HABITAT QUALITY AND INTEGRATIVE CONNECTIVITY ANALYSIS FOR *CALLICEBUS OENANTHE* IN SAN MARTIN, PERU

By

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Executive Summary

The San Martín titi monkey (*Callicebus oenanthe*) is a critically endangered primate of north central Peru. As an endemic, *C. oenanthe's* small geographic range, coupled with some of the highest deforestation rates in South America, highlights its inherent vulnerability. Between 2000 and 2011 alone, San Martín experienced the highest gross forest cover loss of any other department in the country. Moreover, it was recently added to the IUCN's list of the top 25 most endangered primates in the world. To date, there is very little known about *C. oenanthe*. This is due, in part, to the species' cryptic nature and preference for the forest canopy.

The massive deforestation in San Martín threatens *C. oenanthe's* continued survival because as more forest is cleared, its' habitat is fragmented into discrete forest patches. As more patches are created, patch size will decrease over time. Small, disconnected patches threaten *C. oenanthe* due to associated negative feedbacks, such as facilitating invasions and hunter access, eliminating certain food sources, shifting environmental conditions, or increasing inbreeding depression. In time, these feedbacks can lead to patch extirpation on a small scale, and eventually species extinction on a large scale. Proyecto Mono Tocón (PMT), a local non-profit established in 2007, works to protect this species through field studies, community engagement, and environmental education activities. However, they have been unable to conduct a landscape scale assessment for this species. Therefore, this study was designed to complement PMT's efforts through a remote sensing and geospatial evaluation of *C. oenanthe's* remaining suitable habitat.

While primates remain one of the most well studied animal groups, most research has not focused on their response to landscape scale changes. Therefore, this study provides a landscape scale analysis in order for PMT to more efficiently and effectively prioritize their conservation decision-making. This was accomplished through the development of the first land cover map for *C. oenanthe's* entire distributional range using high-resolution satellite imagery. Additionally, a connectivity analysis was conducted to simulate movement and identify areas that both facilitate and impede connectivity across the landscape. Connectivity analysis is becoming a prominent strategy in conservation biology, particularly as deforestation fragments habitats into more discrete patches. Because *C. oenanthe* prefers to move across the landscape via the forest canopy, any gap between canopy cover effectively isolates this species. As such, protecting or reforesting corridors between remaining habitat patches will be a vital part of any management strategy. With this in mind, the connectivity analysis employed least-cost paths to identify areas that both aid and obstruct movement. In addition, mining concessions located in the range were also evaluated for their potential impact. Currently, mining is not a primary economic driver in the region; however, there is reason to believe that this may change into the future. With over 100 mining concessions authorized in San Martín, their development could be ecologically devastating to this species. Finally, all of this information was integrated into a prioritization tool that allows PMT to make tradeoffs in conservation design into the future.

Results of this study suggest that more than one quarter of *C. oenanthe's* range has been cleared and of the 1.6 million ha of forest remaining, more than half of this is likely marginal habitat.

Only 4% of the range overlaps with protected areas, and of these areas, 14% appear to have already been cleared, indicating that the protected areas that do exist are not protecting the biodiversity in the region as they had been intended to do. The connectivity analysis revealed nine patches that are completely isolated and that more than 90% of remaining habitat patches are likely too small to support viable populations. Mining concessions overlap with 6% of the range. Additionally, the analysis suggests that *C. oenanthe* will not only lose important corridors between habitat patches, but will also likely lose their highest quality habitat should these mining concessions become active. In total, the prioritization tool will allow PMT the option of 22 different attributes in which to inform their conservation decision-making.

If deforestation trends continue, which appear likely, results may be devastating for *C. oenanthe* and other threatened species of this area, as well as for local communities whose ecosystem services may be impaired. Because an overwhelming majority of habitat patches may be too small to support viable populations, reforestation programs to increase patch size or connect these sink to source populations would greatly help to limit the feedbacks that contribute to patch extirpation and extinction. Similarly, the nine patches identified as isolated should be evaluated to see if populations exist there currently. If any remain, these populations could be extremely important to target future conservation initiatives. This study also suggests that 14% of protected areas were classified as cleared, stressing the need for better enforcement to ensure these protected areas continue to support the biodiversity they were planned to protect. It is also disappointing that there is a greater percentage of mining concessions in the range than there are protected areas. The information provided by this study may be used by PMT to prioritize conservation targets as the ecological, political, and socioeconomic environments change. This flexibility allows for a dynamic management tool that PMT can utilize as spatial and temporal variations dictate.

INTRODUCTION

Currently, exploding human population growth and increasing per capita consumption trends are the primary drivers in global extinction rates (Pimm et al. 2014). Tropical forest hotspots have been modeled to lose 18-40% of species by 2100 due to deforestation, though some may argue that even these estimates are conservative (Pimm et al. 2014). Such an example is the Department of San Martín, located in north central Peru, which is a globally important area for biodiversity with some of the highest ongoing deforestation rates in South America (Hansen et al. 2013, Shanee et al. 2011). As forest clearing continues to intensify, a wide variety of species that reside in these ecosystems are put at risk of extinction. According to a study conducted by NatureServe, the forest band running from the eastern slopes of the Andes Mountains from Peru to Bolivia share 782 endemic species, highlighting the region as a biodiversity hotspot (Young et al. 2007, Swenson et al. 2012). From 2000 to 2011 alone, only five departments throughout Peru accounted for roughly 80% of total gross forest loss, where San Martín held the highest overall loss at nearly 9% (Potapov et al. 2014). The majority of this loss is attributed to clearing for agriculture and tree plantations (92.2%), while natural disturbances, such as flooding, river meandering, fires, windstorms, and mudslides account for the remaining fraction of forest loss (7.8%) (Potapov et al. 2014).

Fig. 1. ***Callicebus oenanthe*, known locally as mono tocón or the San Martín titi monkey.**

One of the many specialized species of this area is the critically endangered San Martin titi monkey (*Callicebus oenanthe*), recently added to the IUCN's list of the 25 most endangered primates in the world (Fig. 1; IUCN 2013). *C. oenanthe* is a 'narrow endemic' having a very small habitat area (< 13,000 km^2) and existing only in this region of the world (Fig. 2; Young et al. 2007, DeLuycker 2006). Their native habitat consists of humid Amazon and sub-Andean forests from elevations of 1000 m in the Alto Mayo Valley to 600 m in the Huallaga province (Bóveda-Penalba et al. 2008). To date, there is little known about *C. oenanthe*. This is due, in part, to their cryptic nature and preference for the forest canopy (DeLuycker 2006) as well as lack of study until the past decade. Past observational studies have determined their small distributional range with a density estimate for one small reserve; more recently, van Kuijk (2014) found that *C. oenanthe* might prefer forest edge to forest interior, possibly due to the availability of food sources. The escalating deforestation within the San Martín department is posing a substantial threat to the species continued existence. For primates, habitat change is one of the most significant threats to survival (Cowlishaw & Dunbar 2000). Compounding this is *C. oenanthe's* small geographical range and endemism, which have been shown to be important predictors in assessing extinction risk in declining species (Purvis et al. 2000).

As noted previously, deforestation in this area is primarily for small-scale agriculture and has likely reduced *C. oenanthe*'s original range to scattered fragments (DeLuycker 2006, Potopov et al. 2014). Fragmentation poses a severe threat to primate populations because as habitat is cleared, the number of isolates increases while individual isolate size decreases (Cowlishaw & Dunbar 2000). In turn, these fragments may indirectly lead to synergistic feedbacks, such as facilitating biological invasions and hunter access, eliminating food sources, shifting environmental conditions, and increasing inbreeding depression, all of which may hasten extirpation within a patch (Brook et al. 2008). Therefore, connectivity between forest fragments is quickly becoming a prominent strategy for protection (Sawyer et al. 2011). Improved conservation management plans that incorporate more information about the

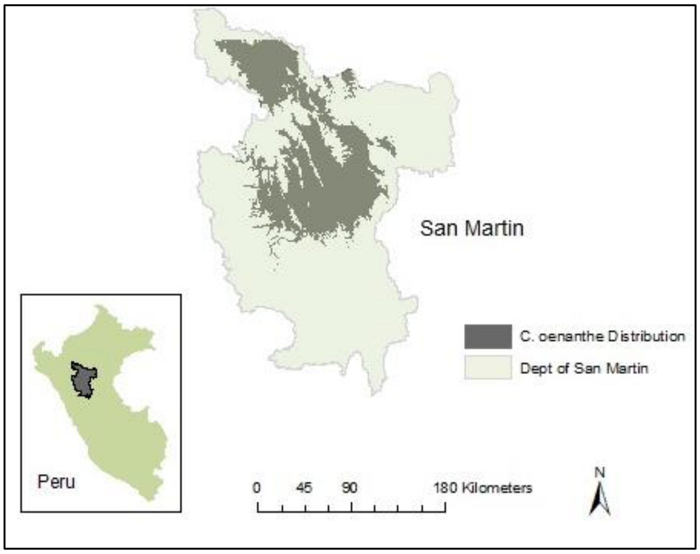


Fig. 2. The study area is defined as the distributional range *of C. oenanthe*, located exclusively within the Department of San Martín in north central Peru.

remaining habitat and its relative connectivity are crucial to *C. oenanthe*'s survival.

