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CONSERVATION OF AN ENDANGERED AMAZONIAN PRIMATE: PRIORITY AREAS FOR THE PIED TAMARIN (*Saguinus bicolor*) IN MANAUS, BRAZIL

Running Title: Areas for the Conservation of the pied tamarin (*Saguinus bicolor*)

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Title: CONSERVATION OF AN ENDANGERED AMAZONIAN PRIMATE: PRIORITY AREAS FOR THE PIED TAMARIN (*Saguinus bicolor*) IN MANAUS, BRAZIL

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ABSTRACT

The pied tamarin (*Saguinus bicolor*), a species that is emblematic of the Manaus region of Brazil, is threatened by the growth of the city and its peri-urban area. Our study aims to identify priority areas for biodiversity conservation in and around Manaus, the largest city in the Brazilian Amazon and home to over 2 million people. The geographic range of the pied tamarin, a critically endangered primate that is a symbol of conservation in the region, was used to define the boundaries of the study area. We treated the urban zone separately because of the greater barriers to conservation there and carried out systematic conservation planning for the rural zone. After defining biodiversity targets and variables and weighting for a cost surface (difficulty of protection), the map of priority areas was generated using MARXAN decision support software. Connectivity was strengthened using the LinkageMapper tool. Although protected areas already cover about 20% of the study area, most are in partially protected categories and are still losing vegetation. The results prioritize 56.1% of the pied tamarin distribution area, including urban and rural zones. The analysis of the current scenario causes concern because it shows that much of the effort to create protected areas is not as effective as it could be. The conservation of the pied tamarin, as well as other threatened primates, depends on a better understanding of the need to increase the amount of land set aside for their protection, improving monitoring, and restoring vegetation where possible.

KEYWORDS: Amazon, systematic conservation planning, critically threatened, urban conservation, MARXAN

INTRODUCTION

Environmental change in recent decades has made clear the need to develop strategies aimed at slowing its rate and reducing or offsetting some of its effects. The occurrence of extreme droughts, which have the potential to spread fires (Costa et al., 2024), and excessive rainfall, which can lead to flooding, are causing significant damage to the natural environment and human populations, creating an urgent need for strategies to reduce impacts on biodiversity. Conservation measures, including the establishment of protected areas and the implementation of strategies to reduce the rate of change or its adverse effects, are essential to prevent further loss of biodiversity and deterioration of quality of life for both humans and wildlife.

One of the main strategies for reducing or compensating for the negative effects of environmental change is the establishment of protected areas, ideally based on careful conservation planning (Brooks et al., 2004). Considerable progress has been made in this area in recent decades. The paradigm shift initiated by the introduction of the concept of complementarity (Kirkpatrick, 1983) was followed by the emergence of other key concepts, including those of persistence (Cowling et al., 1999), cost of conservation (Naidoo et al., 2006), compactness (Possingham et al., 2000) and the development of decision-support software to facilitate comprehensive analysis (Ball et al., 2009; Moilanen et al., 2009; Pressey et al., 2009).

Two main methods are used in the context of systematic conservation planning: the minimum set approach and the maximum coverage approach. In the minimum set approach, targets (species, environments, or processes) and their respective quantities are specified. Then, a set of areas is selected in order to maximize the achievement of these targets at a minimum cost (Wilson et al, 2009). The most commonly used decision support software based on this approach is MARXAN (Ball et al., 2009). In the maximum coverage approach, the main features to be conserved and respective weights are defined, but there are no specific quantities of them to be achieved in the solution. The final map consists of concentric zones that decrease in conservation importance based on the number and weight of targets. Depending on the conservation context, a larger or smaller area may be protected, guided by the calculated importance of the locations. Zonation is the main tool used to support this approach (Moilanen et al., 2009). The use of a framework based on an explicit target, as in the case of the minimum set approach, makes it easier for countries or regions to assess how close they are to achieving the Kunming-Montreal global target three, set at the Convention on Biological Diversity's COP 15, of effectively conserving and managing 30% of areas of key importance for biodiversity and ecosystem functions and services (CBD, 2022). Due to the relative ease with which targets are monitored, the minimum set approach is usually adopted for public policies, as evidenced by Brazil`s maps of priority areas for conservation (MMA, 2023).

Systematic conservation planning, although encompassing many different approaches, generally has two main objectives: to increase the representativeness of biodiversity in protected areas and to reduce direct threats to biodiversity, thereby increasing its chances of persistence (Margules & Pressey, 2000). Species directly threatened with extinction are therefore natural priorities for conservation, as are regions experiencing high rates of environmental change.

The Brazilian Amazon is a relatively well-conserved region, but habitat loss and degradation are not evenly distributed in the region. One of the most degraded areas is the city of Manaus, the capital of Amazonas, the largest state in area in the Brazilian Amazon. The city is home to 2.07 million people (IBGE, 2025), about half of the state's population. Deforestation is advancing, in and around the municipality of Manaus, and simulations indicate that the deforested area will increase by 74% and the urban area will increase by 503% by 2100 as compared to these areas in 2017 (Santos et al., 2022). However, these projections are conservative because they do not consider the planned reconstruction of the BR-319 highway (Manaus-Porto Velho), which would increase migration of people to Manaus (Fearnside, 2022).

The recent increase in smoke from both accidental and criminal fires and consecutive severe droughts (Guimarães et al., 2025) have highlighted the need for more effective environmental protection and management in and around the city. The Manaus area has undergone significant urbanization over the past three decades, with numerous green spaces being replaced by infrastructure and real-estate development, which has also increased settlement pressure in rural areas (Santos et al., 2022).

The pied tamarin (*Saguinus bicolor*) is a species endemic to the municipality of Manaus and the neighboring municipalities of Rio Preto da Eva and Itacoatiara. The species occupies an area of about 8300 km² (Lagroteria et al., 2024), which covers both urban and rural areas in Manaus and Rio Preto da Eva and rural areas in Itacoatiara. The species is found in secondary lowland rainforest, swamps, and forest edges (Baker, 2012). The main threats to the species are habitat loss due to agriculture, ranching and urban expansion (Coelho et al., 2018; Gordo et al., 2013; 2017), but also potential competition with the congeneric species *Saguinus midas* (Gordo et al., 2017; Lagroteria et al., 2024; Röhe, 2006; Sobroza, 2021). *S.midas* is a more flexible species with a putatively superior competitive capacity (Lagroteria et al., 2024; Röhe, 2006; Sobroza et al., 2021; Sobroza, 2021). Its geographic range appears to be expanding, which may further reduce the already limited range of *S. bicolor*. Due to its small range and high level of threats, the IUCN has listed the pied tamarin as “Critically Endangered” and as one of the 25 most endangered primates in the world during the 2018–2020 and 2023–2025 periods (Mittermeier et al, 2024; Schwitzer et al., 2019;). In addition to being listed as critically endangered with extinction, previous studies have shown that the species is underrepresented in the current protected areas, which are insufficient to ensure its long-term survival (Campos et al., 2017; Coelho et al., 2018).

