Effect of oil pipelines on landscape connectivity for long-furred woolly mouse opossum (*Marmosa paraguayana*) in the Brazilian Atlantic Forest

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Effects of pipelines on Marmosa paraguayana movements

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Running title: Effects of pipelines on *Marmosa paraguayana* movements.

Abstract

Linear infrastructures like roads, pipelines, and electrical networks are among the main causes of habitat fragmentation and diversity loss in animal species. We evaluated the effects of 20-30 m wide deforested corridors above underground oil pipelines on the movements of the long-furred woolly mouse opossum *Marmosa paraguayana*, an arboreal marsupial ubiquitous in the Brazilian Atlantic Forest. Using capture, mark, and recapture protocols along four transects, two on either side of the deforested corridor, one within the forest, and one along the forest edge, we compared movements within the forest with those across the deforested corridor. This experimental design was repeated in six locations within two protected areas in the state of Rio de Janeiro, Brazil. Pipeline crossings were rare, performed by few individuals, and significantly less frequent than movements inside the forest fragment, indicating that the deforested pipeline corridors act as a partial barrier to the movements of *M. paraguayana*. All crossings were restricted to the mating season. Both sexes crossed the pipeline strips and males travelled longer distances than females. Also, individuals used the forest interior more frequently and avoided edges, decreasing the likelihood of crossing the unforested corridors. This study revealed an underestimated effect of a narrow-deforested matrix like the ones created by underground pipelines on forest connectivity and the need for the development of measures to mitigate these impacts.

Keywords: Barrier effect, Didelphimorphia, fragmentation, movement ecology, linear infrastructure, petroleum.

Introduction

Tropical forests are essential ecosystems for the survival of many animals, plants, and humans, hosting most of the terrestrial vertebrate species on the planet and providing uncountable services for human well-being (Pillay et al., 2022; Wright, 2005; Pearce, 2001). Nevertheless, the continuous anthropic interventions on landscapes cause significant loss and fragmentation of natural habitats, which represents a threat to the conservation of many native and endemic species (Edwards et al., 2019).

A recurrent and conspicuous type of anthropic intervention is the construction of linear infrastructures, such as roads, electric power lines, and fuel (gas and oil) pipelines (Van Der Ree et al., 2015). Although these structures have a large impact on the environment (Laurance et al., 2009), in many cases they are necessary for the economic, cultural, and political development of human societies. Therefore, it is imperative to find a way to minimize and mitigate their impacts on biodiversity, assuming that human activities cannot be excluded from conservation planning (Ellis and Ramankutty, 2008).

Linear infrastructures can adversely affect forest biodiversity by contributing to habitat loss and fragmentation and increasing animal mortality (Laurance et al., 2009). The creation of an open matrix between forest fragments to accommodate linear structures may function as a spatial barrier to forest-dependent animals (Saunders et al., 1991). For non-volant forest small animals, for instance, changes in vegetation structure may cause problems with orientation, increase their vulnerability to predators, and restrict their movements (Ríos-Uzeda et al., 2019; Brown and Kotler, 2004; Carey, 1996). Ultimately, in the long term, the effect caused by linear barriers could also disrupt demographic and genetic connectivity among populations that inhabit forest fragments separated by unforested corridors, likely increasing the vulnerability of populations to local extinction (Hanski, 2011).

Linear infrastructures can also create edge effects, owing to the contrasting abiotic conditions (temperature, relative humidity, and luminosity) between the matrix and the forest interior (Murcia, 1995). The intermediate conditions found at the forest-matrix border might affect the abundance and distribution of resources, decreasing the abundance or the habitat use by certain species near the forest borders (Moenting and Morris, 2006; Asquith and Mejía-Chang, 2005; Stevens and Husband, 1998), and potentially intensifying the barrier effect caused by the linear infrastructure. For instance, if a forest-specialist species avoids using forest edges due to their lower quality in terms of resources and protection against predators, its likelihood of reaching and crossing the matrix space separating forest fragments will also decrease.

The distances travelled by individuals on a fragmented landscape can serve as a reliable indicator of barrier permeability. In areas where the barrier is impermeable, it is expected that animals will cover longer distances in search of a point with good connectivity between fragments (Xu et al., 2021; Rico et al., 2007). However, movement distances can also be affected by other factors, such as sex, age, reproductive condition, and seasonal availability of food resources (Tolkachev, 2023; Chen and Koprowski, 2019; Loretto et al., 2005). In this context, animals might travel longer distances while searching for food resources during a resource-poor season, or while looking for partners during a reproductive season (Loretto et al., 2005; Pires et al., 2002). Likewise, the intensity of the barrier effects exerted by a linear structure may also depend on the same biological factors that affect the propensity of individuals to disperse long distances (Rico et al., 2007; Szacki and Liro, 1991).