Connectivity modeling is becoming a popular strategy for species conservation management with many approaches available (Sawyer et al. 2011). Currently, one of the most common approaches is to use "least-cost paths" generated from graph theory (Sawyer et al. 2011, Urban & Keitt 2001). This approach employs a landscape resistance surface based on theoretical costs to movement for a particular species and distinguishes the paths that minimize these cumulative costs between habitat patches (Sawyer et al. 2011). For example, Bergl et al. (2012) modeled least-cost paths to analyze potential connectivity for *Gorilla gorilla diehli* (Cross river gorilla) using a habitat suitability model in west central Africa. Their study found that connected habitat had been underestimated in the past, suggesting that these gorillas should be managed as a single population – an important implication to future conservation strategies (Bergl et al. 2012). In a similar approach, this study will utilize least-cost paths because it is a quantitative approach suitable for revealing important areas of connectivity (Bergl et al. 2012). A complete graph theory analysis was not undertaken for *C. oenanthe's* entire range because of a lack of occupancy data. Circuitscape, a common software program for graph theory analysis, was used to model connectivity for the northern portion of *C. oenanthe's* range already, where some occupancy data is available (Fig. 3, Schaffer-Smith et al. unpublished data). Other corridor mapping programs were not used for this analysis because of their inappropriateness for the focal species. Because of *C. oenanthe's* preference to move across the landscape via the forest canopy, any gap intervening between canopy cover restricts the species' movement. In other corridor mapping programs this inability to use a non-forest matrix is not reflected. Therefore, it is imperative to model potential connectivity in regards to species-specific requirements (Sawyer et al. 2011). Moreover, because canopy gaps represent such an important barrier to *C. oenanthe's* potential connectivity, impediments to movement were modeled using accumulated cost-weighted distances from habitat patches.

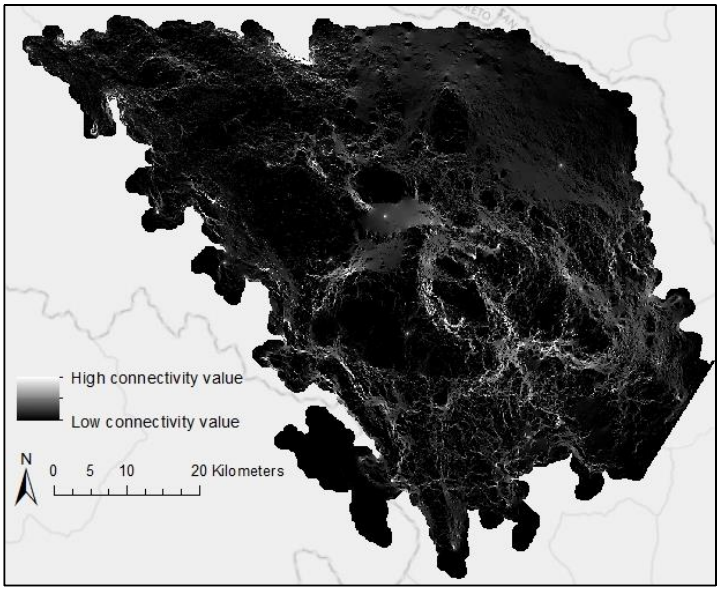


Fig. 3. Circuitscape output produced by Schaffer-Smith et al. (unpublished data) for C. oenanthe's northern range. Darker colors represent low connectivity potential where white shows increasing connectivity potential.

Local Partners

This project is a collaborative effort with the local non-profit organization, Proyecto Mono Tocón (PMT, http://www.monotocon.org/), which aims to better understand *C. oenanthe's* habitat requirements, acquire land to protect the species, and educate local communities about conservation. PMT has helped to coordinate the establishment of the first protected areas in San

Martín known to support *C. oenanthe* populations; one regional conservation area and four *Concesiones para la Conservacion* (conservation concessions) have been established, representing over 10,000 ha. The Peruvian government permits community organizations to manage conservation concessions for up to 40 years. This approach may be more cost effective in time and financing than establishing regional or national-level protected areas and could produce more appropriate consensus-based solutions for conservation. Though PMT is conducting population surveys and community outreach initiatives, they lack the funding and capacity to conduct a large-scale remote sensing and geospatial habitat evaluation to complement these efforts.

Therefore, the objective of this project was to supplement PMT's field studies and conservation efforts by identifying habitat areas that are most important for the survival of *C. oenanthe,* as well as to prioritize conservation sites using biologically constrained metrics. To accomplish this, biological and social values were explicitly integrated to identify remaining forested habitat according to suitability for conservation and reforestation programs. It will also assist in the identification of priority areas for implementation of environmental education and outreach activities. With this informed prioritization, PMT will be able to efficiently aid in conservation decision-making to protect *C. oenanthe*.

MATERIALS AND METHODS

Materials

The study area was confined to the geographical range distribution of *C. oenanthe*, located exclusively within the department of San Martín, Peru. A mosaic of satellite imagery including Landsat (30x30m resolution), ASTER (15x15m resolution), and SPOT (14.25x14.25m resolution) products, were employed for analysis. Other biological and social metrics, such as *C. oenanthe* occurrences and the cost and feasibility of habitat protection, were provided by PMT. Over 300 GPS data points were collected over the summer of 2014 for use in verification of land cover map accuracy.

Methods

(1) Mapping remaining suitable habitat

C. oenanthe requires relatively tall trees and a connected canopy in order to move across the landscape, and as such, a map of remaining forested habitat is integral to implementing conservation strategies. In the past, high cloud cover and lack of local capacity have limited previous efforts to map habitat area and quality in San Martín. Building off of a pilot study conducted by Schaffer-Smith et al. (unpublished data), the first aim was to map remaining suitable habitat within *C. oenanthe*'s entire range using high-resolution satellite imagery. SPOT 5 images from August and September of 2011 and Landsat 8 images from July and December of 2014 were used for the creation of the land cover map (SPOT program, 2011a, 2011b; NASA Landsat Program, 2014a, 2014b). The SPOT images were radiometrically and atmospherically corrected using the dark object subtraction method (Song et al. 2001). The Landsat 8 images were radiometrically and atmospherically corrected using the FLAASH module in ENVI version 5.1 (Exelis Visual Information Solutions, Boulder, Colorado). All images were georeferenced to the high-resolution global forest map produced by Hansen et al. (2013).

Two classification approaches were used to develop the range-wide land cover map. One method was through a supervised classification using maximum likelihood. Using GPS points I collected in the summer of 2014, 12 points of each land cover type, including primary, secondary, and cleared, were used as training data. The second method I employed was an unsupervised classification using the Iterative Self-Organizing Data Analysis Technique (ISODATA) algorithm. Using this method, 65-100 classes were generated per image using 10 iterations. Each image was classified using all visible and near-infrared bands, as well as elevation, slope, and aspect information. Additionally, Landsat 5 imagery from July of 1987 was also classified and combined with the present-day classification outputs (NASA Landsat Program, 1987). Using historical imagery allowed the identification of secondary forests that had been previously cleared, but had grown back since to resemble primary forest. As well, I was able to categorize land use cover that had been repeatedly cleared from 1987 to present-day or those that had only been recently cleared.

Since it is critical to assess the accuracy of land cover mapping before products are used for analysis or decision-making purposes (Arroyo-Mora et al. 2005), I conducted an accuracy assessment using 305 GPS ground control points I collected in June and July of 2014. These ground control points were collected opportunistically using a handheld Trimble Juno GPS unit. Points were taken within 30 m of roads in patches of homogenous land cover of at least 900 m^2. Patches were identified as primary, secondary, or cleared, noting the predominant land cover type. In total, 288 of these points were used for the accuracy assessment. Additionally, Google Earth was used as ancillary data, to supplement for high cloud cover and haze.

(2) Analyzing potential connectivity between patches

Connectivity between suitable habitat patches is essential for *C. oenanthe's* survival. Potential connectivity between forest patches was modeled using the Geospatial Habitat Assessment Tool (GeoHAT), a multi-criteria decision analysis framework (Fay & Urban 2012). GeoHAT applies graph theory and provides a useful evaluation of landscape management objectives for better informed management decisions. For this analysis, PMT identified the area of Gera within the Alto Mayo Valley, which is a small riparian corridor, with potential connections to three neighboring protected areas: Almendra, Mishquiyacu Rumiyacu, and Juningillo La Mina (Fig. 4). PMT is interested in protecting a forest corridor within this part of the range. What makes this area an ideal candidate for a connectivity analysis is its location linking the northern and southern ranges as part of the narrow section of *C. eonanthe's* range.

