulnerable to deforestation from mining. Priority areas for giant otter conservation overlap with the Malinowsky and Castaña corridors proposed by the Amazon Conservation Association, providing support for implementation of these corridors.

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Introduction

The giant otter (*Pteronura brasiliensis*) is a semi-aquatic mammal that is distributed in the Orinoco, Amazonas, and Parana hydrological basins in South America (Groenendijk et al. 2014). Hunting for pelts during the 1940s to the 1970s resulted in extirpation of the giant otter from its historical range in Uruguay, Paraguay, and Argentina. Conservation action was taken when the giant otter was listed as an Appendix I species under the Convention on International Trade in Endangered Species in 1975 (Groenendijk et al. 2014). Appendix I species are those threatened with extinction related to trade and have the highest level of international trade restrictions, with the exception of non-commercial purposes like scientific research, among the CITES-listed species (CITES 1973). Hunting is not as much of a current threat to giant otters, but the species is still threatened by factors including habitat destruction and degradation from human activity, including gold mining, agriculture, and oil exploration (Groenendjik et al. 2015). According to the 2015 IUCN assessment there is no total population estimate and population trends for the giant otter are unknown. Groenendjik et al. (2014) found the population of giant otters in Manú National Park, which is located in Madre de Dios, increased from 1991 to 2006. However, this represents a single population and Williams reported in 2012 declining trends for the total Madre de Dios population of 180-400 individuals (as cited in Groenendjik et al. 2015).

Giant otters have a selective diet, consisting almost entirely of fish with a consumption rate of up to 4kg of fish per day (Groenendjik et al. 2014, Duplaix 1980, Silva et al. 2014). A study of a population in Jaú National Park in Brazil show they feed mostly on fish in the Cichlidae, Erythrinidae, and Characidae families and only sporadically consume non-fish species (Silva et al. 2014). Giant otters show greater food selectivity during the dry season due to the accessibility to prey during this time. Fish are more concentrated and easier to catch during the dry season when the river water depths are more shallow (Cabral et al. 2010). Duplaix (1980) also reports exploitation of fish in shallow areas and suggest giant otter movement is heavily influenced by fish seasonal movement. The two key factors of habitat choice for these species are identified as food availability and low sloping banks with good vegetation cover by Duplaix (1980).

Gold mining activity in the Amazon is becoming a major concern due to increasing rates of mining (Asner et al. 2013 and Swenson et al. 2011). This mining activity has major implications for the giant otter due to the deforestation and pollution it causes. Liquid mercury is often used for gold extraction, which can then be released in residual forms to nearby rivers and transformed to toxic forms by aquatic organisms (Roach et al. 2013). Once in the river systems, the toxic mercury will bioaccumulate as animals higher in the food chain consume greater quantities of potentially contaminated organisms (Hsu-Kim et al. 2013). It is unclear how much mining activity is occurring due to small, illicit gold mines that are difficult to detect. Studies in the Madre de Dios region report estimates ranging from 15,500 ha by Swenson et al (2011) to 32,371 ha by Asner et al. (2013) for the 2003-2009 time period. Elmes et al. (2014) found there was 65,129 hectares of mining activity by 2011, 64% of which occurred outside of active legal mining concessions. More mining activity is clearly occurring than is recognized by the Peruvian government and being detected by satellite imagery. Thus, there is a need to identify contributing factors and land change vulnerability to target monitoring efforts and implement conservation action. In this context, vulnerability refers to how suitable the land is for mining activity and its related environmental impacts. Recent studies have utilized this approach in Madre de Dios for mercury pollution vulnerability and identified watersheds to be prioritized for conservation (Markham and Sangermano 2018).

Effective and targeted conservation action is vital in the face of limited conservation resources and rapid biodiversity and habitat loss. Conservation-priority areas help to target action in areas that have high conservation value and are considered vulnerable (Menon et al. 2001, Sangermano et al. 2012). In this study, conservation value is characterized by giant otter habitat, and vulnerability is characterized by both suitability for mining activity and protection status. Menon et al. (2001) suggest using land change models to identify priority areas because it can inform urgent action without requiring exhaustive knowledge of a species, ecosystem diversity, and ecosystem dynamics.

Study Area

Madre de Dios is a region in southern Peru, bordering Bolivia and Brazil comprised of low-land tropical habitat. The area has 5 natural protected areas, 3 with an IUCN Category II where recreation is permitted and 2 with an IUCN Category VI where sustainable use of natural resources is permitted (Dudley 2008). Other conservation areas include the Los Amigos Conservation Concession owned by the

Amazon Conservation Association (ACA) and a Territorial Reserve for Uncontacted Indigenous Peoples (Figure 1). Gold mining activity is high in this region, with estimates that 70% of Peru's gold production is supplied by the Madre de Dios region (Brooks et al. 2007). This mining activity is negatively impacting the region, and has been identified as 1 of 6 deforestation hotspots in the Andean Amazon (Finer and Mamani 2018). Mercury bioaccumulation from mining pollution could be occurring in Madre de Dios with evidence of mercury in the water and soil downstream from small-scale mines (Diringer et al. 2014) and intolerable mercury levels for humans and the related European otter in fish sampled from Manú National Park (Gutleb et al. 1997, Roach et al. 2013). The prevalence of gold mining activity and its related threats to the giant otter make Madre de Dios an ideal location for this study.

This project aims to evaluate the impacts of mining activity on giant otter habitat and movement in Madre de Dios, Peru by: (1) modelling habitat suitability and movement patterns for the giant otter; (2) modelling vulnerability, as indicated by suitability for mining activity, to mining-related deforestation; and (3) identifying priority areas where giant otter suitability and deforestation vulnerability intersect.

Methods

Data

Presence point data for the giant otter was downloaded from the Global Biodiversity Information Facility (GBIF), which archives global georeferenced observation from various sources such as museum collections and published datasets. Data of deforestation due to mining and polygons of concessions in Madre de Dios, including mining, reforestation, and conservation concessions, was provided by the Center for Amazonian Scientific Innovation (CINCIA). Elevation and NDVI were obtained from remotely sensed data, as detailed in Table 1. Additional ancillary data including rivers, navigable rivers, and roads were sourced from the Ministry of Transportation and Communication (MTC) and CINCIA, which were used to create distance rasters. All data was projected in UTM 19S and all raster data had a pixel resolution of 30 meters.

Habitat Suitability

There were 18 presence points for the giant otter in Madre de Dios, all of which were used as training sites in the Maxent species distribution model (Phillips et al. 2004, Phillips et al. 2006). Maxent is a machine-learning algorithm that uses presence sample points and environmental predictor variables to estimate the likelihood of species presence in locations across the study area. It does this by transforming the predictor variables to a scale from 0 to 1 and using them to find the most uniform distribution, based on the principle of maximum entropy, across the study area. Under this distribution, the estimated value for each predictor variable should equal the average across the sample presence points (Phillips et al. 2004, Phillips et al. 2006). Maxent also outputs variable importance with a heuristic approach measuring the increase in model gain from each variable, and with a jackknife approach that measures model performance at runs where a variable is excluded one at a time (Baldwin 2009). Maxent has been shown to outperform other models, including BIOCLIM, GARP, and Mahalanobis Typicalities, and works well with a low number of sample presence points, making it appropriate for this study (Elith et al. 2006, Hernandez et al. 2008).

The environmental predictor variables utilized in these models were elevation in meters, slope in degrees, NDVI during the dry season, and distance to rivers in meters. Elevation and NDVI were used as proxies for temperature, precipitation, and vegetation cover. Slope, which was derived from elevation, was included to capture giant otter preferences for low-sloping areas and river banks suitable for denning. Distance to rivers was included to capture the giant otter's reliance on rivers for their source of prey.

All presence points were used for calibration and none set aside for validation due to the low number of observations (n = 18). Instead, model evaluation was completed by extracting the habitat suitability values for each known presence point. These values were then used to calculate descriptive statistics and create box-plots summarizing the model. A model that fits the data well should have a high mean value with little variation in the range of values and no outliers because the species is known to be present at the locations that these values were extracted from. After evaluation, other iterations were run to find the best fit model. These iterations included models using different versions of the rivers data, a major rivers layer compared to a rivers and streams layer, and models with presence points that had outlier suitability values removed, detailed in Table 2.

Movement

Circuitscape was used to model giant otter movement between protected areas (McRae et al. 2013). The software models movement using circuit theory, such that a landscape is represented as an electrical circuit, made up of a network of nodes connected by resistors that conduct current. The lower the resistance between nodes, or the higher the conductance, the greater current flow there is between nodes. Thus, the software requires a map of focal nodes, the connection points to model movement between, and a layer representing either resistance or conductance across the landscape. Circuitscape outputs current maps, representing the probability of a random walker to pass through, for each pair of focal nodes and a cumulative map with the current between all pairs (McRae et al. 2008).

The best habitat suitability model was chosen to derive the conductance map. A map of major protected areas were input as focal node locations in Circuitscape, which was run using the pairwise modelling mode. Due to software limitations, the pixel resolution of the habitat suitability model was increased to 150 meters by averaging the suitability value over twenty-five 30 x 30 meter pixels. This study focused on the cumulative current map, which represents the probability of movement between all protected areas in Madre de Dios.