The pied tamarin is a flagship species for Manaus and has been the subject of many environmental campaigns, resulting in the creation of at least three protected areas bearing its Portuguese common names: REVIS Sauim-de-Coleira, REVIS Sauim-Castanheira, and APA Sauim-de-Manaus. Research on the ecology of the species has also contributed to the design and creation of urban ecological corridors and to better protect urban green areas (Coelho et al., 2017). Based on the encouraging results obtained so far, we believe that both the species and the environment in and around Manaus can benefit from the development of an objective conservation plan for this region.

Here we present the results of work undertaken by a group of researchers with diverse expertise and backgrounds (conservation planning, GIS, ecology, primatology) to identify priority areas for the conservation of this primate, which is one of the actions required by the National Action Plan for the conservation of the Pied Tamarin (ICMBIO, 2024). The study was based on the theoretical framework of systematic conservation planning, which relies on the use of spatially explicit information on conservation targets and costs to define the areas where conservation actions have the best chance of success (Margules & Pressey, 2000; Naidoo et al., 2006). Although target formulation is recognized as subjective, its explicitness is regarded as valuable because it provides a means of measuring the conservation value of different areas during the selection process (Margules & Pressey, 2000). As stakeholder engagement is also a relevant part of systematic planning, the study included an opportunity for public involvement before defining the final map. While the primary focus is on the pied tamarin, our planning process is also designed to increase representativeness of other species and environments in and around Manaus.

METHODS

All decisions, starting with the definition of the study area, were made collectively during eight virtual meetings attended by most of the authors. Based on the group's experience and available literature, we defined targets and how to spatially represent each of them. We collectively decided on the main threats and attributed weights to them to create the cost surface. The rationale for each decision was revisited in the subsequent meeting to ensure that all participants had the opportunity to provide input and that the decision-making process was transparent and inclusive.

Study Area

The boundaries of the study area were defined based on the range of the pied tamarin proposed by Röhe (2006), adding a 10-km buffer to the north to allow for further distribution extension resulting from ongoing studies. In all other directions, the boundaries are naturally defined by rivers (Fig. 1). The area includes parts of the municipalities of Manaus, Rio Preto da Eva and Itacoatiara in the state of Amazonas.

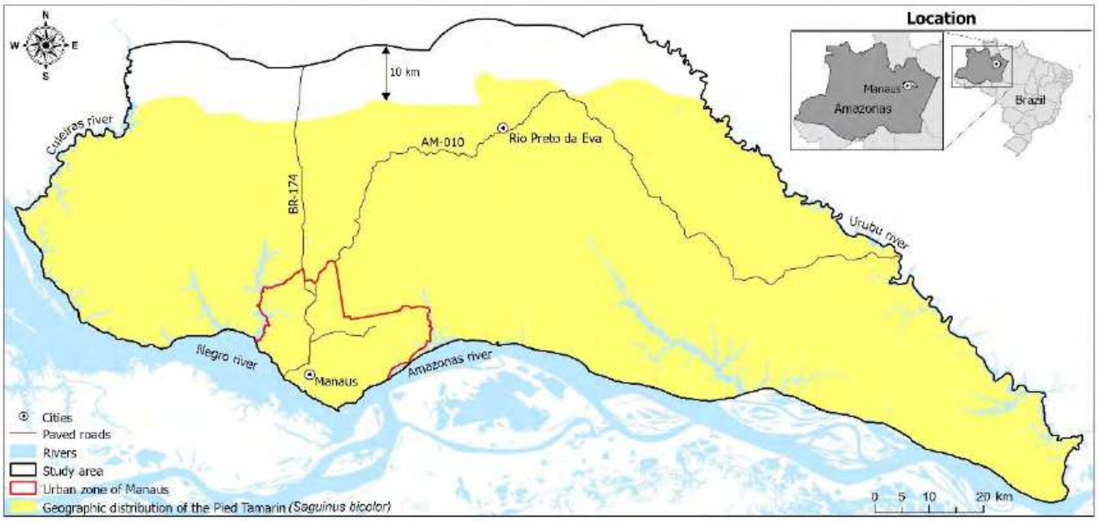

Figure 1. Study area, based on the distribution of the pied tamarin (*Saguinus bicolor*) proposed by Rohe (2006) plus a 10-km buffer to the north, and the boundaries of the of the Manaus urban zone.

The study area includes the urban area of Manaus and because this urban zone has a finer scale and requires different conservation actions and strategies, we treated this area separately and did not apply the systematic planning approach to it. As the establishment of protected areas is more constrained in the urban zone, the priority for this zone is the conservation of all remaining green areas, including primary and secondary vegetation.

The boundaries of the urban zone were defined according to the Directorate Plan of the Municipality of Manaus (IMPLURB, 2021). Green areas were identified using the MapBiomas classification with a resolution of 30 m (MapBiomas, 2022). Old-growth and secondary forests were combined into a single class. To avoid prioritizing very small, isolated patches of vegetation, we considered only green areas larger than 1 ha. For the urban zone, we compiled the available information on protected areas and analyzed their effectiveness in preventing the loss of vegetation cover. As recommended in the public seminar (see the "stakeholder input and involvement" section below), we included in the final city map the permanent preservation areas (APPs) defined by the Brazilian law nº 12.651/2012, better known as the "Forest Code". Spatial data for APPs were provided by the Fundação Brasileira para o Desenvolvimento Sustentável (FBDS, 2024).

To apply systematic conservation planning, we created a planning unit (PU) shapefile consisting of 100-ha hexagons that surrounded the urban zone and included the known geographic range of the pied tamarin, plus a 10 km wide buffer to the north (Fig. 2). The boundaries of the protected areas were inserted into the planning-unit layer, but only the strictly protected areas, indigenous land or the zones defined as "preserved" or "conserved" within the sustainable-use protected areas were given the status of "protected." The other zones or areas that are not strictly protected were given the status "initial" in the corresponding MARXAN input file. This status was given because their effective protection could be more easily achieved if they were prioritized in the final solution generated by the algorithm. We excluded the urban zone from this layer.

Figure 2. Left: detail of the urban zone, with protected areas. Right: the study area as a whole, showing the planning units and their status as “protected,” “initial,” or “available.”