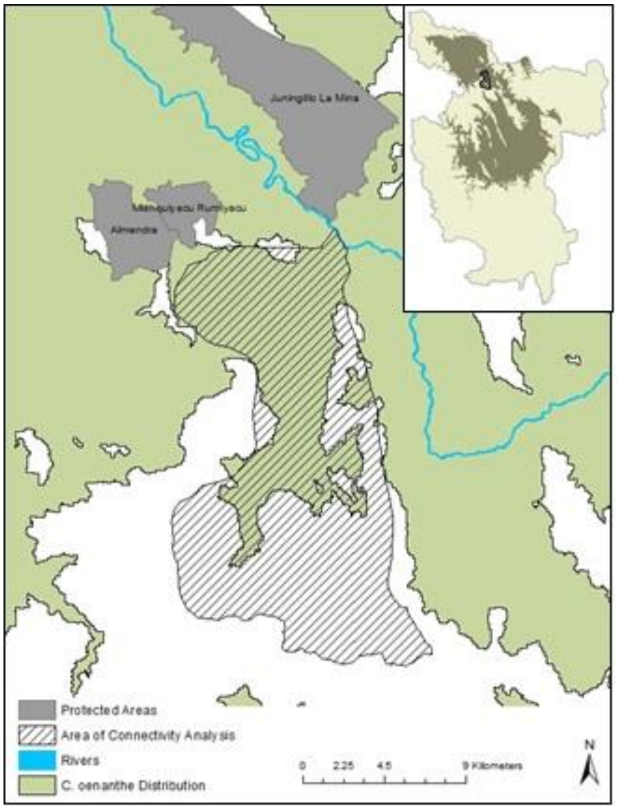


Fig. 4. Gera, the area of the connectivity analysis, is located within the northern section of *C. oenanthe's* range in the Alto Mayo Valley.

All classes containing forest identified by the range-wide land cover map were used to create the habitat patch raster. As well, all cover types were categorized as a function of landscape resistance (e.g. cleared = high resistance [100], primary forest = low resistance [1]) to create a resistance raster. These rasters were used in GeoHAT to determine least-cost paths and develop key attribute groups including patch size and shape, patch connectivity to other patches, patch connectivity to protected areas, and patch vulnerability. Habitat patches with a size of 2.5 ha or greater were considered "nodes" and the least-cost paths connecting these forest fragments were considered the "edges." DeLuycker (2007) estimated *C. oenanthe's* home range size as 2.5 ha, which guided the criteria for "nodes." Finally, social metrics including cost of protection and feasibility of protection were added to the attribute table using a majority rule operation in zonal statistics. These social metrics were derived by the expertise of PMT staff using a coarse grain delineation of high, medium, and low costs of land acquisition (using land use/zoning information) and high and low feasibility of protection (using land use/zoning information). While highly subjective, these social values can provide foundational insight towards informed prioritization.

In addition to the connectivity analysis advanced by GeoHAT, I also used Linkage Mapper version 0.7 BETA to develop a map of corridors linking core areas of habitat patches (McRae & Kavanagh 2011). Linkage Mapper is a GIS tool that employs vector maps of core habitat areas and raster maps of landscape resistance to identify least-cost corridors between habitat patches. Traditionally, most conservation planners have focused on conserving areas that facilitate movement in order to promote connectivity (McRae et al. 2012). McRae et al. (2012) posit that another strategy to support connectivity is to restore connections across areas that impede movement and should be incorporated into conservation planning and management. Moreover, as noted previously, *C. oenanthe* prefers to move across the landscape through forest canopy, highlighting the species' sensitivity to canopy gaps resulting in movement barriers. By evaluating areas that facilitate connectivity, as well as identifying areas in need of connectivity restoration, a more comprehensive picture of possible management strategies are made available to PMT planners.

(3) Identifying potential development pressures in the future: a mining scenario

In addition to San Martín's notable biodiversity, the region is also home to a growing human population of over 800,000 (IENI 2014). The development pressure resulting from this growth has had and will continue to directly affect *C. oenanthe's* chance of survival as more land is cleared. However, another development risk is also possible for the region. San Martín's natural resources are currently vulnerable to untapped mining concessions as well as a market-driven increase in mining which could have devastating ecological and environmental health effects, evident already in heavily-mined departments, such as Madre de Dios. Though mining is not a primary economic driver in the region currently, there are indications that this may be changing in the near future, especially for gold mining (e.g. *Voces*, 2013). The regional government has already authorized 103 mining concessions in San Martín and an additional 20 proposed concessions are currently under review (DREMSM 2013). Expansion of mining will lead to further habitat loss and degradation of the already fragmented forest, putting the survival of critically endangered endemics, such as *C. oenanthe*, at further risk for extinction. Additionally, growth of industry will likely increase erosion and mudslides, reduce soil fertility, and decrease water quality. Communities are already concerned about ecosystem services – the newest conservation areas were implemented in large part for protection of watershed integrity (personal communication, Antonio Bóveda-Penalba). Characterizing the potential spatial and temporal threats from mining activities will enable dialogue between communities, the government, and the mining industry to strategically preserve ecosystem services and biodiversity values.

In order to assess the possible implications of future mining concessions, all authorized concessions were incorporated into the analysis. First, San Martín mining concessions were clipped to the land cover map to determine how much land would be threatened within *C. oenanthe's* range, if these concessions became active. Additionally, GeoHAT was used for another connectivity analysis, this time using habitat patch and resistance rasters that incorporate these concessions within Gera (e.g. mining = high resistance [100]). This provides PMT with the ability to compare current connectivity with potential connectivity under a mining scenario, which may be an important metric for prioritization in the future.

(4) Identifying targets for conservation initiatives

The range-wide land cover map and connectivity assessment provide a multifaceted tool for PMT to use for conservation prioritization exercises. For example, using the biologically constrained information integrated with social metrics provided by this study, PMT can rank remaining forested habitat within *C. oenanthe's* range using: (1) habitat quality (or habitat area), (2) relative importance of patches for connectivity, (3) comparative connectivity to neighboring protected areas, (4) possible connectivity restoration corridors, (5) locations of mining concessions, (6) relative cost of protection, and (7) feasibility of protection. Prioritization of these metrics rests with the local knowledge of PMT staff and consensus-based community decisions; however, for the purposes of this study, an example prioritization was conducted for reference.

RESULTS

Remaining suitable habitat

The land cover map resulted in six land cover types: (1) primary forest, (2) secondary forest, (3) forest/agriculture, (4) secondary forest/agriculture, (5) agriculture/cleared, and (6) cleared since 1987. Primary forest reflects land cover that was classified as forested in both 1987 as well as from recent satellite imagery, whereas secondary forest was classified as cleared in 1987, but reforested in recent imagery. Both primary and secondary forest cover represent high quality habitat for *C. oenanthe*. Forest/agriculture represents a matrix of recently converted agricultural lands and forests. The class is mixed due to the classification algorithm's inability to parse out spectral differences, likely due to imagery resolution. Similarly, secondary forest/agriculture represents a mixed land cover matrix, but in contrast, has been identified as repeatedly converted since 1987. Both of these mixed classes represents low quality habitat for *C. oenanthe*. There is observational evidence that the species can use these lands as corridors or food sources, though are not expected to be important for other ecological services (personal communication, Antonio Bóveda-Penalba). Agriculture/cleared is classified as land recently deforested for agriculture or other anthropogenic activities. Finally, cleared since 1987 represents land cover that has been consistently deforested since 1987. These latter classes represent no suitable habitat for *C. oenanthe*.

As anticipated, the land cover map for *C. oenanthe* revealed that its original range has been decimated into a patchwork of forest fragments (Table 1 & Fig. 5). Over one quarter of *C. oenanthe's* distribution has been cleared, of which a majority has been cleared recently. An estimated 1,646,782 ha of forest remain, though more than half of this is likely marginal habitat. This marginal habitat accounts for 39% of *C. oenanthe's* range and while they may be able to use this land cover for connectivity or foraging, it does not represent the high quality habitat necessary for their survival. This agriculture/forest matrix may also increase human-wildlife conflict as *C. oenanthe* can be seen as a pest to farmers because they eat agricultural crops. Therefore, approximately 65% of *C. oenanthe's* range is likely unsuitable for supporting populations over time. Moreover, less than 4% (46,419 ha) of *C. oenanthe's* potential distribution overlap with protected areas. Of this percentage, the analysis suggests that nearly 14% of these protected areas have already been cleared.