Land Change for Mining

Land Change Modeler for Ecological Sustainability (LCM) (Eastman 2009) predicts land cover change by relating historical land change to a set of driver variables and extrapolating future change. Driver variables are related to land change between two time points with transition potentials, which represent the potential of the land to experience a transition from one land cover type to another (Sangermano et al. 2012). No categorical variables were used in this study, but any should be converted to a continuous input using empirical likelihoods. Empirical likelihoods represent the proportion of a category that experienced land change. Driver variables are static by default but they can be set to dynamic, meaning they change over time (Sangermano et al. 2012). Transition potentials were calculated using a multi-layer perceptron neural network (MLP), a non-parametric machine-learning tool that can model complex relationships including non-linear ones (Bishop 1995). Future change can then be predicted by distributing the amount of predicted change among pixels with the highest transition potential values. A Markov Chain matrix extrapolated the amount of future change based on the amount of observed change (Burnham 1973). LCM outputs a hard, classified prediction representing a particular land cover scenario in the future and a soft, continuous prediction indicating suitability to change, which in this study represents deforestation vulnerability (Sangermano et al. 2012)

The importance of each driver variable was also evaluated using various elimination methods. Importance was evaluated by measuring the model's skill when one variable at a time was removed from the model (all but one variable forced to be constant), and by including only one variable at a time (Eastman 2009). The change in skill measure gives an indication of how influential the variable is in the model, with large changes in skill indicating the variable heavily impacts the model's prediction (Eastman 2009). Model evaluation can be done with a total operating characteristic (TOC) curve, which measures the ability of the transition potential index to determine land cover change and persistence. The TOC procedure considers multiple thresholds, where values above a threshold is characterized as change and values below as persistence, and calculates a two-by-two contingency table for each threshold scenario

(Pontius and Si 2013). The contingency table compares the pixels of modeled change and persistence to the observed change and persistence. Hits represent where modeled change and observed change overlap and correct rejections represent where modeled persistence and observed persistence overlap. When combined, hits and correct rejections indicate accurately predicted pixels. Misses are those where modeled persistence overlaps with observed change. On the other hand, false alarms happen in locations where the model predicted change when in reality no change (persistence) was observed. The TOC curve graphs the proportion of change that was correctly predicted. The area under the TOC curve (AUC) summarizes the model diagnostic ability across multiple thresholds, with values greater than 0.5 indicating the model is capable of predicting change better than random, and higher values indicating stronger capability of discrimination between change and persistence (Pontius and Si 2013). Validation of the hard prediction can be done using the same two-by-two contingency table. The soft prediction can be validated by comparing the distribution of vulnerability values for the areas with observed change to those with observed persistence. Areas of change should have high vulnerability values with a right-skewed histogram, and areas of persistence should have low vulnerability values with a left-skewed histogram (Sangermano et al. 2012).

Land conversion from non-deforested to deforested for mining from 2000 to 2010 was used to build the model, which was then used to predict deforestation in 2017. The driver variables for this model were set as static and included the following: elevation, slope, distance to roads, distance to navigable rivers, and distance to existing mining deforestation. Infrastructure like roads change over time, but the dates of road completion was not available. The roads layer used in this study include proposed roads, thus capturing the road infrastructure in the foreseeable future and applicable for future predictions. Protected areas were not used as constraints as mining activity has been identified within protected areas like the Amarakaeri Communal Reserve and Tambopata National Reserve (Finer and Mamani 2018).

Giant Otter Vulnerability and Priority Areas

Priority areas can be identified using information about conservation value and vulnerability (Menon et al. 2001; Brooks et al. 2006; Linke et al. 2007). In this study, conservation value was characterized by key habitat for the giant otter, identified as areas with suitable habitat and utilized for movement, and vulnerability was characterized by suitability for deforestation related to mining activity. Thus, priority areas were identified by finding key habitat that experience high risk to deforestation, representing a reactive approach that requires more immediate action, and key habitat experiencing low risk to deforestation, representing a proactive approach to conservation (Brooks et al. 2006).

Key habitat was characterized by habitat suitability and movement models. Both habitat suitability and movement probability were classified into Boolean maps representing suitable habitat and movement pathways for the giant otter. Classification was done using a threshold calculated as the average value among the sample presence points. This thresholding approach is a simple, yet effective approach when compared to others like the fixed threshold, usually a threshold of 0.5, and overall prediction success maximization approaches (Liu et al. 2005). The threshold in this study was 0.58 for habitat suitability and 0.02 for movement probability. The resulting suitable habitat and movement pathways maps were then combined using an or logic, such that key habitat is where there is either suitable habitat or a movement pathway present.

The soft output of the land change model was classified into low, medium, and high vulnerability. Classification was completed using thresholds based on the model-building data, with the mean value calculated where change occurred and where persistence occurred. Areas with low vulnerability were those with a value less than the mean for persistence (< 0.1), high vulnerability were those with a value greater than the mean for change (≥0.88), and moderate vulnerability were those with values between the two means (0.1-0.88).

The resulting key habitat and deforestation vulnerability maps were then overlaid to identify low, moderate, and highly vulnerable key giant otter habitat. These categories were further grouped into high and low-risk key habitat to identify the four types of priority areas utilized by Menon et al. (2001). High-risk key habitat are those with moderate to high deforestation vulnerability and low-risk key habitat are those with low deforestation vulnerability. A protection gap analysis was conducted by identifying the protection state of high and low risk giant otter key habitat. Based on the information provided by vulnerability and gap analysis, the following four types of priority areas were identified: 1) unprotected, high-risk habitat, which should take highest priority for action, 2) protected, high-risk habitat, 3) protected low-risk habitat, and 4) unprotected low-risk habitat (Menon et al. 2001).

Results

Habitat Suitability Maps

Five habitat suitability models were created, which are detailed in Table 2. Model B using the more detailed rivers and streams layer for distance to rivers had the highest maximum suitability value, but it also had the greatest range in suitability within observations (Figure 2). Model A presented a shorter range between quartiles, but there is an outlier. When this outlier was removed (Model C), another outlier was revealed, which was also removed (Model D). Both outliers were removed in Model E, which resulted in the smallest interquartile range, indicating minimal variation in values, and no present outliers. (Figure 2). Thus, Model E was chosen as the final habitat suitability model. In this model, elevation was the most important variable with a 65.3% contribution and gain of 1.1 when it is used as the only variable in the model. Distance to rivers was the second most important variable with a 29.5% contribution and gain of 0.57 when it is the only variable in the model. NDVI was the least important variable with a percent contribution of 1.3 and gain of 0.04 when it is the only variable in the model (Table 3, Figure 3)

The final habitat suitability map for the giant otter is shown in Figure 4a with points representing families of fish species preferred by the giant otter to confirm whether prey are present. High suitability values are concentrated along the rivers. A large patch of high suitability is present inside and outside the northern border of the

Tambopata National Reserve, along the Madre de Dios and Tambopata rivers (Figure 4b). While there are giant otter presence points and presence of prey inside Manu National Park, the suitability values are generally lower along the rivers in Manu National park and the Territorial Reserve (Figure 4c). There is also high suitability with few giant otter observations along the Madre de Dios and Inambari rivers that run between the Los Amigos Conservation Concession and Tambopata National Reserve, which is highlighted by the black arrow in Figure 4d. There is some disparity in the number of presence observations with 4 west of the Los Amigos Conservation Concession and 12 in eastern Madre de Dios.

Movement Pathways

The cumulative current map for giant otter movement between protected areas or areas for conservation indicates there is overall low connectivity because the highest probability of movement between all protected areas is 0.08 (Figure 5a). There is a concentration of high movement probability along the Madre de Dios and Inambari rivers, extending between the Manu National Park and Tambopata National Reserve as highlighted by the black arrow in Figure 5b. This indicates the giant otter is most likely to move along these routes, particularly along the Madre de Dios River, to travel between protected areas.

Observed deforestation from mining activity is concentrated along the Madre de Dios, Puquiri, Setapo, Inambari, and Caichihue rivers and intersects these key movement pathways (Figure 5a). This deforestation divides the group of giant otter observations in Manu National Park in Western Madre de Dios and the group of giant otter observations by the Tambopata National Reserve and Bahuaja Sonene National Park in Eastern Madre de Dios (Figure 5a). Deforestation is most concentrated along the Puquiri, Caichihue, and Setapo rivers just outside the Amarakaeri Communal Reserve boundary, and less concentrated along the Madre de Dios river just south of the Los Amigos Conservation Concession (Figure 5b).

Deforestation Vulnerability

The resulting predictions of deforestation for mining in 2017 indicate there is high probability of conversion along the Madre de Dios, Puquiri, Caichihue, and Inambari rivers (Figure 6). While areas with high deforestation vulnerability are concentrated in the unprotected areas north of the Tambopata National Reserve and areas between the Bahuaja Sonene National Park and Amarakaeri Communal Reserve, there are areas with high and moderate deforestation vulnerability within the borders of all the surrounding protected areas, particularly the Tambopata National Reserve, Bahuaja Sonene National Park, Amarakaeri Communal Reserve, and Los Amigos Conservation Concession (Figure 6).