Data preparation - Targets

In this study we adopted the concept of targets based on (Margules & Pressey, 2000). The targets are the features to be conserved, each with an explicit quantity that we want to achieve with the plan. We then conducted our initial discussions to identify the main features of interest: firstly, the area`s other endemic species that could potentially benefit from actions to conserve the pied tamarin; and secondly, areas with different environmental composition, because areas with different vegetation types, geomorphology, and proximity to water may harbor different species. Their inclusion as targets can therefore increase the representation of biodiversity, as well as the availability of resources that some of these environments provide to the pied tamarin.

The availability of spatial data was a requirement for inclusion of each target species, which excluded some indicated taxa that had been recently discovered in the Manaus and surrounding municipalities, namely *Eugenia kerianthera* (Souza et al., 2015) and a *Monodelphis* sp. (Pavan et al., 2014). Only a few observation points are available, such that evaluating their entire geographic distribution is not possible at present time. Nevertheless, even if not explicitly included, these species are likely to benefit from the increase in protection in the study area. All targets’ species and vegetation types are described in detail below (Fig. 3, Table 1).

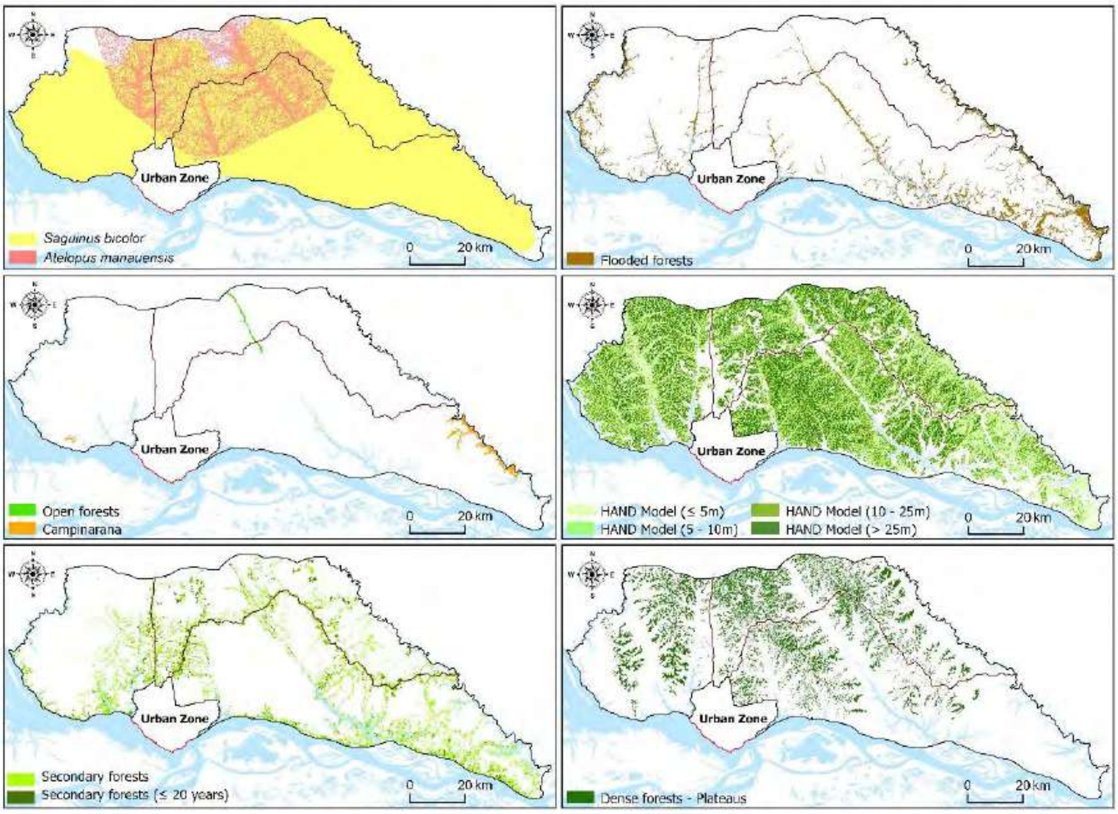

Figure 3. The spatial distribution of the selected targets.

Saguinus bicolor

The limits of the distribution of the pied tamarin, the main focus of this study, were updated based on the new Extension of Occurrence (EOO) proposed by (Lagroteria et al., 2024). Most of the new EOO (98.8%) was within our delineated study area, so the final distribution polygon has an area of 826,991 ha. The conservation goal for the tamarin was set at 50% of its range.

Atelopus manauensis

This small frog is also a small-range species endemic to the Manaus region, with approximately half of its distribution overlapping the range of the pied tamarin, and its inclusion as a target increases the representativeness of the priority areas. Since the occurrence of this species is limited to environments close to water, it was recommended to focus only on these environments within the range of the species. For this purpose, the points of occurrence registered by Jorge et al. (2020) were digitized and superimposed on a Height Above the Nearest Drainage (HAND) model (Nobre et al., 2011) to obtain its value for each point. The result was a mean of 3.06 m, SD 5.98. To be conservative, in the sense of including a larger habitat area that could be used by the species, we used the mean ± 2SD, which resulted in the inclusion of all pixels with values <15 m in the HAND model. As the species is not only endemic but also has a very limited habitat availability, the target for this species was also set at 50% of the resulting distribution area.

Flooded forests

Flooded forests are high-productivity environments that support a variety of economically and ecologically valuable species in the Brazilian Amazon (Castello & Macedo, 2016). Due to the considerable fluctuations in water levels throughout the year, these ecosystems support species that have adapted to this significant seasonal change, which is not always observed in other habitats (Wittmann et al., 2017). It remains unclear whether the pied tamarin utilizes this environment, and if so, with what frequency. However, due to the distinctive nature of such flooded forests and their function as a nursery for numerous aquatic species, we considered it crucial to include them as targets.

Given that these environments are stratified along strips at the land-water interface, it is probable that more than one of their subclassifications would be represented within a single PU. Accordingly, all the classes present in the study area were grouped together and deemed relevant for representation. The subclasses included in the database were non-flooded shrub, flooded forest, non-flooded forest, and flooded forest. The database was provided by the Large Scale Biosphere-Atmosphere Experiment (Hess et al., 2015) and the target was 80%.

Open forest and Campinarana

Vegetation types are typically identified as conservation targets because they provide a habitat for diverse species of plants and animals. Therefore, different types of vegetation, like campinaranas and open forests, help increase biodiversity representation. In the case of the pied tamarin and other vertebrates, it is common for them to utilize different vegetation types to obtain different resources (Gordo, 2012). Consequently, vegetation types play important roles in maintaining food diversity and availability. The database utilized for vegetation types was that from the Brazilian Institute of Geography and Statistics, a vector file with a spatial resolution of 250 meters (IBGE, 2023b). For each vegetation type we set a target of 30% of the area, corresponding to that recommended by the Kunming-Montreal global biodiversity framework.