Land Cover Class	Area (ha)	Land Cover (%)
Primary	409,499	29%
Secondary	91,408	6%
Forest/Agriculture	437,083	31%
Secondary Forest/Agriculture	108,792	8%
Cleared/Agriculture	259,769	18%
Cleared since 1987	120,685	8%

Table 1. Breakdown of each land cover by total area (in hectares) and percentage.

In comparing the accuracy of each classification approach, the unsupervised method performed with the greatest accuracy. The remaining habitat was therefore mapped with an overall accuracy of 87.07% (see Appendix 1). The northern section of the range, mapped by Schaffer-Smith et al., had a similar accuracy of 87.9% (unpublished data). The supervised classification method was tested using the western SPOT image; however map accuracy was poorer than the unsupervised classification output and was thus not incorporated into the final land cover map (see Appendix 2).

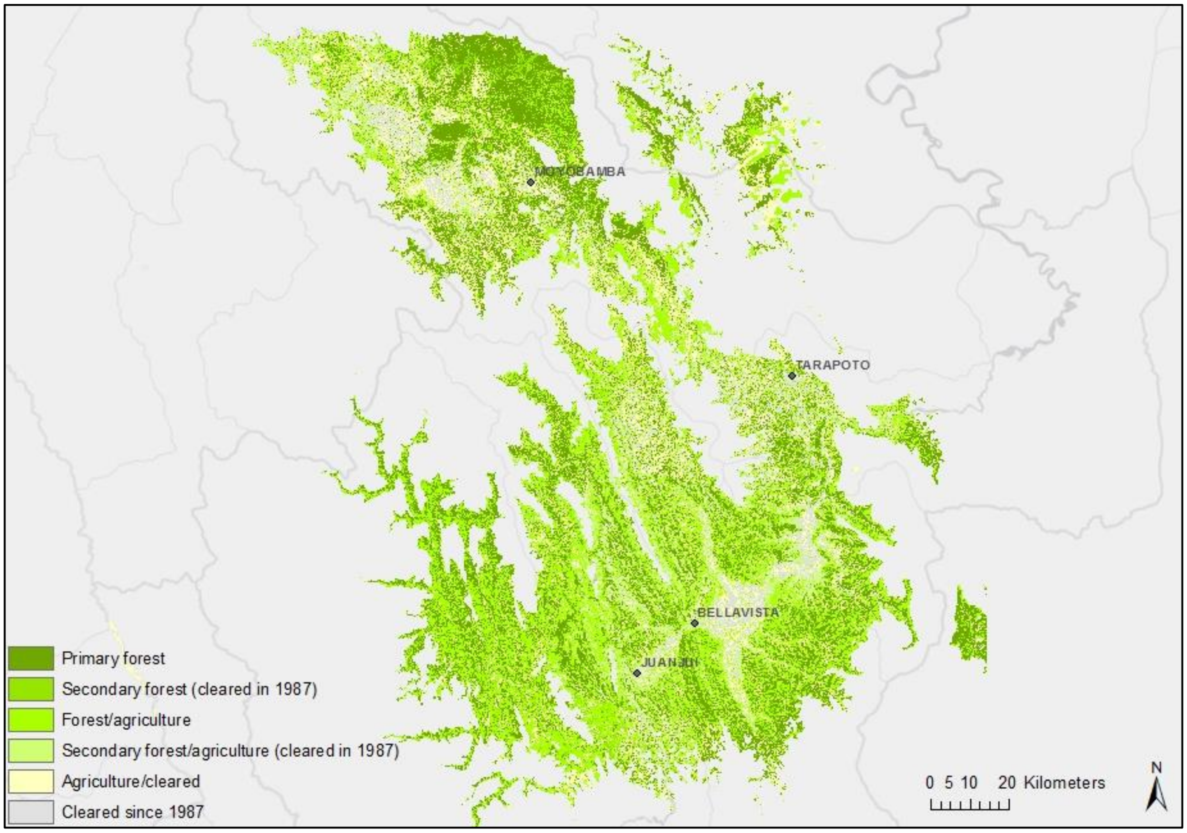


Fig. 5. Range wide land cover map with overall accuracy of 87.07%. More than one quarter of *C. oenanthe's* range has been cleared.

Connectivity analysis

The connectivity analysis was focused on Gera, a corridor within the northern section of *C. oenanthe's* range. This area includes 599 potential habitat patches with an average size of 16.9 ha. However, this average is skewed by a few outlying patches of substantial size, in reality, approximately 92% of these patches are 2.5 ha (*C. eonanthe's* home range size) or smaller (DeLuycker 2007). This suggests that remaining habitat patches may not be able to support viable populations of *C. oenanthe*; nonetheless, these small fragments may be important for connectivity (Schaffer-Smith et al., unpublished data). These patches have an average distance to edge of 31.1 m while the species' daily travel distance is estimated at 660 m (DeLuycker 2007). The connectivity analysis also revealed that nine patches are completely isolated with a connectivity score of zero. Moreover, less than 15% of patches are connected to surrounding protected areas. Least-cost paths generated from the analysis indicate two likely major pathways, each running vertically along east and west corridors (Fig. 6). While Figure 6 appears to show a complicated network of least-cost paths, it should be noted that 40% of these pathways are not overlapped by any others, highlighting the inherent isolation across the landscape. In conjunction with these biologically constrained metrics, cost and feasibility of protection was also assessed for prioritization purposes. Nearly 63% of habitat patches scored a 2 out of 4 in cost of protection, meaning the cost to protect is estimated to be of moderate difficulty (Fig. 7). As well, more than 73% of habitat patches scored a 1 out of 3 in feasibility of protection, meaning that protection of patches may be relatively easy (Fig. 8).

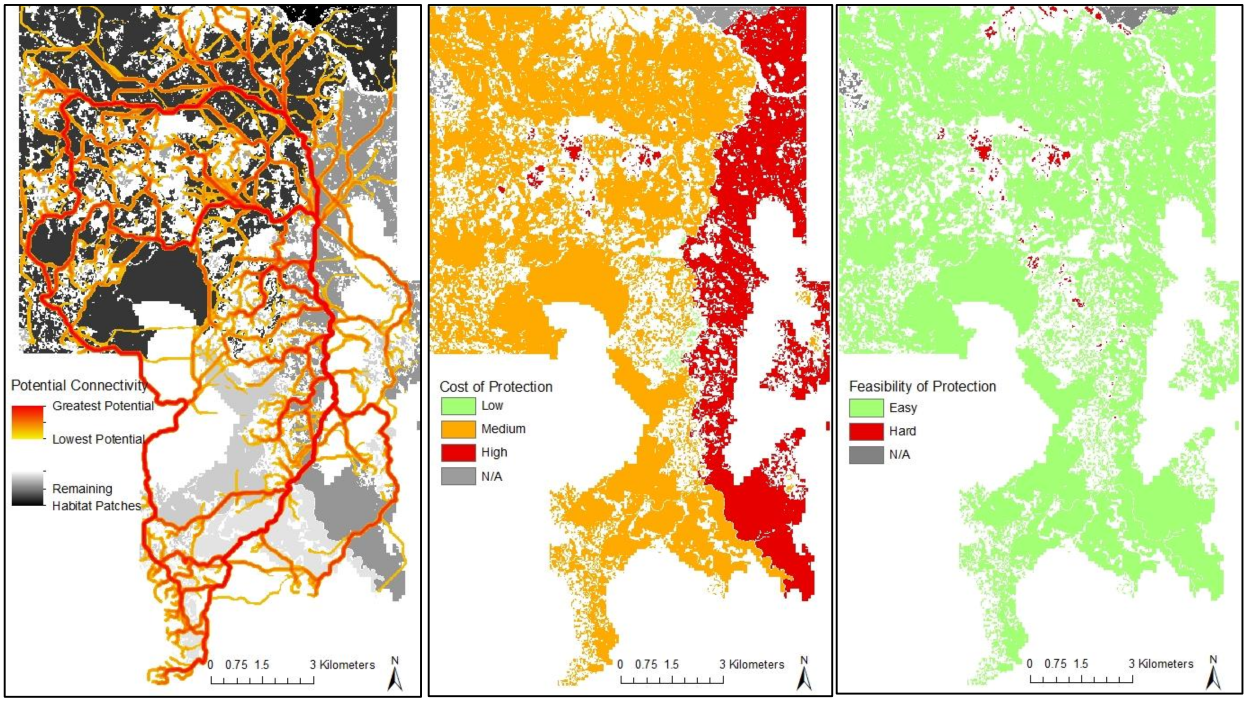


Fig. 6-8. Connectivity potential (red indicates increasing potential) (Left), Cost of protection (middle), Feasibility of protection (Right). N/A are patches that overlap with protected areas.