The TOC curve for the LCM deforestation vulnerability model is above the uniform line and the AUC is greater than the random baseline of 0.5 (AUC = 0.96), indicating the transition potential produced by the model is better than random at predicting deforestation from 2010 to 2017 (Figure 7). The most important variable in the model was distance to existing mining deforestation, followed by distance to roads, then distance to navigable rivers, and elevation. Slope was the least important variable in this model (Table 4). The skill measure of the model is 0.62 with only distance to mining deforestation in the model, increasing to 0.86 when distance to roads is included, then to 0.87 when distance to rivers is added, and finally to the maximum of 0.88 with the addition of elevation (Figure 8).

The hard, classified prediction has an overall accuracy of 99.33% with 1,229 hectares (0.01%) of hits, 8,381,049 hectares (99.32%) of correct rejections, 15,064 hectares (0.18%) of false alarms, and 41,159 hectares (0.49%) of misses (Table 5). The histogram approach of evaluating the model's prediction (Sangermano et al. 2012) indicates a good model performance to predict deforestation vulnerability. Areas that experienced deforestation during 2010-2017 had a high deforestation vulnerability values with a mean of 0.88, and areas of forest persistence had low vulnerability values with a mean of 0.1 (Figure 9).

Priority Areas

There are 319,226 hectares of suitable giant otter habitat in Madre de Dios, which is largely unprotected with only 31% in a protected area (Figure 10). Most of the suitable habitat that is protected is located in the Tambopata National Reserve (18%) and Bahuaja Sonene National Park (12%) (Figure 10). Of the suitable giant otter habitat, 128,274 hectares (40%) had low vulnerability for deforestation, 81,435 hectares (26%) had moderate vulnerability for deforestation, and 109,517 hectares (34%) had high vulnerability for deforestation (Table 6). Habitat areas with low deforestation vulnerability was 60% protected, while most of the habitat with moderate (76%) and high (97%) vulnerability for deforestation were unprotected (Table 6).

Habitat with high vulnerability for deforestation was concentrated along the Madre de Dios River, particularly north of the Tambopata National Reserve border. Habitat along the western Madre de Dios River between the Tambopata National Reserve, Amarakaeri Communal Reserve, and Los Amigos Conservation Concession, where there is also high probability of movement, also experienced high deforestation vulnerability (Figure 11). Highly suitable habitat and high movement probabilities are also located along the Las Piedras River extending north from the Madre de Dios River, north of the Tambopata National Reserve (Figure 11).

Discussion

The habitat suitability model indicates giant otter habitat is concentrated in the southeastern portion of Madre de Dios, particularly along the Madre de Dios, Tambopata, Palma Real, and de Las Piedras rivers (Figure 4). This matches past surveys that have observed giant otter individuals on the Madre de Dios, Los Amigos, Tambopata, Palma Real, and Patuyacu rivers (Carter and Rosas 1997, Groenendjik et al. 2001, Groenendjik et al. 2004) Only 0.01% of suitable habitat was located in Manú National Park, surprising considering that several giant otter studies have observed and even focused on populations in Manú (Carter and Rosas 1997, Gutleb et al. 1997, Groenendjik et al. 2014). Analysis of suitable habitat reveals it is largely unprotected in Madre de Dios, concentrated in the southeastern portion of Madre de Dios. Most of the protected areas however are located in the western half of Madre de Dios (Figure 4a). Tambopata National Reserve and Bahuaja Sonene National Park are the only protected areas in the eastern half of Madre de Dios and they contain the greatest percentage of highly suitable habitat among the protected and conservation areas (Figure 10). This highlights a need in protection along the eastern border of Madre de Dios, where there is habitat that could be critical for giant otters but currently has no protection against environmental impacts.

Results of the deforestation vulnerability model had similar results to other classification models. Distance to roads and distance to rivers has been identified as key variables for identifying mining activity (Elmes et al. 2014), and they were second and third most important variables in this model, respectively (Table 4 and Figure 8). While distance to existing deforestation was the most important variable in this model, it was not used in the Elmes et al. (2014) classification model. The model predicting deforestation vulnerability from 2010 to 2017 was able to locate deforestation hotspots identified by Finer and Mamani (2018). Deforestation hotspots in 2017 located in the La Pampa region that is north of the Tambopata National Reserve-Bahuaja Sonene National Park border, Upper Malinousqui, and Santa Rita and Guacamayo regions along the Inambari river also had high deforestation vulnerability in the model (Figure 6). The model was even able to identify deforestation encroaching protected areas. In 2015, 11 hectares of the Amarakaeri Communal Reserve and 550 hectares of the Tambopata National Reserve were deforested for mining activity, which has since been stopped (Finer and Mamani 2018). The deforestation vulnerability model identified these locations with moderate to high vulnerability for deforestation, indicating the model has good predictive power (Figure 6). Deforestation was also identified by Finer and Mamani (2018) in northeastern Madre de Dios, in the Iberia, Tahuamanu and Las

Piedras regions; however, these were attributed to agricultural and logging activity not included in this study.

The results of this analysis show key giant otter habitat and movement pathways are being impacted by gold mining activity in Madre de Dios. Deforestation from mining divides the cluster of giant otter observation points in Manu National Park and the cluster around Tambopata National Reserve and Bahuaja Sonene National Park, intersecting the key movement pathway along the Madre de Dios river that connect them (Figure 5). This overlap could explain the disparity in observations in western Madre de Dios compared to eastern Madre de Dios. Mining activity is destroying the habitat necessary for travel between Manu national Park and Tambopata National Reserve, thus preventing individuals from travelling between them. Limited movement prevents dispersal from habitat patches, which can lead to isolation of sink habitats from source habitats. Sinks can be vital for species persistence, particularly if a source is threatened with habitat destruction like that caused by mining, because they can serve as short-term refuges or connections to other sources (Heinrichs et al. 2015). If individuals cannot disperse in the face of threatened habitat, then the overall population will decline as individual deaths increase, recolonization decreases due to limited dispersal, and births decrease (Fahrig and Merriam 1994; Heinrichs et al. 2015). Thus, increasingly limited access to the highly suitable habitat in eastern Madre de Dios due to mining activity, particularly the path between Manu National Park and Tambopata National Reserve along the Madre de Dios river and Inambari rivers (Figure 5b), can result in population declines. Further study is needed to identify which habitats are sources or sinks in Madre de Dios and better understand the dynamics between sources and sinks; however, the threat of mining deforestation clearly has implications for giant otter dispersal and persistence as the area is increasingly threatened.

Types of priority areas were identified following a modified version of the Menon et al. (2001) approach, which measures and combines conservation value, areas with suitable habitat and key movement pathways, with deforestation vulnerability, and completes a protection gap analysis to identify the four types of priority areas. Type 1 priority areas should have the highest priority because the key habitat in these locations will be the first to go if no conservation action is taken, thus representing reactive conservation action (Brooks et al. 2006). Type 2 priority areas require enhanced enforcement of existing protection to ensure the habitat under high deforestation vulnerability is not deforested in the future for illegal mining activity in the protected area. Types 3 and 4 priority areas represent proactive conservation since any conservation action in these locations aim to protect the land before it becomes highly vulnerable for mining-related deforestation (Brooks et al. 2006). Type 3 priority areas have low protection enforcement priority, while protection should be established in Type 4 priority areas because these areas contain key giant otter habitat (Menon et al. 2001).

The unprotected and highly vulnerable to mining habitat north of the Tambopata National Reserve, particularly the area where there is high probability of movement along the Madre de Dios River between the Tambopata National Reserve and Amarakaeri Communal Reserve, falls into the first type of priority area and should take highest priority. The protected, highly vulnerable habitat, located at the northern border of the Tambopata National Reserve, falls into the second type of priority area and efforts should focus on enforcement of protection. The unprotected, slightly vulnerable habitat, mostly located along the de Las Piedras River and the rivers at the eastern border of Madre de Dios fall into the fourth type of priority area. Establishment of protection is easier in this type of priority area because it does not have the qualities typical for mining activity. However, it can be useful to proactively protect the land before it becomes desirable and then susceptible to change, especially since there is high probability of movement here. The protected, slightly vulnerable habitat falls into the fourth type of priority area. These areas have lowest priority for conservation, but efforts to upgrade protection status can be done (Figure 12).

The Amazon Conservation Association (ACA) has proposed 2 corridors in Madre de Dios: the Castaña Corridor and the Malinowsky Corridor. The Castaña Corridor overlaps a type 4 priority area, where there is slightly vulnerable habitat and high movement probabilities that are unprotected. This corridor would help to address the lack of giant otter habitat protection in eastern Madre de Dios and would represent proactive conservation action. The Malinowsky Corridor extends from the Los Amigos Conservation Concession to the Bahuaja Sonene National Park, which intersects type 1 priority areas, where there is highly vulnerable habitat and key movement pathways that are unprotected. It also intersects concessions for reforestation along the Inambari, Jayave, and Malinousqui rivers, which should encourage restoration of this habitat and facilitate movement from the highly vulnerable protected areas in the east to the less vulnerable protected areas in the west (Figure 12). The Castaña Corridor should be easier to establish, but establishment of the Malinowsky Corridor is more urgent.

Conclusion

This study identifies priority areas for giant otter conservation using the intersection of conservation value and vulnerability. Habitat suitability and movement pathways defined conservation value, while suitability for mining activity, or deforestation vulnerability, and lack of protection defined vulnerability. Identified priority areas highlight a need for protection in eastern Madre de Dios, where there is high giant otter habitat suitability. It also highlights the need to address deforestation due to mining activity because it is occurring along movement pathways that connect giant otters in highly suitable habitat in the east to protected areas in the west.