Dense Forests

Dense forest occupies most of the geographic range of the pied tamarin, and, given that this species uses a variety of vegetation types, it was considered relevant to differentiate vegetation within this IBGE class. The basis chosen for this differentiation was the study of Schietti et al. (2014), which shows that vegetation responds to vertical distance from drainage, as represented by the HAND model (Nobre et al., 2011). According to their results, four classes were defined: (1) < 5 m; (2) 5.001-10 m; (3) 10.001- 25 m; (4) >25 m. Because little support was found in the literature to differentiate the targets for these environments, a general target of 30% was assigned to each vegetation type.

Secondary forests

The pied tamarin uses secondary forests for its normal activities and also to obtain food resources (Egler, 1992; Gordo, 2012). For this reason, and because of the importance of secondary forests for connectivity between environments, it was proposed to set specific targets for these forests. Since more-mature areas have a better chance of survival and a better structure, a target of 40% was set for areas over 20 years old and a target of 30% for areas less than 20 years old or of undetermined age. The boundaries of the secondary forests were obtained from TerraClass 2020 (INPE, 2023b), which has a good general classification of this environment, and the ages of the secondary forests were derived from the MapBiomas database (MapBiomas, 2022) which details the years of conversion.

Plateaus

Plateaus were included as a specific target because these low-slope areas, with relatively high altitude, are home to a number of specialized species and are highly threatened by both deforestation and mechanized agriculture (Soares-Filho et al., 2004). The spatial definition of the plateaus was constructed by crossing the dense forests (from the IBGE database), with a slope of less than 8% and an altitude greater than 75 m, from the Forest and Buildings Removed Copernicus DEM -FABDEM 1.0 database (Hawker & Neal, 2021). A target of 50% was set for the plateau areas.

Table 1: Synthesis of targets, including types, names, and amounts.

Type	Name	Target (%)
Species	*Saguinus bicolor*	0.5
Species	*Atelopus manauensis*	0.5
Vegetation	Flooded forests	0.8
Vegetation	Campinarana	0.3
Vegetation	Open vegetation	0.3
Vegetation	Dense forest- HAND up to 5 m	0.3
Vegetation	Dense forest- HAND 5 - 10 m	0.3
Vegetation	Dense forest- HAND 10 - 25 m	0.3
Vegetation	Dense forest- HAND > 25 m	0.3
Vegetation	Secondary forest - > 20 years	0.4
Vegetation	Secondary forest - < 20 years	0.3
Vegetation	Plateaus- dense forest	0.5

Data preparation - Costs

Incorporating a cost surface is an important step in systematic conservation planning because it helps select areas with fewer conflicts with conservation efforts (Naidoo et al, 2006; Wilson et al., 2009). The reasoning is that areas with high impact usually have low conservation value and require investment to recover or to control degradation, which is not always successful. Here, we have used the cost surface to select areas that, given equal contributions to the targets, are exposed to less threats that could compromise conservation success. To construct a cost surface, we identified the major threats to the persistence of natural environments in the region of interest and assigned weights between 1 and 10 to reflect the relative impact of each of these threats. We assumed that the likelihood of loss or degradation caused by these threats increases the management costs of conservation (Naidoo et al., 2006). The major threats listed are presented in the following sections, along with the description of spatial data used to represent them (Fig. 4, Table 2).

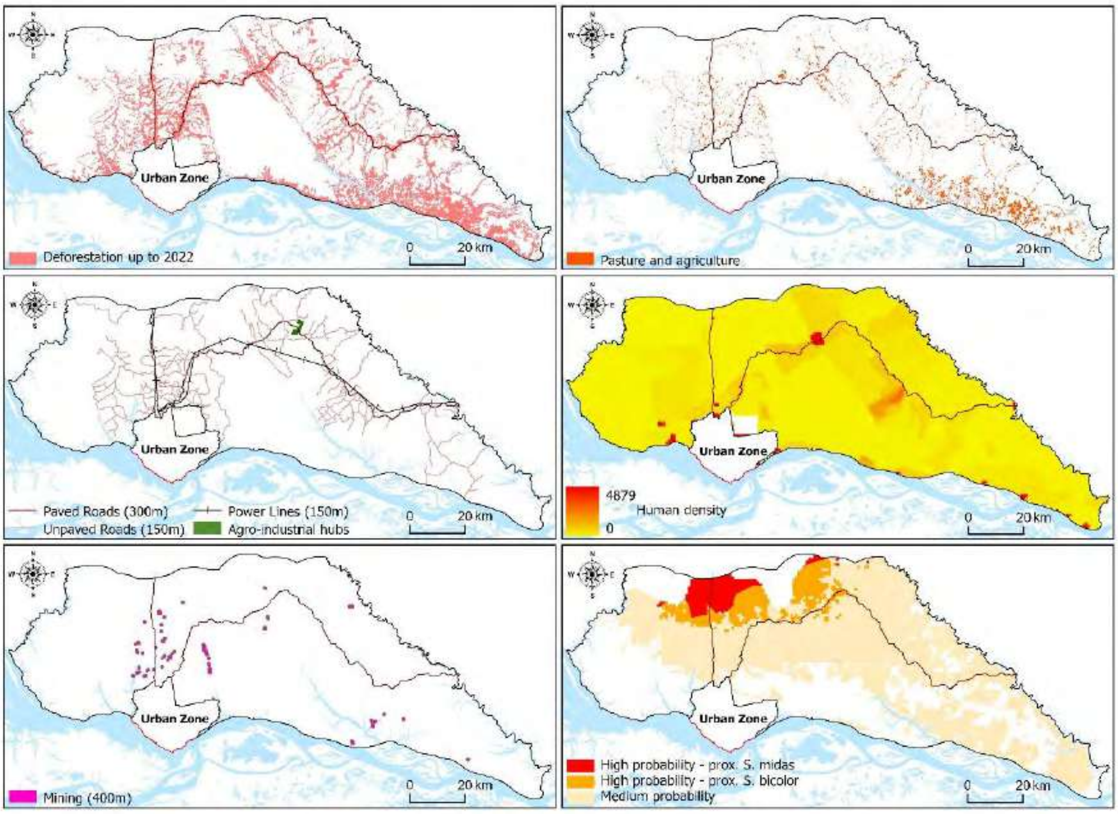

Figure 4. Spatial distribution of the main threats that constitutes the cost surface

Deforestation up to 2022

Habitat loss and fragmentation, associated with both urbanization and agricultural expansion, are among the major threats to the pied tamarin population. Deforestation is therefore one of the main causes of population decline and has been identified as the greatest threat to the species. The raster database of the Program for the Calculation of Deforestation in Amazonia (PRODES) (INPE, 2023a) was chosen as the database to represent deforestation.