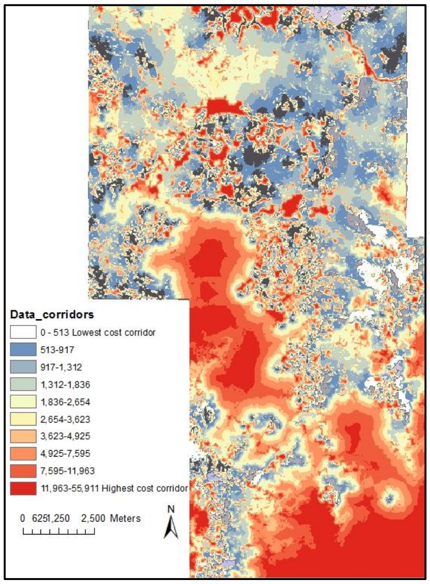


Fig. 9. Cost weighted distances from patches identify areas that aid movement (blue) and impede movement (red).

Linkage Mapper provided another perspective on relative connectivity as it applies to this study. For example, in contrast to GeoHAT, Linkage Mapper creates corridors using accumulated cost-weighted distances from patches. This assists in the identification of areas that may impede connectivity and could constitute candidate areas for corridor reforestation projects (Fig. 9). In Figure 9 I have detected areas with corridors that range from lowest cost (blue), thus facilitating movement for *C. oenanthe*, to corridors with higher costs (red), thus impeding movement for *C. oenanthe*. From this perspective, PMT has the opportunity to prioritize their efforts at re-establishing connections between certain habitat fragments, or, to focus on preserving corridors already intact. Each of these management decisions may be a valuable metric to not only conserve fragmented populations, but to possibly rehabilitate them from small isolate synergistic effects.

Future Development Pressures

Mining poses a significant risk to the survival of this species. Whereas less than 4% of *C. oenanethe's* range overlaps with protected areas, nearly 6% overlaps with mining concessions (Fig. 10). If all of the authorized mining concessions were to begin operating, nearly 84,361 ha from *C. oenanthe's* range would be lost, of which approximately 70% is currently forested. Overall, the forest/agriculture matrix loses the most in land cover at nearly 25,000 ha (Graph 1). This represents an important loss in land cover that may provide connectivity and foraging opportunities for *C. oenanthe*. In second, primary forest is greatly affected, with a decrease in land cover by 19,642 ha. Primary forest is especially important for *C. oenanthe* as it represents this species' highest quality habitat available.

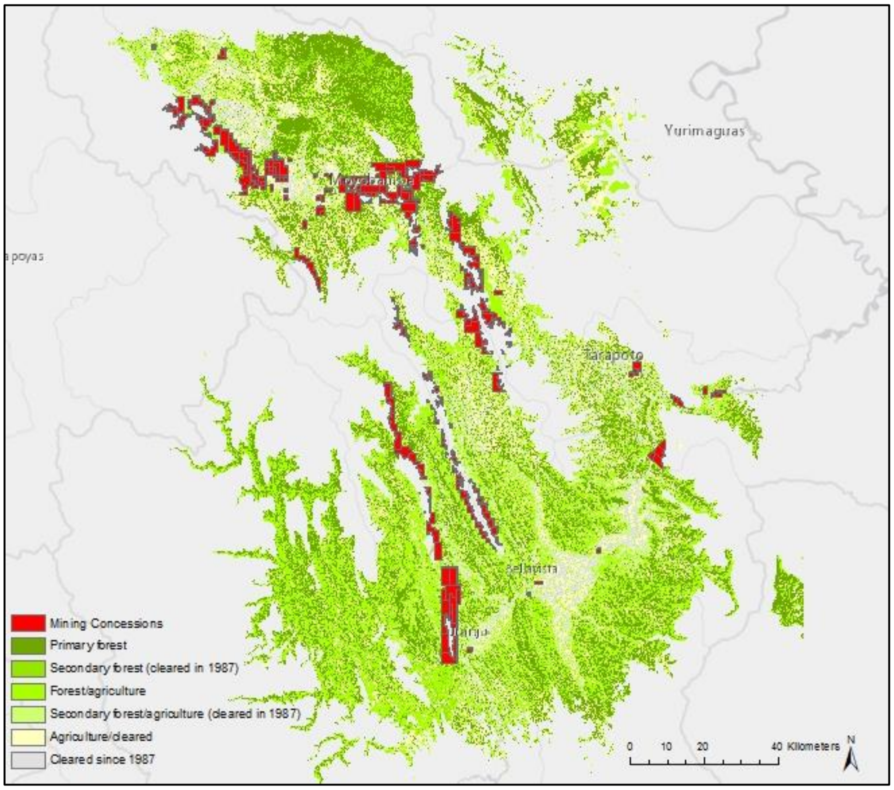
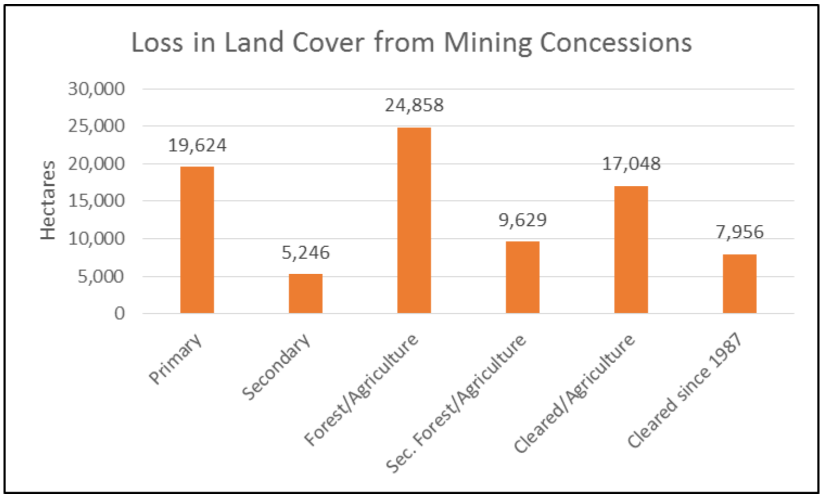


Fig. 10. ***C oenanthe's* range distribution with authorized mining concessions overlaid. If these concessions begin operating, they threaten 84,361ha, of which 70% is currently forested.**



Graph 1. Loss in land cover from future mining concessions throughout C. oenanthe's range, which may pose substantial ecological implications for the species.

The connectivity analysis for the mining scenario revealed that concessions could have a major impact on habitat connectivity within Gera. For instance, with active mining concessions, patches were reduced in number from 599 to 502 with the majority of these patches (92%) 2.5 ha or smaller. Again, this may suggest that patch size is too small to support viable populations. Average connectivity to protected areas was considerably reduced from 15% to 6%. As could be expected, the average distance to land use threat increased substantially. In the current connectivity analysis, only 9% of patches were affected with an average distance to land use threat of 0.009. Under the mining scenario, nearly 45% of patches were affected with an increase in average distance to land use threat to 0.09, an order of magnitude greater.

In addition, comparing the connectivity potential between current and mining scenarios, emphasizes areas that may be of greater conservation value into the future. For example, if the mining concessions become active, this would radically change the connectivity between forest patches, especially in the upper east corner where most mining concessions are located and where most of *C. oenanthe's* high quality habitat is located (Fig. 11). Therefore, not only would mining dramatically reduce connectivity, it would also eliminate the highest quality habitat available to *C. oenanthe* in Gera, making their continued survival in the area uncertain.