Conservation efforts like the corridors proposed by ACA should be established to increase protection where there is highly suitable habitat, increase connectivity between protected areas to prevent isolation and provide a refuge for giant otters being impacted by mining, and limit future mining activity or encourage reforestation efforts in valuable giant otter habitat. While these proposed corridors would help protect key giant otter habitats, there is still a need for action in the type 1 priority areas just north of the Tambopata National Reserve border. To effectively protect the giant otter in Madre de Dios, proactive and reactive conservation efforts are needed.

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Tables

Table 1. List of data used in this study

Data	Type (Resolution)	Date	Source
Giant Otter Presence	Vector (Points)	1991-2018	GBIF
Elevation (ASTER GDEM)	Raster (30m)	2017	USGS
NDVI (Landsat-8 OLI)	Raster (30m)	2014	USGS
Deforestation due to Mining	Vector (Polygons)	1984-2017	CINCIA
Mining Concessions	Vector (Polygons)	1977-2011	CINCIA
Rivers	Vector (Lines)		CINCIA
Navigable Rivers	Vector (Lines)		CINCIA
Roads	Vector (Lines)		MTC
Protected Areas and Reforestation Concessions	Vector (Polygons)		CINCIA

Table 2. Descriptions of each habitat suitability model

Model Run	Method	Observations (n)	Rivers File Used
A	Maxent	18	Major Rivers
B	Maxent	18	Rivers and Streams
C	Maxent	17	Major Rivers
D	Maxent	17	Major Rivers
E	Maxent	16	Major Rivers

Table 3. Variable importance for the habitat suitability model, measured as estimate of relative contributions of each variable to the model

Variable	Percent Contribution	Permutation Importance
Elevation	65.3	77.5
Distance to rivers	29.5	19.1
Slope	3.9	3.1
NDVI	1.3	0.4

Table 4. Variable importance for the land change model, measured with model sensitivity when forcing a single independent variable to be constant

Model	Accuracy (%)	Skill Measure	Influence order
All variables	93.99	0.8797	N/A
Elevation constant	93.59	0.8717	4
Distance to roads constant	88.95	0.7791	2
Distance to navigable rivers constant	93.51	0.8701	3
Slope constant	93.90	0.8779	5 (least)
Distance to existing deforestation constant	41.23	-0.1754	1 (most)

Table 5. Contingency table for 2017 prediction of deforestation in hectares

Predicted	Reference Change	Reference Persistence	Total
Change	1,229	15,064	16,293
Persistence	41,159	8,381,049	8,422,208
Total	42,388	8,396,113	8,438,501

Table 6. Protection of vulnerable key habitat (area in square kilometers)

Vulnerability	Unprotected	Protected	Total
Low	4,798	2,493	7,291
Moderate	3,088	421	3,510
High	3,732	60	3,792

Figures

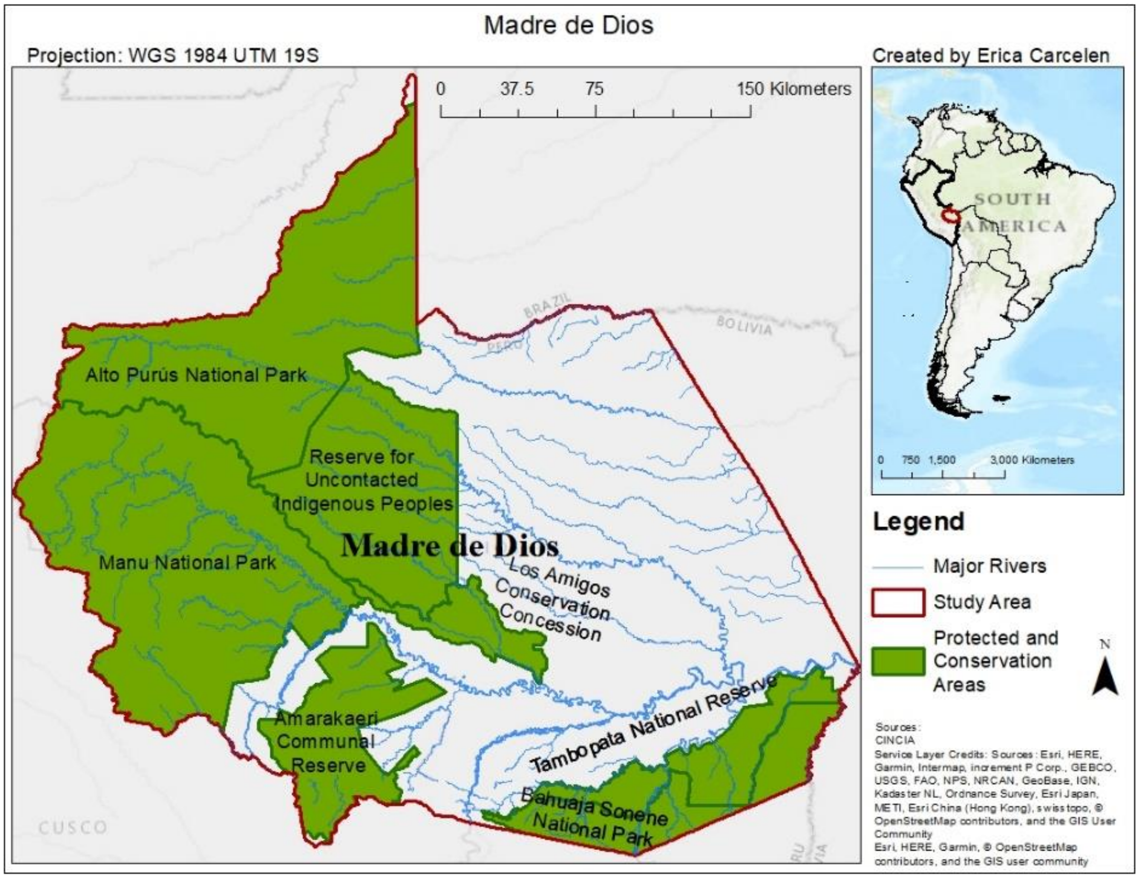

Figure 1. Study area map of the Madre de Dios region, Peru

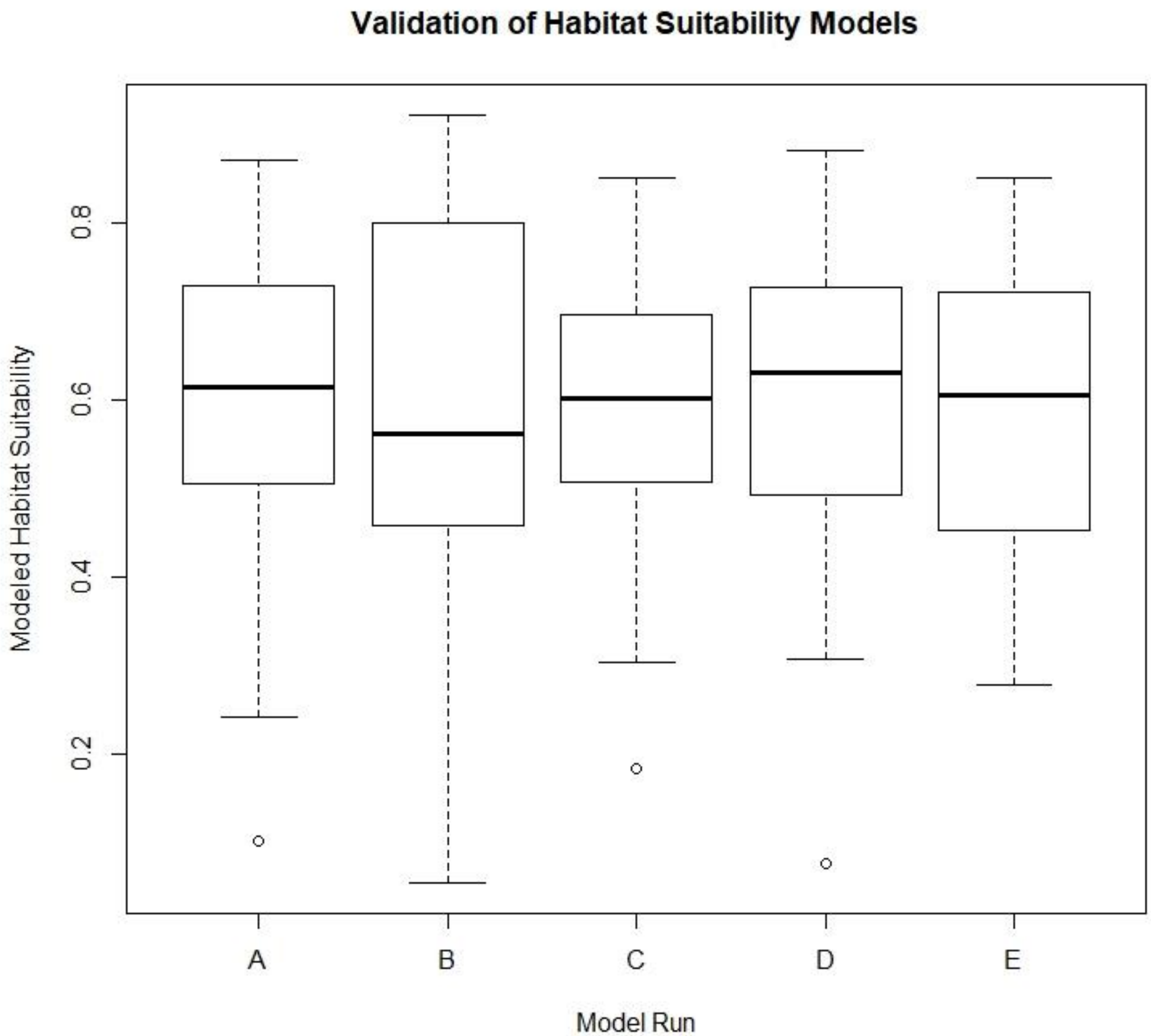

Figure 2. Box and whisker plots for the suitability values at each input presence point. Detailed descriptions of each model are shown in Table 2.