Pasture and agriculture

The establishment of pasture and agriculture after deforestation consolidates land use change and makes it more difficult for the area to become a habitat for the species in the near future. The database chosen to represent these areas was TerraClass raster (INPE, 2023b).

Roads and highways

There is usually a correlation between road and highway access and deforestation (Aguiar et al., 2007; Laurance et al., 2002). However, although the opening of roads is usually a precursor to forest conversion, we considered it to be a separate threat because it poses some additional risks, especially to fauna (Gordo et al., 2013; Ree et al., 2015). The effect of roads on deforestation and animal killing depends on the quality of the access they provide: highways and paved roads, either federal or state managed, have a stronger effect than secondary roads, which are usually unpaved (Bennett, 2017). Paved roads were assumed to have an impact up to 300 m away, while unpaved roads were assumed to have an impact up to 150 m away (Laurance et al., 2002). Our road database was a combination of the IBGE (2023a) and Banco de Dados Geográficos do Exército (BDGEx) (2024) databases.

Power Lines

Similar to roads, power lines open up vegetation, reduce canopy density and habitat continuity for arboreal animals, and facilitate access for more-intensive economic activities. The database selected for power lines was developed by Hyde et al.(2018).

Agro-industrial hub

The government of the State of Amazonas has adopted a policy of creating agro-industrial parks to stimulate economic development. The first one was created around the city of Rio Preto da Eva, which is within the geographic range of the pied tamarin. Since this policy conflicts with the possibility of creating protected areas and is also a potential driver of deforestation, habitat loss and fragmentation, we decided to include this area in the cost surface. The location of the agro-industrial park was provided by the Superintendency of Manaus Free-Trade Zone (SUFRAMA).

Human population

People produce food and goods in order to acquire other products that they cannot produce. Even when not producing, hunting or extracting other resources from the forest are common practices that lead to forest degradation (Bogoni et al., 2023; Costa et al., 2023; Wilkie et al., 2011). When forests are too degraded and no more resources can be found, they usually are converted to other uses. This is a common process throughout the Amazon (Putz & Redford, 2010). For this reason, we considered higher human density as a potential conflict with the creation of protected areas and included it as a cost. The database used to represent human density was the map of night lights from the Socioeconomic Data and Applications Center (SEDAC, 2020).

Mining

We considered mining in the area as a threat of very high intensity, but with a relatively small spatial extent. Official data from the National Mineral Agency (ANM, 2023) were used as spatial information on mining. Within the database, areas applied for and already licensed were selected. Since these areas are very small, but the damage extends beyond the exploited areas, it was decided to insert in the cost surface a buffer of 400 m around each area. The definition of this distance was based on field observation on degradation around local mining projects.

Saguinus midas

Due to the risk of *S. midas* expanding its geographic range at the expense of the pied tamarin (Lagroteria et al., 2024; Röhe, 2006; Sobroza et al., 2021a; Sobroza, 2021), we also included part of the *S. midas* geographic range as a cost. In other words, other things being equal, it is recommended that ideal areas for pied tamarin conservation are not occupied by *S. midas* or have a low probability of becoming occupied by *S. midas*. To represent the likelihood of areas being occupied by *S. midas*, we used the results of a predictive modeling study (Lagroteria et al., 2024). Their model generated two classes, "areas with high probability of invasion" and "areas with medium probability of invasion." We superimposed the occurrence points from the study of Lagroteria et al. (2024) on these classes and noticed that in some of them there were only occurrences of *Saguinus midas*, but in others there were only occurrences of *Saguinus bicolor*. Based on these observations, we decided to reclassify the "high probability" areas into two new classes based on the proximity of the occurrences. We used Thiessen polygons to assess points closer to *S. midas* or *S. bicolor* occurrences. We then assigned different weights to areas that were modeled as having high probability of *S. midas* invasion but that currently are closer to *S. bicolor* occurrences, and to areas that were modeled as having a high probability of *S. midas* invasion and that are closer to *S. midas* occurrences. A smaller weight was assigned to areas that were modeled as having a "medium probability" of invasion.

Table 2. Synthesis of costs: types and respective weights.

Type	Weight
Deforestation	10
Pasture and Agriculture	9
Roads and highways -paved	8
Unpaved roads	6
Power lines	4
Agro-industrial hub	8
Human Population	5
Mining	4
S. midas – high probability and prox *S. midas* occurrences	6
S. midas – high probability and prox *S. bicolor* occurrences	3
S. midas- medium probability of occupation	2

Data integration and support for decision making

We calculated the corresponding area of each target within each PU and merged all of the resulting tables into one table containing PU IDs and the corresponding area for each target. After organizing the shapefiles to create the cost surface, we extracted the information of each cost component into each PU. We then rescaled the resulting values for each component before weighting and summing. The resulting cost surface is represented by a single value for each PU.

MARXAN formatting and usage

We used the ArcMarxan Toolbox version 2.0.2 (Apropos Information Systems) to create input folders and files. We selected the Simulated Annealing with Adaptive Improvement algorithm and set the parameters to run MARXAN directly in its Inedit interface. The Boundary Length Modifier (BLM) was enabled to promote compactness of the selected areas. The parameter for the BLM was adjusted based on the results of preliminary simulations (Ardron et al., 2010). We also did some preliminary analysis to make sure that the cost values were numerically capable of minimizing the total area of the solution, improving the efficiency of the solution (Wilson et al., 2009). We then multiplied the rescaled cost values by 30 to improve the minimization effect. We also specified that a target would be considered to be missed if the proportion achieved in the solution was less than 0.95 of the amounts that had been set. After defining all parameters and values, 5000 runs were performed to obtain the best solution.

Increasing connectivity

Although large areas were connected, some areas remained isolated. To create the final map, we looked for the best ways to connect isolated areas using linkage pathways from the Linkage Mapper Tools extension for ArcGIS (Gallo et al, 2020). For this analysis, we considered the PUs selected by MARXAN as core areas and converted the cost surface to use as the resistance raster. We used the cost-weighted & Euclidean method to generate the least-cost paths. The final corridors created by buffering the resulting paths were 400 m wide.

Stakeholder input and involvement

After obtaining a preliminary version of the map, we organized a public seminar to present the study's rationale, methods, and results, as well as to allow for questions and suggestions. We sent about a hundred invitations to citizens, farmers, researchers, and institutions such as environmental bodies and NGOs. The seminar was also publicized in the media, including newspapers, radio, and television.