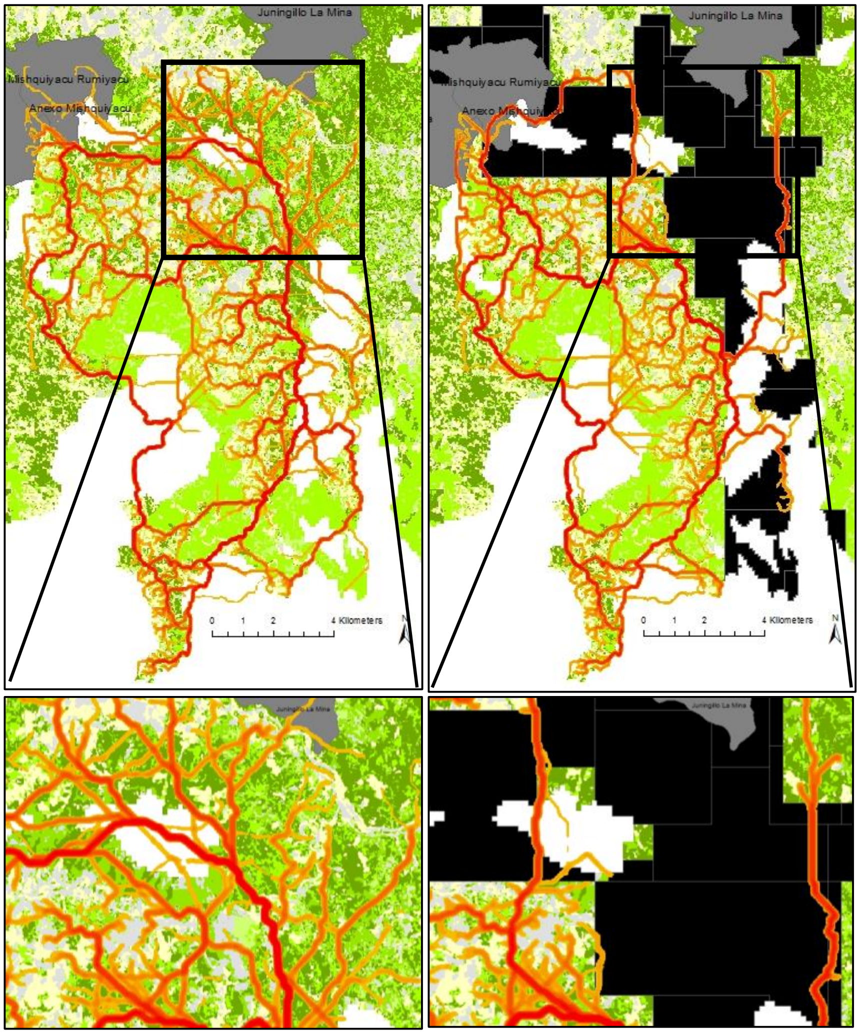


Fig. 11. Connectivity potential is greatly reduced when mining concessions become active. High quality habitat (primary and secondary forest) are also threatened by mining. Current connectivity results (Left) and mining connectivity results (Right).

How this information can be used: a case study of Gera

In total, the information generated from this analysis provides PMT with 22 different attribute groups in which to base their decision-making (see Appendix 3). For example, some patch metrics include total size, core area size, distance to edge, connectivity value, connectivity to protected areas, as well as cost and feasibility of protection (Fig. 12). PMT can use these same metrics from the mining scenario for future forecasting if they deem this an appropriate management strategy.

Total Patch Size (ha)	3.22
Core Area Size (ha)	3.22
Distance to Edge (m)	35.2
Connectivity Value	8,073
Connectivity to Protected Areas	7,043
Cost of Protection	Medium
Feasibility of Protection	Hard

Total Patch Size (ha)	3.05
Core Area Size (ha)	3.05
Distance to Edge (m)	43
Connectivity Value	8,056
Connectivity to Protected Areas	7,030
Cost of Protection	Medium
Feasibility of Protection	Hard

Total Patch Size (ha)	5,403
Core Area Size (ha)	5,403
Distance to Edge (m)	95.8
Connectivity Value	3,739
Connectivity to Protected Areas	8,639
Cost of Protection	Medium
Feasibility of Protection	Easy

Fig. 12. Example of attribute groups available for each habitat patch located within Gera. There are 22 available per patch (see Appendix 3).

In addition, PMT may also utilize the least-cost paths and accumulated cost weighted distances developed from connectivity modeling to base their decision-making (Fig. 13-14). To illustrate this, Figure 13 characterizes the connectivity potential for three remaining habitat patches. In this scenario, PMT may choose to forgo the isolated patches located to the north of the road and focus on the larger patch to the south because high connectivity value already exists there. Conversely in Figure 14, accumulated cost weighted distances indicate barriers to movement. From this perspective, PMT may choose to target their conservation efforts at rehabilitating connections between habitat patches. For instance, they could choose to plant a line of trees to reconnect the isolated patches to the north. There is observational evidence that *C. oenanthe* necessitates only a small line of mid-canopy height trees to move across the landscape, making this a viable management option (personal communication, Antonio Bóveda-Penalba). If *C. oenanthe* populations exist in either of these patches, it would greatly improve their viability by providing more habitat and resources to utilize.

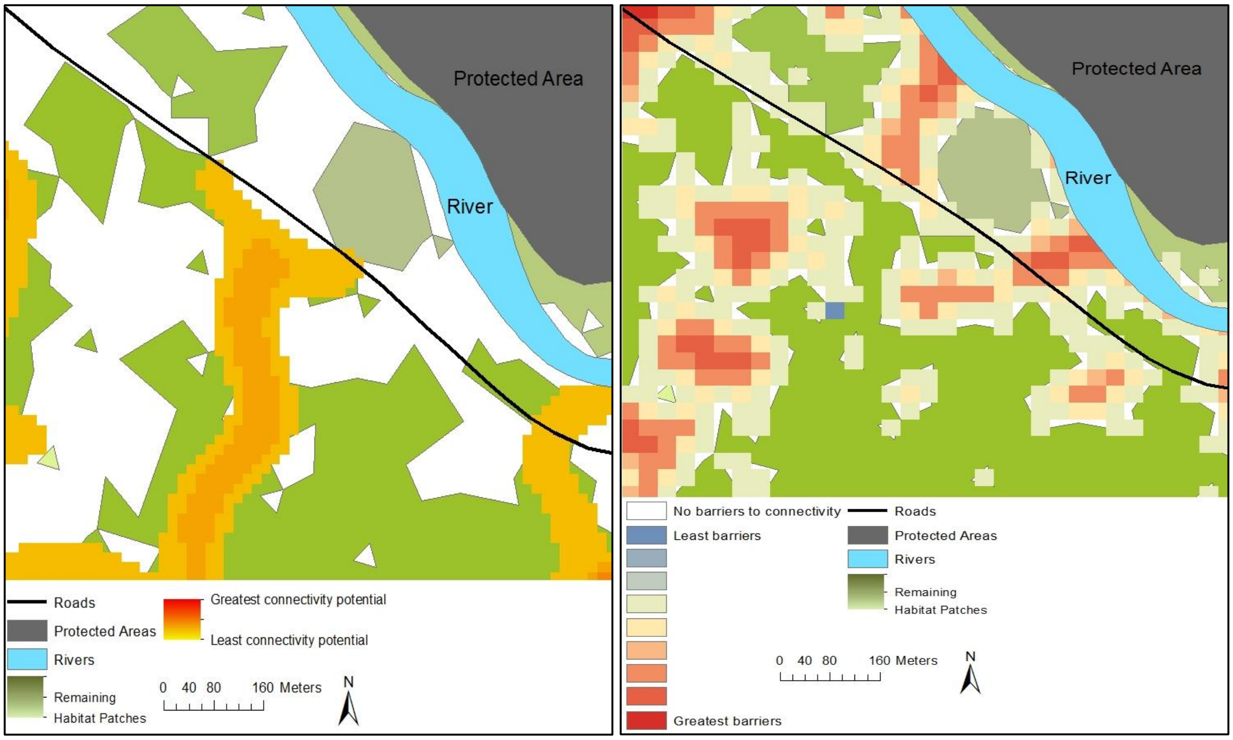


Fig. 13-14. Least-cost paths show connectivity potential (Left) and accumulated cost weighted distances show connectivity barriers (Right). This provides the opportunity to take different management strategies.

To illustrate further how the information garnered from this analysis can be used for future management decisions, an example prioritization exercise was undertaken for Gera. Habitat patches were first selected based on patch size. Those greater than or equal to 2.5 ha (*C. oenanthe's* home range size) were chosen as a priority because of a desire to minimize synergistic feedbacks common in small forest fragments (Brook et al. 2008). This narrowed the selection of habitat patches from 599 possibilities to 46 sites (Fig. 15). Next, patches were selected based on their connectivity value to other patches. Because *C. oenanthe* has a preference for the forest canopy, the species utilizes a connected canopy to move across the landscape, emphasizing connectivity to other habitat patches as a particularly important metric for conservation (DeLuycker 2006). Selecting by the average connectivity value or greater for all sites, ensured that patches would provide useful connectivity to other forest fragments within the analysis area. This reduced the selection of habitat patches to 30 possibilities (Fig. 16). Next, sites were prioritized by selecting for feasibility of protection (1 out of 3: "easy") and cost of protection (1 out of 4: "low"). This reduced targeted patches to 18 and 2, respectively (Fig. 17-18). Feasibility and cost of protection were used as prioritization criteria because non-profits are often limited by funds, labor, and resources, as well as the socioeconomic and political climate, so targeting sites that are both ecologically important as well as feasible may allow PMT to have the biggest impact while conserving their limited resources. This case study also illustrates how different metrics can barely change a prioritization exercise, while others may drastically alter which patches to target.