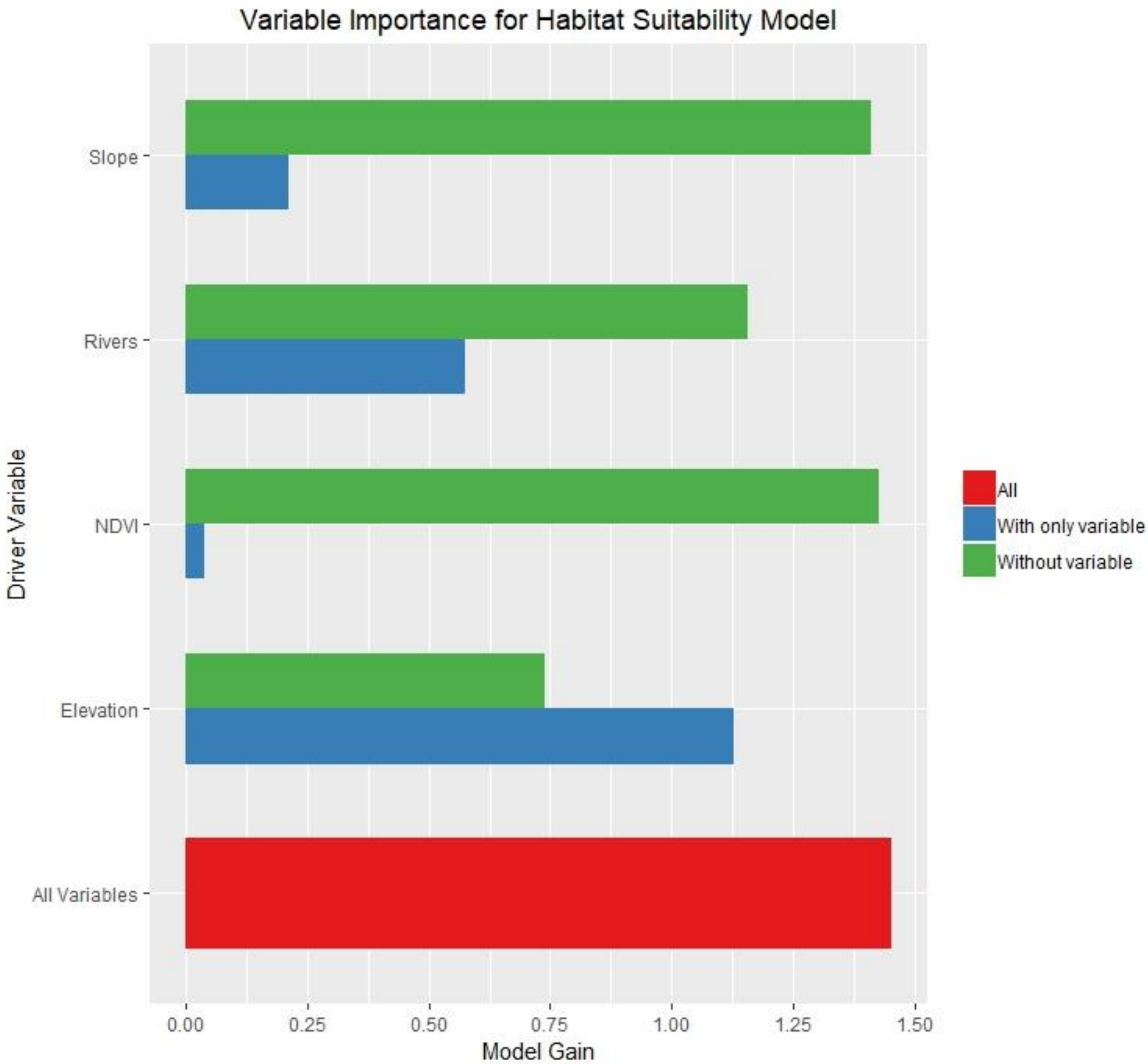

Figure 3. Jackknife test of variable importance for the habitat suitability model

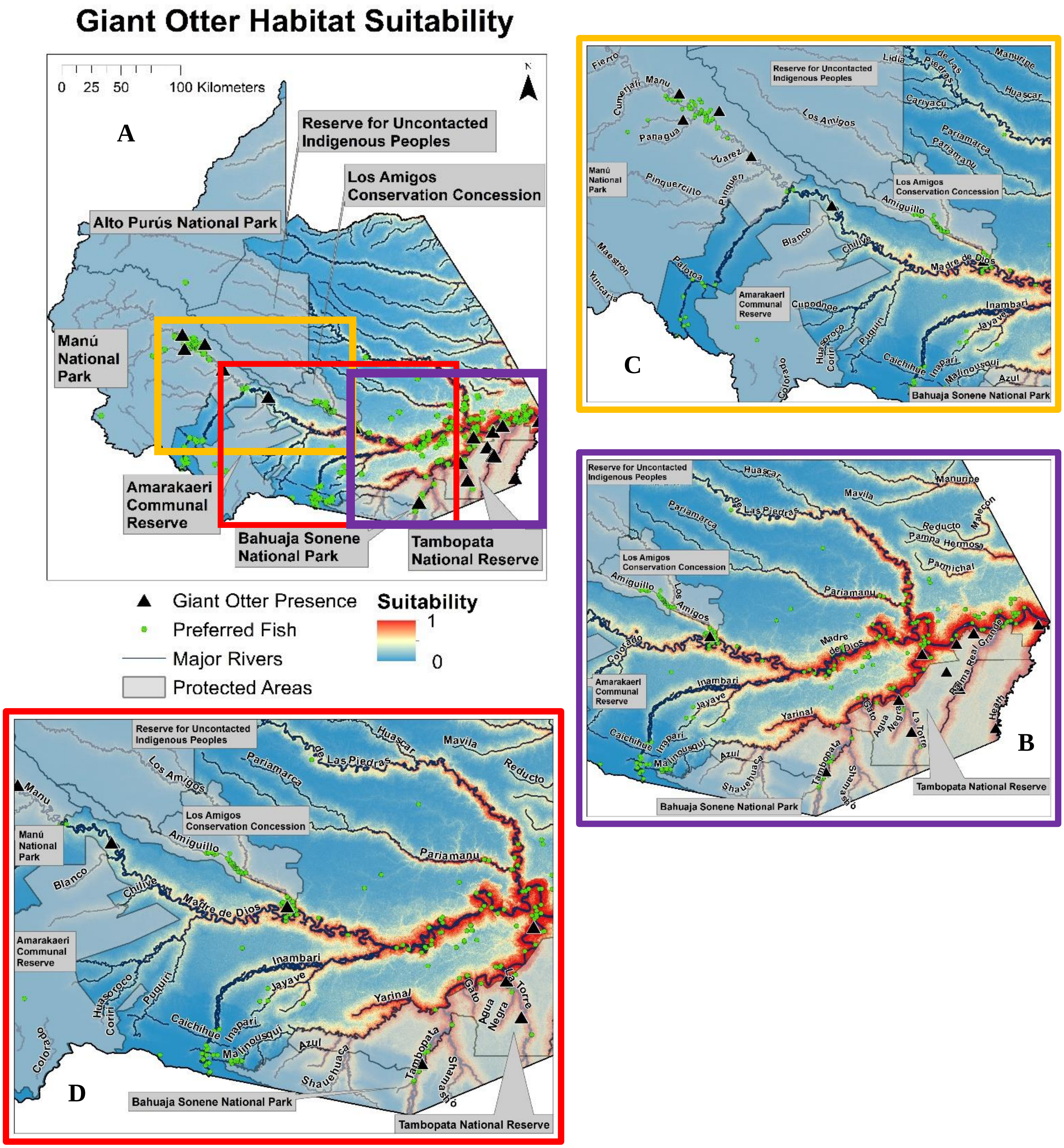

Figure 4. Full map of habitat suitability for the giant otter (a), habitat suitability in eastern MDD (b), habitat suitability in south-central MDD (c), and habitat suitability in western MDD (d)