RESULTS

Urban area

The urban area of Manaus covers 48,612 ha, of which 17,550 ha (36%) is still covered with vegetation and 14,327.51 ha (29.5%) is under some kind of protection. However, almost all (95.7%) of the area with protected status is in less-strict categories, while only 4.3% is strictly protected. As a result, 48% of the vegetation within protected areas has already been lost, reducing the amount of habitat available to the pied tamarin (Table 1).

Table 1. Protected areas within urban boundaries: categories (RVS= Wildlife Refuge, RPPN= Private Nature Reserve, RESERVA= Ducke Reserve (part), PAREST= State Park, CEU= Ecological Urban Corridor, PARMUN= Municipal Park, APA= Environmental Protected Area); total area occupied by the category within urban boundaries; area still vegetated within the protected areas in hectares and percentage of vegetation remaining within each category of protected area. Protection: ST= strict protection; SU= sustainable use.

Category	Protection	Total Area (ha)	Vegetated Area (ha)	Vegetation (%)
CEU	ST	394.61	309.71	78.5
PAREST	ST	52.72	46.28	87. 8
PARMUN	ST	65.13	50.46	77.5
RESERVA	ST	10.19	9.16	89.9
RVS	ST	95.45	95.29	99.8
APA	SU	13,555.52	6,928.35	51.1
RPPN	SU	265.99	254.67	95.7

Vegetation that remains unprotected totals 9967 ha. Although 55% of the vegetated patches are fragments of up to 5 ha within highly urbanized areas, there are six patches with more than 500 ha of continuous vegetation, especially in the eastern and northern portions of the urban zone (Fig. 5). The resultant priorities within the urban area, consisting of green spaces and permanent preservation areas, amount to 20,365.9 ha, or 41.8%.

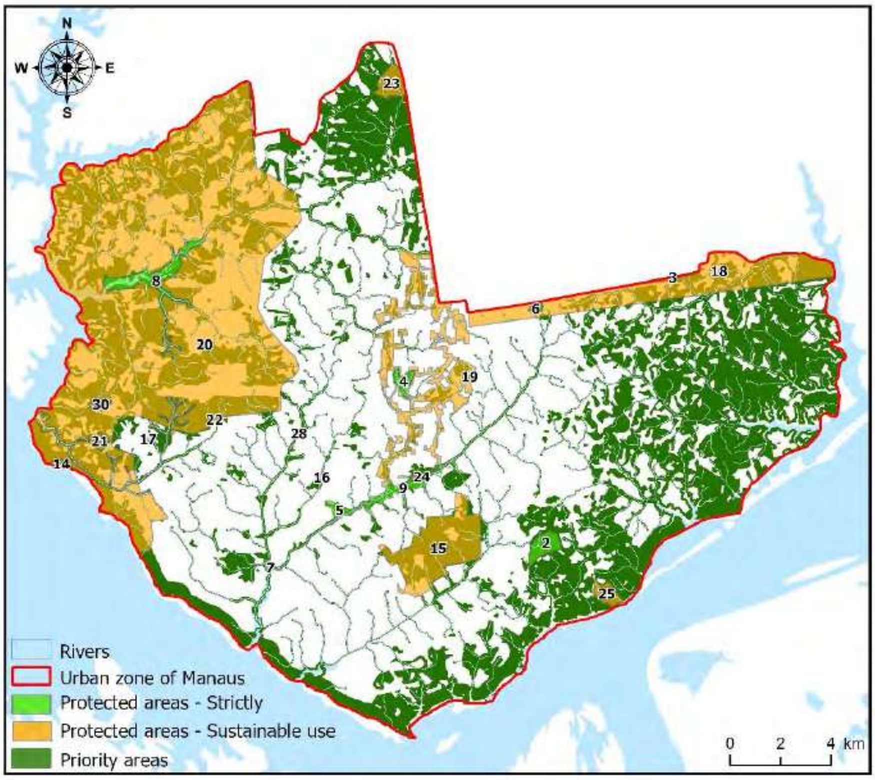

Figure 5. Priority areas (including green and permanent preservation areas - APPs) and protected areas within the urban zone of Manaus. The names of the numbered protected areas are in the supplementary material.

Rural area

The PU shapefile for the systematic planning application had a total area of 838,418 ha. The composite cost surface reflected the relative weight of the major threats, such as roads and deforestation, as well as the high-probability-of-invasion areas with the registered occurrence of *S. midas*. Some of the lowest-cost PUs were in already protected areas (Figure 6).

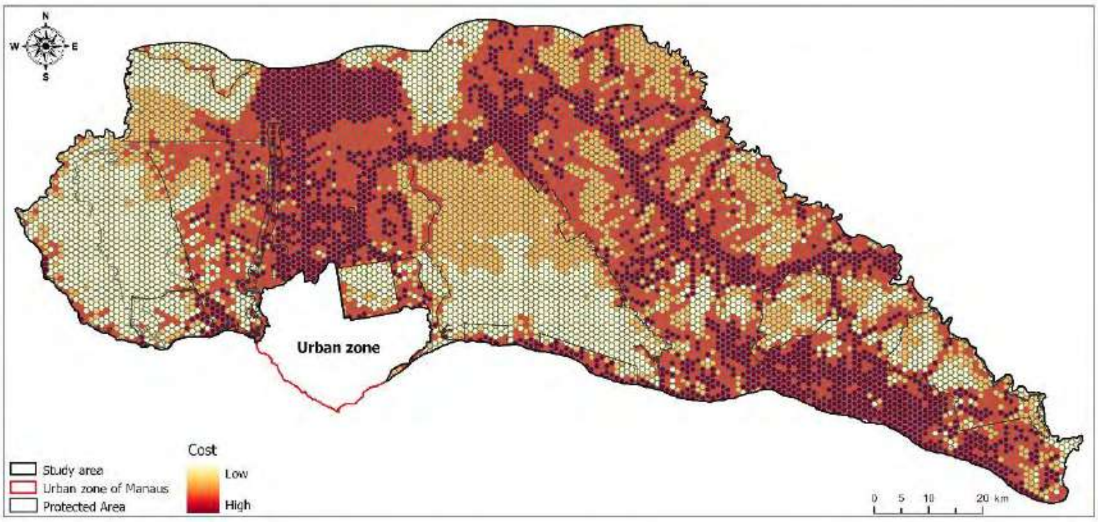

Figure 6. Systematic planning area, with the cost surface based on major threats and the contour of already protected areas

All (100%) of the targets were met by the best (lowest score) solution. The set of selected areas covered 55.36% of the total area. More than half of the selected PUs (60.4%) were either already under some degree of protection or belonged to the Brazilian Army. On the other hand, some parts of the already protected areas or Army land were not included in the best solution (Table 2 and Figure 7).