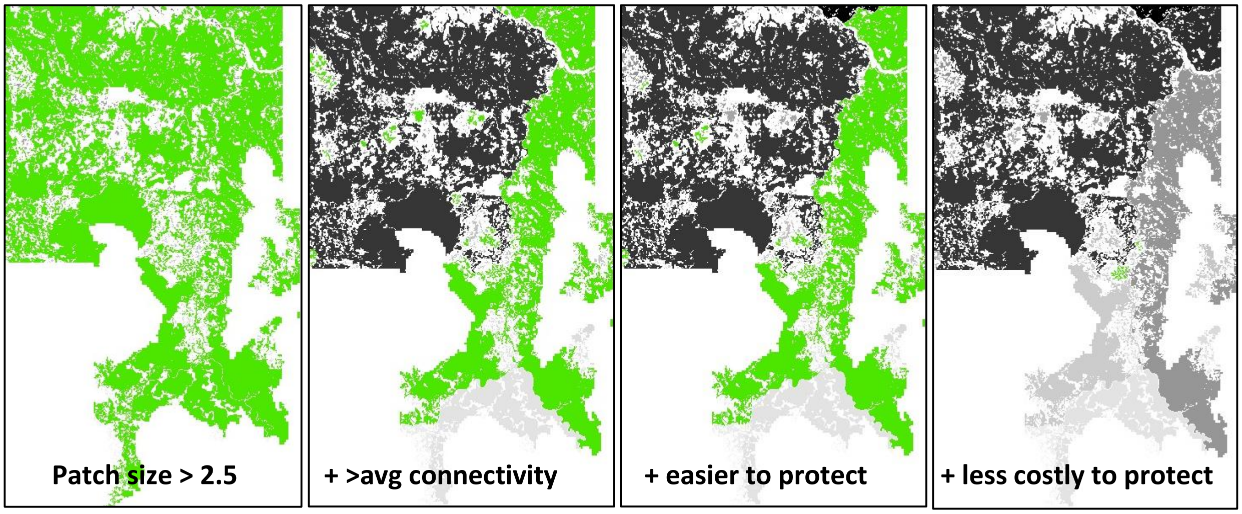


Fig. 15-18. Figures represent the process of narrowing conservation sites through the case study prioritization exercise. Green shows selected sites. Sites selected based on patch size greater than or equal to 2.5 ha (far left), connectivity with scores of average connectivity or greater (middle left), score of easy on feasibility of protection (middle right), and score of easy on cost of protection (far right).

This case study exercise is not meant to direct future conservation initiatives, but simply is a way to sketch how these constrained metrics can be used. PMT should prioritize these results in collaboration with surrounding communities in order to identify the metrics with the greatest importance to their mission while balancing the social and economic realities on the ground. Importantly, these results can be prioritized over time as the ecological, political, social, and economic environments change. This flexibility allows for a dynamic management tool that PMT can utilize as spatial and temporal variations dictate.

DISCUSSION

More than one quarter of *C. oenanthe's* habitat has been cleared. If deforestation trends continue, which appear likely, results may be devastating for *C. oenanthe* and other threatened species of this area, as well as for local communities whose ecosystem services may be impaired. Because an overwhelming 92% of habitat patches may be too small to support viable populations, reforestation programs to increase patch size or connect these sink to source populations would greatly help to limit the feedbacks, such as facilitating hunter access and inbreeding depression, that contribute to patch extirpation and extinction. Similarly, the nine patches identified as completely isolated should be evaluated to see if populations exist there currently. If any remain, these populations could be extremely important to target future conservation initiatives. This study also found that nearly 14% of protected areas were classified as cleared, stressing the need for better enforcement to ensure these protected areas continue to support the biodiversity it was intended to protect. It is also disappointing to find that there is a greater percentage of mining concessions in *C. oenanthe's* range than there are protected areas (6 and 4%, respectively).

The results of this study are comparable to the pilot study conducted for the Alto Mayo Valley in the northern part of *C. oenanthe's* distribution. Schaffer-Smith et al. found that more than one third of the species range has been cleared (unpublished data), whereas this total range analysis suggests that more than one quarter has been cleared. While still not positive statistics, this range-wide evaluation provides hope that there is still time to conserve more habitat and relative connectivity to support this species' continued survival. Schaffer-Smith et al. also ran several scenarios on emerging threats in the Alto Mayo region including mining concessions and the development of a high urban-industrial complex, which found that 11 and 13%, respectively, of remaining suitable habitat could be affected (unpublished data). In this study I found that Gera could be largely impacted by mining concessions, particularly within the upper east portion of the analysis area.

While primates remain one of the most well studied animal groups, most research has not focused on their response to landscape changes (Arroyo-Rodrigues & Fahrig 2014). Consequently, this gap affects the conservation community's ability to effectively understand and manage primate populations in the face of rapid human population growth and deforestation (Arroyo-Rodrigues & Fahrig 2014). In a recent review of fragmentation studies of primates, all 100 studies were focused on a patch-scale analysis rather than a landscape scale analysis (Arroyo-Rodrigues et al. 2013). Moreover, 40% of these studies involved fewer than five habitat patches (Arroyo-Rodrigues et al. 2013). However, primate responses may vary greatly depending on the habitat type, size, and configuration of the patch (Arroyo-Rodrigues et al. 2013). Therefore, this study expands the literature on habitat evaluation of a primate through a landscape scale analysis. Future studies into the behavior and ecology of *C. oenanthe* will be complimented by this analysis while also providing a baseline in which to prioritize future conservation actions.

Limitations

There are limitations to this analysis which should be taken into account. Since the department of San Martín is primarily characterized as humid tropical forest and mountainous, cloud cover and haze restricts the clarity of imagery. Due to this, most satellite images for this study are from different seasons. For example, the eastern SPOT image was taken on August 19, 2011 and the western SPOT image was taken on September 2, 2011. These dates correspond to the end of the dry season and the beginning of a short transition into the rainy season (DeLuycker 2006). Different seasons can impact spectral signatures used for classification depending on the amount and moisture content of the vegetation. Similarly, images taken from different years can also yield different classification results. For example, the SPOT images, taken in 2011, often overestimated forest cover compared to the Landsat 8 images taken from 2014. There could be a variety of reasons for this, including phenological variances, cloud cover, and other environmental variables; however, it seems reasonable to suspect that in those years further deforestation could have been occurring. Unfortunately, these problems are limited by clarity of available imagery which require the use of images from different years or seasons. Finally, it is also important to point out the limitations of a connectivity analysis. Remotely sensed land cover data was used as a proxy for habitat suitability which effectively limits movement of least-cost paths to the grain size of 900 m^2 (Sawyer et al. 2011). As well, this analysis was not validated, which may help to reflect least-cost paths with more biological relevance (Sawyer et al. 2011).

CONCLUSION

The San Martín titi monkey is a critically endangered endemic of Peru. The massive deforestation occurring in the San Martín region highlights this primate's vulnerability and it's place on the list of the top 25 most endangered primates in the world. This species' small geographical range and endemism, as well as its preference for the forest canopy, present the challenges that managers will face as they seek to continue to protect and preserve *C. oenanthe* from extinction. Currently, there is a major gap in primatological literature assessing landscape scale factors for conservation. This study, however, provides a landscape scale analysis of *C. oenanthe's* remaining suitable habitat, which will allow PMT to effectively prioritize conservation actions for efficiency and effectiveness over time. With a better understanding of where remaining habitat patches are, their connectedness, their distance to mining concessions, and their relative cost and feasibility for protection, PMT can utilize a dynamic management tool for the conservation of *C. oenanthe*.

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APPENDIX

		Ground Truthed							
		Primary Forest	**Secondary Forest**	**Cleared since 1987**	**Cleared/ Ag**	**Mixed Repeatedly**	**Mixed Recently**	**Totals**	**User's Accuracy**
From Classified Map	**Primary Forest**	22	10	1	0	0	0	33	66.67
	Secondary Forest	1	43	1	2	1	0	48	89.58
	Cleared since 1987	2	2	54	0	1	4	63	85.71
	Cleared/Ag	2	2	0	25	0	0	29	86.21
	Mixed Repeatedly	1	1	0	1	52	0	55	94.55
	Mixed Recently	0	2	0	0	0	56	58	96.55
	Totals	28	60	56	28	54	60	286	86.54
	Producer's Accuracy	78.57	71.67	96.43	89.29	96.30	93.33	87.60	**Total Accuracy: 87.07%**

Appendix 1. Confusion matrix for accuracy assessment of final land cover map. Producer accuracy of 87.60% and user accuracy of 86.54% for an overall total accuracy of 87.07%. Note that the northern portion of the land cover map, developed by Schaffer-Smith et al. had an overall accuracy of 87.90% (unpublished data).