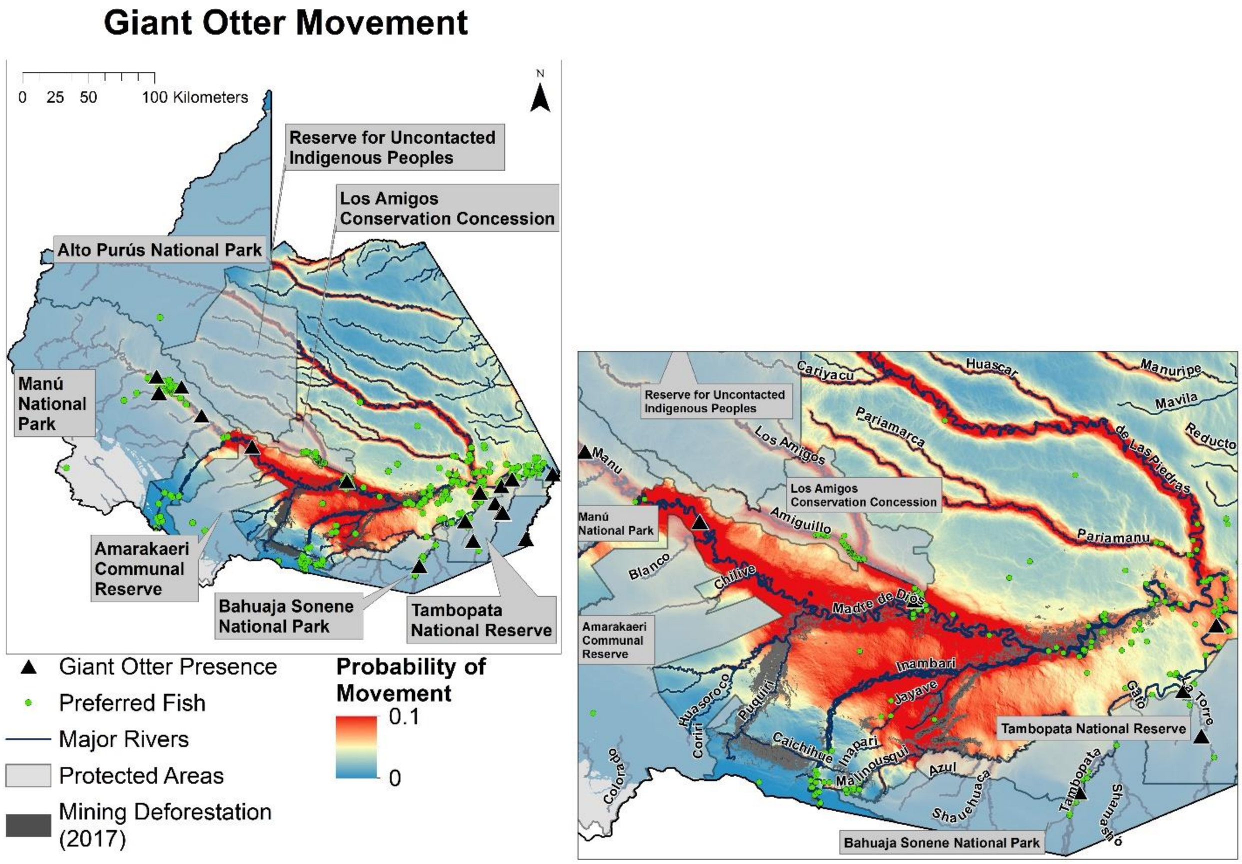

Figure 5. Probability of giant otter movement between protected areas throughout the study area (left) and between eastern and western protected areas (right).

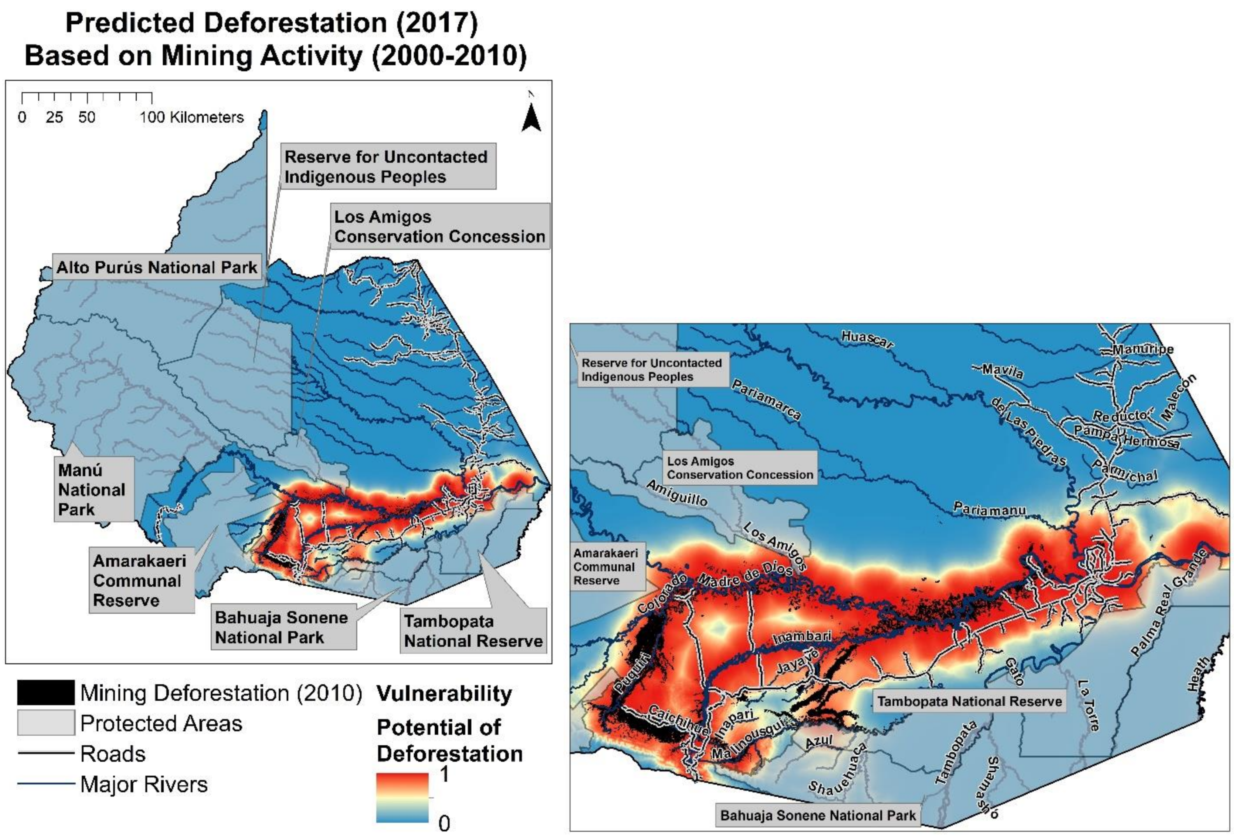

Figure 6. Predicted deforestation vulnerability for mining in 2017 based on a model calibrated with data from 2000 to 2010 for the full study area (left) and between eastern and western protected areas (right).

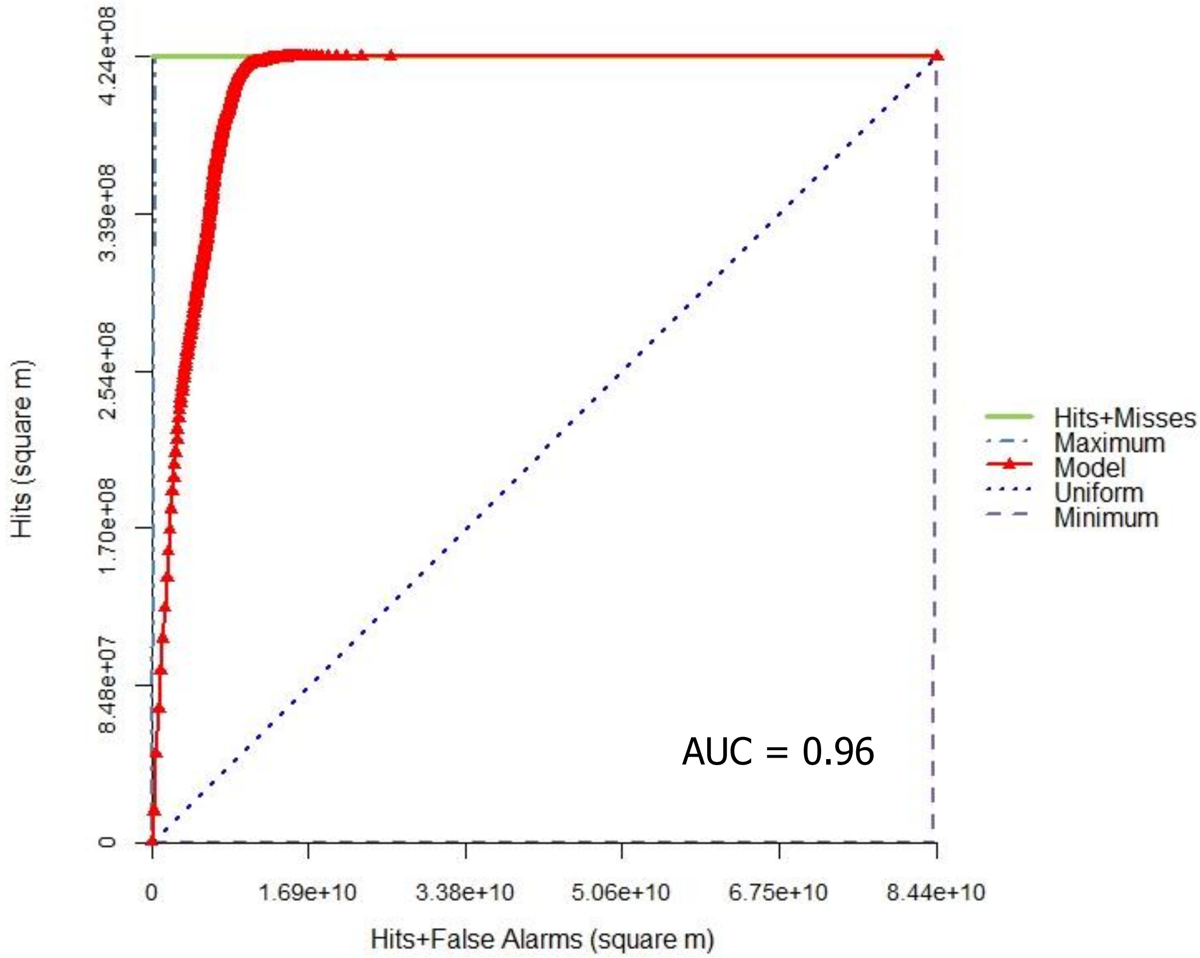

Figure 7. Total operating characteristic (TOC) curve for the land change model. The area under the curve (AUC) is 0.96.