Table 2. Proportion of areas selected and not selected under different status of protection

Status	**Selected** ha (%)	**Not Selected** ha (%)
Protected	185,803.9 (22.2)	31,891.7 (3.8)
Army	94,396.5 (11.3)	9,939.6 (1.2)
Unprotected	183,971.1 (21.9)	332,415.6 (39.6)
TOTAL	464,171.6 (55.4)	374.246.9 (44.6)

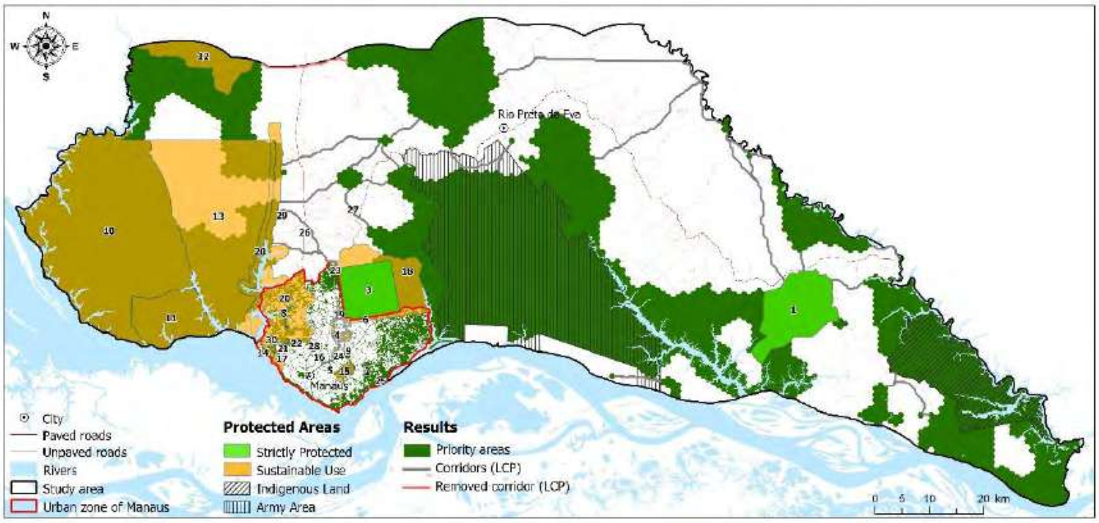

Figure 7. Priority areas for the conservation of the pied tamarin (composed of selected areas and corridors (Least Cost Paths), Protected Areas (Strict and Sustainable Use) and Army Area. The names of the numbered protected areas are in the supplementary material.

The best solution generated 18 patches ranging in size from 32 to 199,698 ha (mean 25,787, SD 57,513 ha). All of the largest patches contained protected areas. Most of them could be connected using the Linkage Mapper (Fig. 7). Because we are concerned with the possible expansion of the geographic distribution of *S. midas*, we excluded a linkage that would allow connection through the area of high potential and confirmed occurrence of this species. Including the final 400 m wide corridors, the priority area increases to 477,223.71 ha. Together, the urban and rural priority areas cover 497,589.61 ha or 56.1% of the study area.

Stakeholder input and involvement

Seventy people attended the public seminar, including representatives from all the main interest groups. The main suggestion was to include the permanent preservation areas in the priority map for the urban area, as detailed above.

Other relevant considerations were also raised. Participants recognized the seminar as an opportunity to better understand conservation needs and agreed that urgent action is necessary given the increasing impact of environmental change on human life. However, residents of the recently created "Refúgio de Vida Silvestre Sauim-de-Coleira" (Lagroteria et al, 2025) expressed concern about the creation of this strictly protected area, which was established without a clear communication of the economic activities allowed and without planning or support for an economic transition. They pointed out that they need support to transition away from their main economic activity. One resident said that charcoal production was their main activity prior to the establishment of the protected area, but this is not permitted in a strictly protected area.

DISCUSSION

Our analysis revealed that about one-third of the urban zone is covered by some type of formal protection. However, it also revealed that nearly all the protected areas fall under partial-protection categories, and that some of these categories have experienced a significant loss of vegetation, among other impacts. The Manaus airport, for instance, with all its noise and asphalt, is located in an Environmental Protected Area (APA in Brazilian denomination), which demonstrates the low level of protection in some formally protected areas. Even though pied tamarins can communicate and live in noisy areas (Sobroza et al., 2024; Sobroza, 2024), the potential impact of such human activity on the long-term well-being and reproductive success of species is not clear. In some extreme situations, such as that of the airport, it would be difficult to change the situation, but in other parts of the same protected area (APA Tarumã/Ponta Negra), as well as in other already protected areas within the urban zone, the recovery of vegetation should be promoted to increase the habitat available to local fauna and flora, including the pied tamarin. Additionally, it is crucial to take measures to protect the 20% of remaining green areas within the urban area that are not currently formally protected, preferably in categories with more-restricted use.

We initially did not conduct formal analyses to promote connectivity in the urban matrix for two reasons: the relative difficulty of planning corridors in heavily occupied areas and the fact that Brazilian legislation already states that riparian vegetation must be protected. However, this legislation has been relaxed in recent years, and vegetation along water bodies can now be converted under public utility or social interest (Azevedo-Santos et al., 2023). This has been exploited by the real-estate sector, which is converting and occupying the majority of riparian zones. Therefore, the participants of the public seminar recommended including permanent preservation areas (APPs) required by the Forest Code in the urban map to emphasize the need to protect these environments, both for their role in protecting water sources, providing infiltration areas, and maintaining connectivity for biota.

For rural areas, target setting has been the main challenge. While there is a substantial body of literature on the ecology of the pied tamarin, only a limited number of studies have specifically addressed its use of different habitats at the population level (Kinap et al., 2021; Vidal & Cintra, 2006). Both studies were conducted in the same area (Ducke Reserve), but with different results: while the first (Kinap et al, 2021) found the plateau to be the most used habitat, the second (Vidal & Cintra, 2006) found pied tamarins using all slopes and no seasonal variation in use. Mean home range of pied tamarin groups in continuous forests has been estimated to be around 100 ha (Gordo et al., 2011), while in urban areas they have home ranges between eight and 65 ha including primary and secondary forests at different successional stages, as well as white-sand forests (*campinaranas*) and flooded forests (*igapos*) (Egler, 1992; Gordo et al., 2017). Most of the studies are concentrated in urban areas or in the Ducke Reserve, which makes it difficult to know if there are variations in population parameters or habitat-use patterns between different areas or landscape contexts. The lack of more detailed data on spatial ecology makes it difficult to define a target that takes into account the specific needs of the species.