		Ground Truthed							
		Primary Forest	**Secondary Forest**	**Cleared since 1987**	**Cleared/ Ag**	**Mixed Repeatedly**	**Mixed Recently**	**Totals**	**User's Accuracy**
From Classified Map	**Primary Forest**	8	13	2	17	5	4	49	16.33
	Secondary Forest	1	28	8	26	6	3	72	38.89
	Cleared since 1987	0	1	5	0	0	0	6	83.33
	Cleared/Ag	0	0	0	1	0	0	1	100.00
	Mixed Repeatedly	0	0	0	0	13	1	14	92.86
	Mixed Recently	0	0	0	0	0	3	3	100.00
	Totals	9	42	15	44	24	11	142	71.90
	Producer's Accuracy	88.89	66.67	33.33	2.27	54.17	27.27	45.43	**Total Accuracy: 58.67%**

Appendix 2. Confusion matrix for accuracy assessment of western SPOT image using a Maximum Likelihood Classifier algorithm. Secondary and primary forest was overwhelmingly overestimated in comparison to what was evidenced to be there by the ground control points. Because accuracy proved poor, this classification was not incorporated into the final land cover map.

Patch ID	COUNT	COST	CONNECTED AREA	IDW AREA	DEGREE	BETWEENNESS	CLOSENESS	EIGENVECTOR	PA COUNT	CONNECTED PA	IDW PA	PATCHAREA (HA)
12,988	883	29.92955208	7,977	2,454	16	0	0.0086	0.0086	1	6,174.40	6,174.40	79.1
14,612	4,042	4,444.31	7,693	2,450	20	0	0.0086	0.0086	1	6,174.40	6,174.40	362.07
14,865	60,314	17,358.38	3,739	2,910	363	0	0.0099	0.0099	4	8,639.30	4,609.74	5,402.80
17,059	23	30,191.94	0	0	3	0	0.0124	0.0124	0	0	0	2.06
17,158	22	14,293.19	5,430	1,191	5	0	0.0151	0.0151	0	0	0	1.97
17,161	1	38,154.57	5,430	1,571	4	0	0.0151	0.0151	2	868.6125	161.903	0.09
17,186	1	27,748.79	3	1	2	40	0.0136	0.0136	0	0	0	0.09
17,203	36	24,191.77	8,073	6,067	41	0	0.016	0.016	3	7,043.02	1,506.18	3.22
17,206	28	33,051.66	0	0	3	60	0.0188	0.0188	0	0	0	2.51
17,212	1	15,670.95	5,430	2,130	7	0	0.011	0.011	3	2,464.90	432.4813	0.09
17,221	6	22,492.24	5,431	2,130	4	0	0.0265	0.0265	3	2,464.90	1,173.07	0.54
17,251	8	12,638.52	5,433	1,028	3	0	0.0265	0.0265	0	0	0	0.72
17,259	1	32,875.59	0	0	0	0	0	0	0	0	0	0.09
17,282	2	36,894.32	5	2	5	0	0.0124	0.0124	0	0	0	0.18
17,291	1	16,363.42	5,432	1,064	4	0	0.0098	0.0098	0	0	0	0.09
17,292	1	19,589.31	5,430	771	1	76.693	0.027	0.027	0	0	0	0.09
17,296	34	12,323.23	8,056	3,664	25	0	0.0159	0.0159	2	7,030.85	2,412.16	3.05
17,302	4	17,026.58	5,437	2,483	12	0	0.016	0.016	3	2,464.90	348.3111	0.36
17,318	2	20,724.59	5,882	1,786	14	0	0.0086	0.0086	1	6,174.40	5,810.25	0.18
17,325	1	15,957.39	5,433	2,920	7	0	0.025	0.025	3	2,464.90	1,171.28	0.09
17,326	1	36,103.23	5,432	1,139	4	0.3419	0.01	0.01	0	0	0	0.09
17,331	2	2,941.35	5	2	4	0	0.0124	0.0124	0	0	0	0.18
17,343	1	18,489.84	2	0	3	40	0.0176	0.0176	0	0	0	0.09
17,351	1	18,073.24	0	0	0	0	0	0	0	0	0	0.09
17,352	4	10,515.31	7,614	3,422	22	0	0.016	0.016	2	868.6125	121.4305	0.36
17,379	3	6,479.34	5,440	2,769	12	0	0.016	0.016	3	2,464.90	391.9387	0.27
17,385	5	17,364.27	5,436	2,769	14	0	0.025	0.025	3	2,464.90	530.0516	0.45
17,410	9	14,615.09	5,875	1,527	6	0.3495	0.0124	0.0124	1	6,174.40	1,536.72	0.81
17,420	1	11,502.32	7,612	3,025	16	0	0.016	0.016	2	868.6125	122.7515	0.09
17,423	57	15,449.48	5,433	2,360	11	0	0.025	0.025	3	2,464.90	436.8908	5.11
17,426	1	10,925.64	8,055	2,028	9	65.7195	0.027	0.027	1	6,174.40	1,461.49	0.09
17,431	11	20,867.58	8,056	1,963	12	0	0.0086	0.0086	1	6,174.40	2,589.38	0.99
17,434	2	5,132.92	5,431	572	2	0	0.0111	0.0111	0	0	0	0.18
17,435	8	13,345.46	5,430	1,595	4	0	0.0151	0.0151	0	0	0	0.72
17,452	1	10,451.75	7,612	2,929	13	65.7195	0.027	0.027	1	856.44	98.2193	0.09
17,459	3	3,210.71	8,059	3,300	22	0	0.0159	0.0159	1	6,174.40	1,287.35	0.27
17,485	3	13,296.01	8,058	3,414	21	65.7195	0.027	0.027	1	6,174.40	1,299.86	0.27
17,497	1	15,856.62	5,430	812	1	76.693	0.027	0.027	0	0	0	0.09

Patch ID	COREAREA (HA)	AVG DIST TO EDGE	CORE AREA RATIO	SHAPE INDEX	THRT DIST	THRT WTD DIST	THRT NBR MEAN	PA ID	FEASIBILITY	COST OF PROT	KERNEL DENSITY
12,988	79.1	76	1	0.29567	0	0	0	0	4	4	883
14,612	362.07	79.8	1	0.1993	0	0	0	0	1	3	4,042
14,865	5,402.80	95.8	1	0.03787	0	0.01	0	0	1	2	60,129
17,059	2.06	31	1	0.47958	0	0	0	0	3	2	23
17,158	1.97	32.7	1	0.55181	0	0	0	0	3	2	22
17,161	0.09	29.9	1	1	0	0	0	0	3	2	1
17,186	0.09	29.9	1	1	0	0	0	0	3	2	1
17,203	3.22	35.2	1	0.52174	0	0	0	0	3	2	36
17,206	2.51	41.2	1	0.81408	0	0	0	0	3	2	28
17,212	0.09	29.9	1	1	0	0	0	0	3	2	1
17,221	0.54	29.9	1	0.69985	0	0	0	0	4	4	6
17,251	0.72	31.5	1	0.70711	0	0	0	0	3	2	8
17,259	0.09	29.9	1	1	0	0	0	0	3	2	1
17,282	0.18	29.9	1	0.94281	0	0	0	0	3	2	2
17,291	0.09	29.9	1	1	0	0	0	0	3	2	1
17,292	0.09	29.9	1	1	0	0	0	0	3	2	1
17,296	3.05	43	1	0.72887	0	0	0	0	3	2	34
17,302	0.36	29.9	1	0.8	0	0	0	0	3	2	4
17,318	0.18	29.9	1	0.94281	0	0	0	0	1	3	2
17,325	0.09	29.9	1	1	0	0	0	0	4	4	1
17,326	0.09	29.9	1	1	0	0	0	0	3	2	1
17,331	0.18	29.9	1	0.70711	0	0	0	0	3	2	2
17,343	0.09	29.9	1	1	0	0	0	0	3	2	1
17,351	0.09	29.9	1	1	0	0	0	0	3	2	1
17,352	0.36	29.9	1	0.8	0	0	0	0	3	2	4
17,379	0.27	29.9	1	0.86603	0	0	0	0	3	2	3
17,385	0.45	29.9	1	0.89443	0	0	0	0	3	2	5
17,410	0.81	31.3	1	0.85714	0	0	0	0	3	2	9
17,420	0.09	29.9	1	1	0	0	0	0	3	2	1
17,423	5.11	33.4	1	0.39736	0	0	0	0	3	2	57
17,426	0.09	29.9	1	1	0	0	0	0	3	2	1
17,431	0.99	29.9	1	0.44222	0	0	0	0	3	2	11
17,434	0.18	29.9	1	0.94281	0	0	0	0	3	2	2
17,435	0.72	29.9	1	0.80812	0	0	0	0	3	2	8
17,452	0.09	29.9	1	1	0	0	0	0	3	2	1
17,459	0.27	29.9	1	0.86603	0	0	0	0	3	2	3
17,485	0.27	29.9	1	0.86603	0	0	0	0	3	2	3
17,497	0.09	29.9	1	1	0	0	0	0	3	2	1

Appendix 3. The attribute groups for habitat patches, showing the metrics for 38 of 599 patches generated from connectivity modeling of Gera. The mining scenario also has these metrics for all 502 patches.