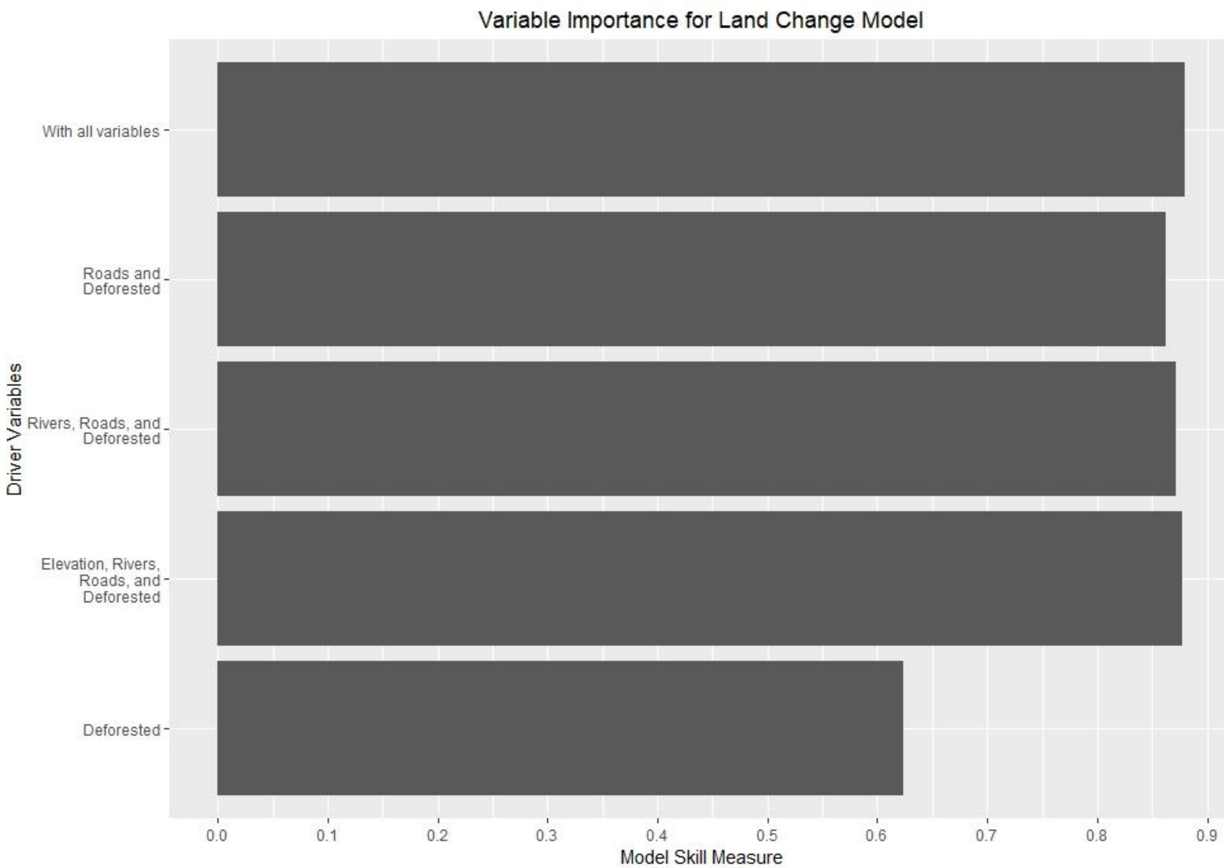

Figure 8. Backwards elimination stepwise analysis indicating variable importance for the land change model

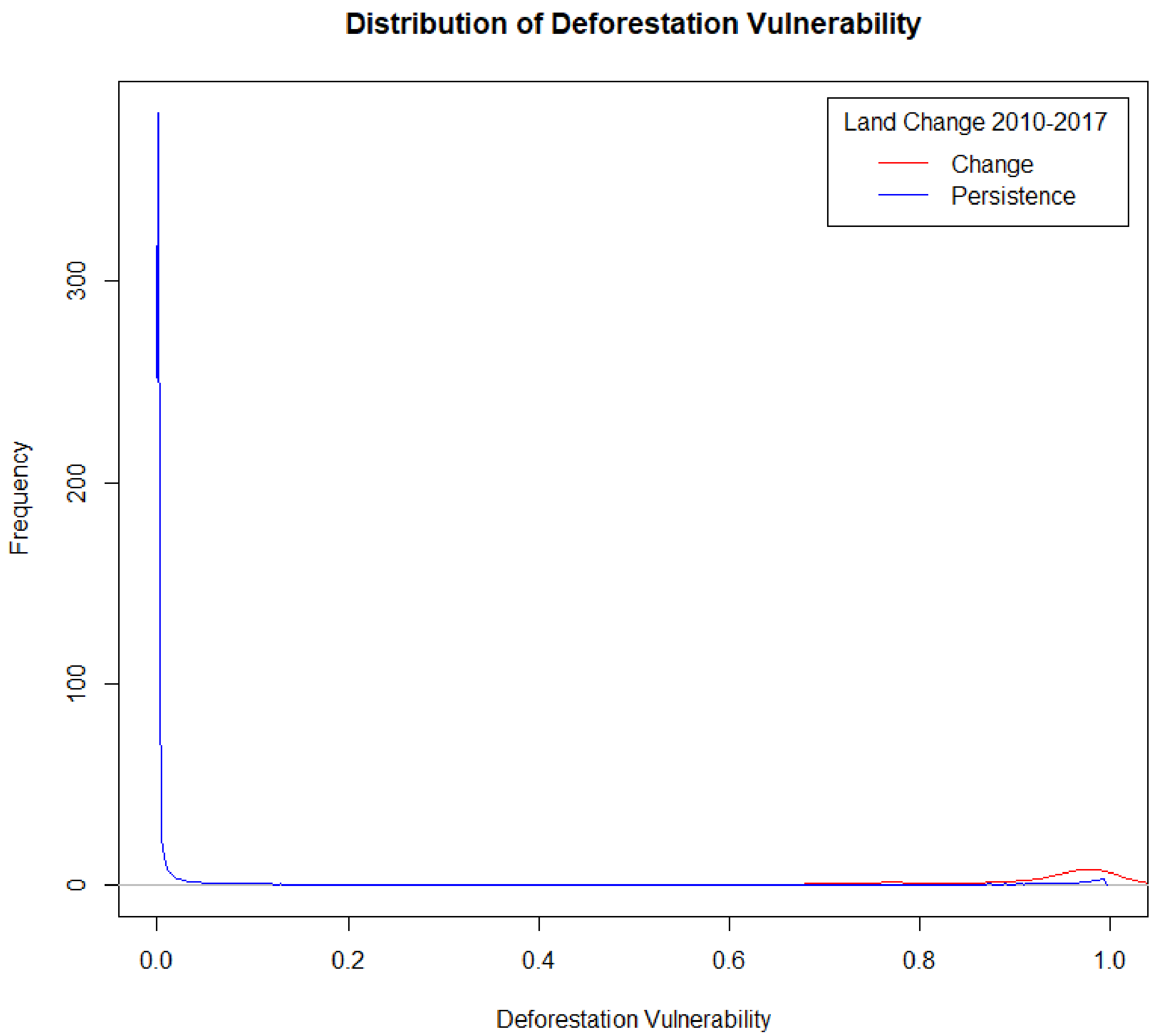

Figure 9. Histograms of predicted deforestation vulnerability values for pixels that experienced change (red) and persistence (blue) during 2010 to 2017.