In the last update of the Brazilian Map of Priorities for Conservation, Sustainable Use and Benefit Sharing of Biodiversity for the Amazon Biome (MMA, 2023), a target of 100% was set for all mammal species with a distribution of less than 10,000 km^2, as is the case of the pied tamarin. However, we did not consider it feasible to propose a priority map based on a target higher than 50% for the pied tamarin due to geographical and political constraints. Updates to the systematic conservation-planning processes recommend the inclusion of new steps related to the implementation of conservation actions and the maintenance and monitoring of protected areas (Adams et al., 2019; McIntosh et al., 2017). For the pied tamarin, review and monitoring will be critical to determine if actions have been successful in conserving the species and if it still needs increased protection. In addition, there have been recent changes to the proposed geographic distribution of the species (Lagroteria et al., 2024), and ongoing studies may lead to further changes - either an expansion due to occurrences in new areas or a reduction in range due to the expansion of *S. midas*.

The only other endemic species included in our study as a target was the frog *Atelopus manauensis*. Including this species increased the biodiversity represented in the final map, making it a stronger public policy tool. Approximately half of the frog's distribution area overlaps that of the pied tamarin, only that portion was included in our planning. Future conservation plans focused on this species or considering an expanded area must account for the entire distribution of the frog.

The availability of occurrence points for *Atelopus manauensis* allowed us to refine this species' spatial information, indicating its proximity to water. However, other fine-scale habitat information, such as pH and connectivity between pools, which influence occurrence of the species (Jorge et al., 2020), could not be mapped at the scale of this study. Despite the limited extent of the superimposed range (approximately 300,000 ha) and the restricted area around the water where the species has been observed, we set a target area of 50% because most of its habitat is already nominally protected by the permanent preservation areas (APPs, see above).

The remaining targets were based on environmental variation, including combinations of vegetation, topography, and the presence or proximity of water. In addition to improving the representation of biodiversity, their inclusion contributes to resilience in the context of an uncertain future. Environmental gradients facilitate short-range migrations in response to change, allowing species to persist (Pressey et al., 2003; 2007). The majority of environmental targets were set at 30%, in line with the Kunming Montreal Decision (CBD, 2022). Exceptions were due to a relatively higher degree of threat from resource extraction or agriculture (plateau), relevance for traditional human use (flooded forest), or importance as a resource provider for the pied tamarin (young secondary forest) (Egler, 1992; Gordo et al., 2017).

Deforestation and land-use change, such as conversion to agriculture and grazing, are usually preceded or accompanied by road construction. These, and other threats that cause environmental impacts and habitat loss to our area of interest, such as mining, power lines, human settlements, and an agro-industrial hub were included in our cost surface because they lead to biodiversity loss (Laurance et al., 2002) and make conservation efforts difficult, expensive, or impossible. The likelihood of occupation by another species is a less-common component of cost surfaces. However, concerns about the expansion of the geographic range of *Saguinus midas* over that of *S. bicolor* have been raised by various authors (e.g., Ayres et al., 1982; Subirá, 1998) and addressed in specific studies by niche models (Lagroteria et al., 2024; Röhe, 2006). By incorporating the two classes of occupancy probability derived from the model of Lagroteria et al. (2024), and refining this information using the actual occurrence of one or the other species, we reasoned that the best areas for pied tamarins would be those less likely to be occupied by *S. midas*.

Most of the already protected areas were given the status of "initial" and were selected. This result reinforced the importance of the existing protected areas (even those in sustainable-use categories) for the conservation of the pied tamarin, and of the large area that belongs to the Brazilian Army. The notable exception was most of the APA Margem Esquerda do Rio Negro - Setor Tarumã-Açu/Tarumã Mirim. Despite its protected status, conservation actions there are complicated by the many threats faced by this area, since it is crossed by roads, has human occupation and agricultural activities, and also coincides with the probable invasion area of *Saguinus midas*. In contrast, the military area contains one of the largest patches relatively well-preserved contiguous vegetation. Its protection is crucial, but uncertain as the army currently has no legal obligation to preserve the area, and the institution has the right to use the land as it chooses.

Most of the patches in the rural zone were isolated by the presence of roads, which indicates some difficulty in establishing connections between them. Although their preservation is of great importance, because most of the roads cross water divides, it is not possible to connect the separate patches based on the Permanent Preservation Areas (APPs) along watercourses (Law nº 12.651/12), as recommended in the urban matrix. Considering that being run over by vehicles is a relatively common occurrence among pied tamarins (Gordo et al., 2013), many of the connections identified in our analysis highlight the need to create wildlife corridors as well as animal crossings on these roads.

The current scenario shows that much of the effort made to create protected areas is not as effective as it should be. Although almost 30% of the urban area is protected in some way and about 20% of the systematic-planning area has the same status, a significant part of it is already degraded. The large proportion of the protected area that is in categories that allow other uses gives a false sense of conservation achievement and makes the creation of new areas or other conservation actions more difficult (Magris & Pressey, 2018). The results, as well as the discussions at the end of the seminar, showed that it is not only necessary to create new protected areas, but also to improve the management of the existing ones, especially in the urban zone. None of the protected areas in the urban zone have management plans, which is the basic tool to define their zoning and which areas are effectively destined for conservation. They also lack consultative or advisory councils, which are essential for monitoring their conservation status and demanding improvements.

Debates at the final seminar also made it clear that the success of rural conservation efforts will depend on developing incentives to shift current production chains to those with less impact on biodiversity. It remains a challenge to identify the most compatible economic activities and to involve local people in conservation efforts. There is undeniable progress in promoting more sustainable use of forest resources. However, there is also a risk of simply substituting products without changing the production system, and of continuing the conversion of natural and cultural systems into poorer ones (Clement et al., 2024; Vieira et al., 2024).

Conservation of the pied tamarin, as well as other threatened species, depends on a better understanding of the need to increase the amount of land set aside for their protection and on good management in and around these areas. For example, improved monitoring and vegetation restoration could help to enhance the effectiveness of existing protected areas and be applied to new ones. In a world where environmental change is occurring much faster than predicted, and in some cases with catastrophic consequences, our own existence and quality of life is increasingly dependent on this understanding.

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AUTHOR CONTRIBUTIONS

All authors contributed to the design of the study, ALA and MCT performed the analyses, ALA wrote the first draft, all authors revised, edited, and approved the final version of the manuscript.