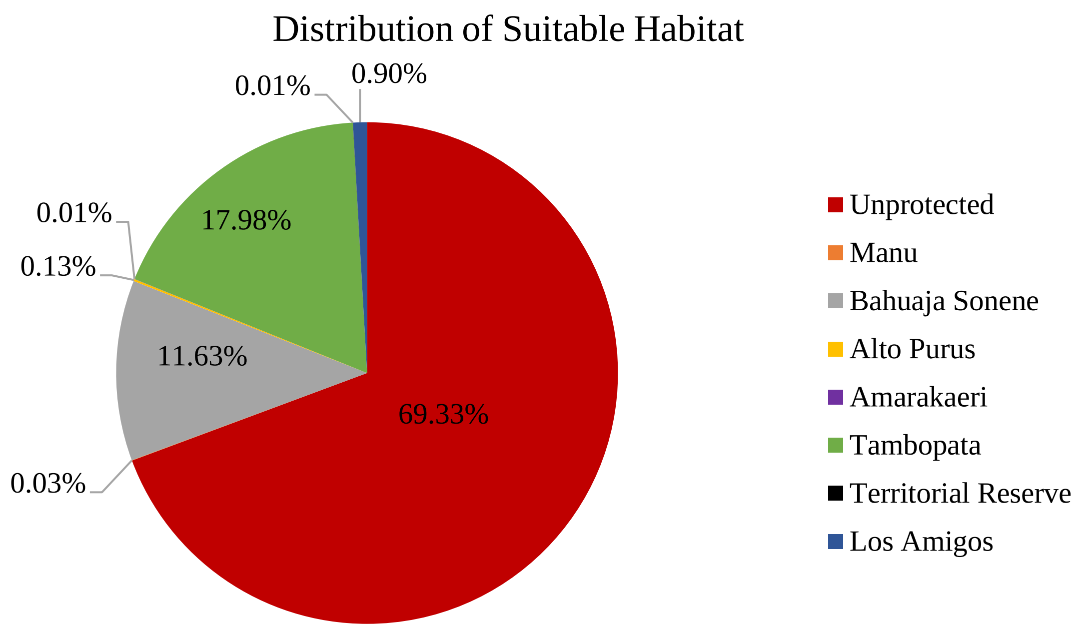

Figure 10. Pie chart depicting amount of suitable giant otter habitat within protected and unprotected areas.

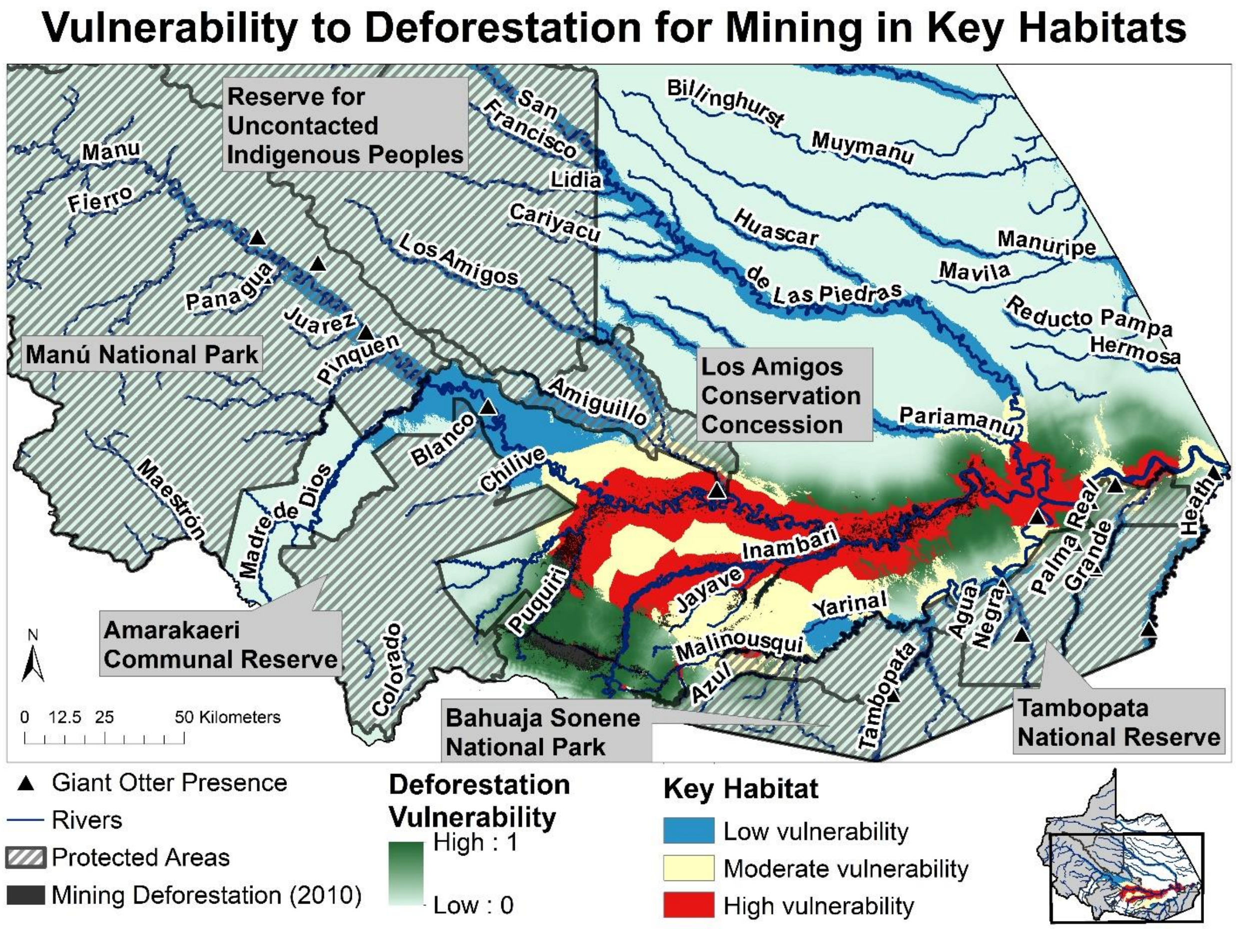

Figure 11. Deforestation vulnerability of giant otter key habitats.

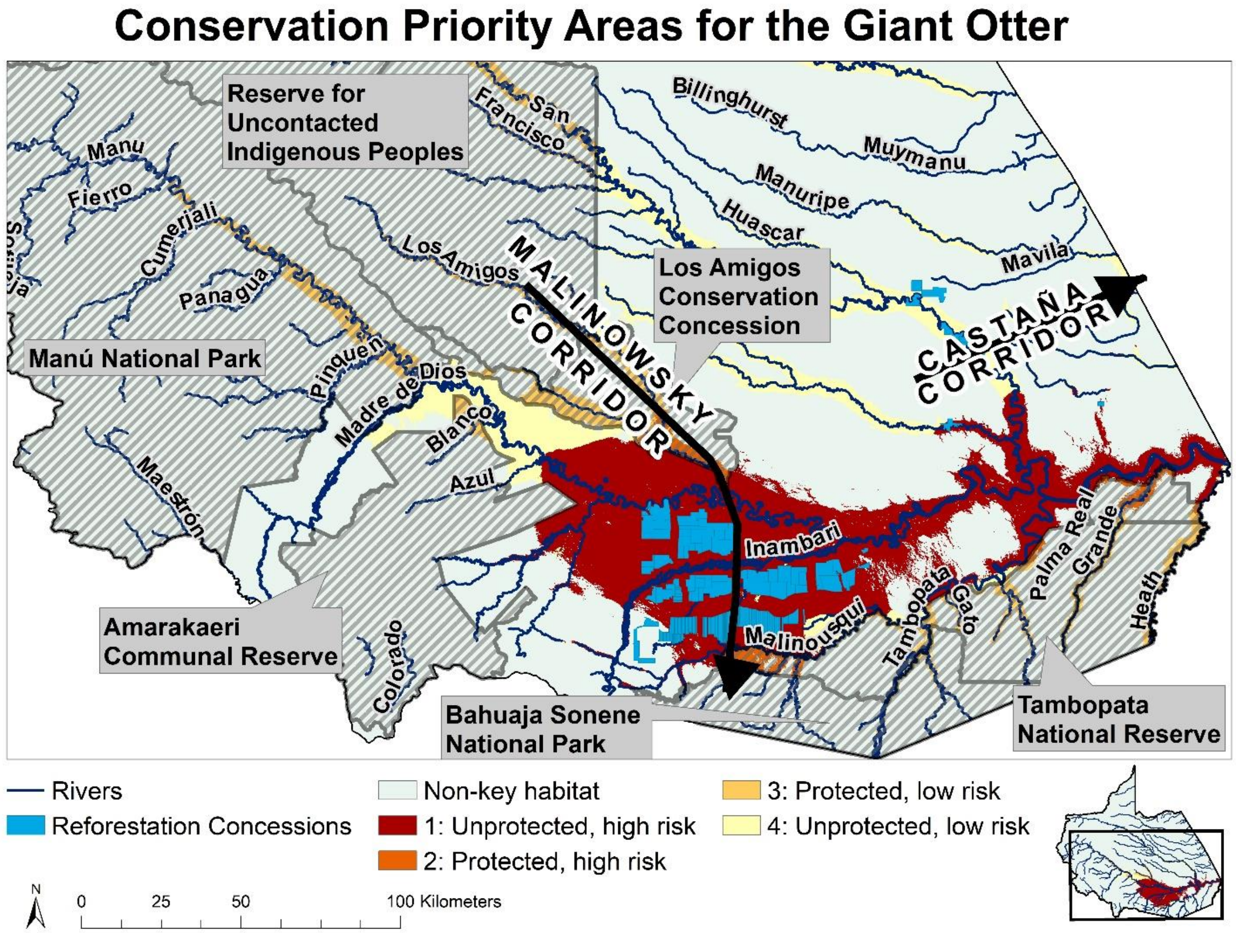

Figure 12. Conservation priority areas, labeled by type, based on giant otter habitat vulnerability and conservation protection. Proposed corridors by the ACA are shown by the blue arrows.