Among the several linear barriers created by humans, the construction and maintenance of pipeline rights-of-way (hereafter: pipeline strips) for the transportation of oil and/or gas deserves special attention (Figure 1). Pipelines are important for the energy and industrial sectors, especially in countries that are still highly dependent on fossil fuels, such as Brazil, where an extensive network of this type of structure already exists and is planned to be expanded (Cianciarullo, 2022). Pipelines are normally buried 1.5 meters into the ground, and to avoid damages to the ducts that could result in oil spills or gas leaks, a strip of cleared land is created above them by removing all the arboreal vegetation, and by periodically mowing any colonizing vegetation (Vasek et al., 1975). The area where the vegetation is removed forms an open strip 20-30 m wide dividing the forest that might affect the movements and population connectivity of tropical forest mammal species (Lucas et al., 2019; Laurance et al., 2009).

Animal responses to the deforested strips produced by pipelines may vary depending on the species' traits, such as body size and locomotion habits (Fahrig, 2017). Smaller animals tend to be more affected by the barrier effect compared to larger ones (Chen and Koprowski, 2019). This is evident in the study conducted by Pires et al. (2002) on fragmented Brazilian Atlantic Forest, where larger marsupials, such as the black-eared opossum (*Didelphis aurita*) and the brown four-eyed opossum (*Metachirus myosuros*), exhibited higher rates of inter-fragment movements compared to the long-furred woolly mouse opossum (*Marmosa paraguayana*) and other smaller marsupials and rodents. Many forest species depend on the existence of the canopy for survival (Rodríguez-Gómez et al., 2022). Therefore, spaces without arboreal vegetation may act as barriers to the passage of such animals. Carey (1996) attributed the barrier effect to what he called the level of "arboreality"; a scale that he developed measuring how much the animal uses the canopy. He assumed that the barrier effect is smaller in animals that use trees less frequently. Locomotion through open areas is also less efficient for some small mammals because it increases their susceptibility to predation (Arthur et al., 2004). Finally, animals' diets could also be altered by the pipeline strip, since the open area generates edges that change the availability of food resources, the structure of vegetation cover, and the micro-climatic conditions (Fahrig, 2007).

In this study, we evaluate the impacts of the pipeline strip on the movements of *Marmosa paraguayana* (Tate, 1931), a forest-dependent arboreal marsupial (Figure 1) relatively abundant in the Atlantic Forest in Rio de Janeiro state (Moraes Junior and Chiarello, 2005). Previous studies investigated the movement ecology of this species, comparing the barrier effect produced by fragmentation, the variables that can intensify the effect in the Atlantic Forest (Honorato et al., 2015, Pires et al., 2002), and the use of space, explaining the variables that affect the size of the home ranges (Pires and Fernandez, 1999). However, most of these studies focused on areas separated by wide matrices (< 30 m), and it is not known whether a much narrower matrix, such as that produced by the pipeline, could affect the movements of *M. paraguayana*. Specifically, we tested the hypothesis that the pipeline strip limits the movements of woolly mouse opossums between forest fragments. If this hypothesis was correct, we would observe a lower rate of pipeline crossings compared to the rate of movements within the forest interior. We also tested if the pipeline strip exerted a negative edge effect on *M. paraguayana* spatial use; in this case, we expected to capture individuals more frequently in forest interiors than in forest edges. Finally, we evaluated whether the movement distances of individuals were influenced by area, sex, and reproductive condition: if males were more promiscuous than females and showed less philopatric behaviour, we would expect them to travel longer distances during the mating season and, therefore, perform a higher number of pipeline crossings.

Methods

Studied species

The long-furred woolly mouse opossum *Marmosa paraguayana* is a marsupial belonging to the order Didelphimorphia and the family Didelphidae, presenting an average total length of 164.7 mm (Faria et al., 2019). It is distributed in Paraguay, Argentina, and eastern Brazil, from Minas Gerais to Rio Grande do Sul, and it is more abundant in dense forests, rich in palms and vines (Dias et al., 2010). *Marmosa paraguayana* is considered an arboreal species (Wilson et al., 2015), but it can eventually use the forest floor to forage and move (Pires and Fernandez, 1999). It can inhabit both primary and secondary forests (Smith, 2009). It has a moderate degree of tolerance towards anthropic intervention and is highly abundant and ubiquitous in our study areas (Smith, 2009, Gardner, 2008). The species is considered as "Least Concern" (LC) worldwide (Brito et al., 2018). The reproductive cycle of *M. paraguayana* is seasonal, and the breeding season is linked to the wet season, between October and March, when there is greater resource availability (Barros et al., 2008).

Study areas

We selected six study areas in the São João river basin (Figure 2), belonging to the Landscape Connectivity project- *Assessment of the effect of pipeline strips on landscape connectivity for mammals and analysis of the effectiveness of fauna crossing structures* – coordinated by PETROBRAS, a corporation that operates in the oil, natural gas, and energy industry. The basin is 3,000 km^2, encompassing eight municipalities in the lowlands of the state of Rio de Janeiro, south-eastern Brazil. The main natural vegetation is the submontane rainforest, and the regional climate is characterized by a wet season, from September to April, and a dry season, from May to August (Alvares et al., 2013).

Three of the six sampling areas were in forest fragments of rural properties located in a less restrictive legally protected area, which allows sustainable use, the Área de Proteção Ambiental da Bacia do Rio São João (hereafter APA): Fazenda Flandria (FL) (-22.505250°, -42.316260°) (average pipeline strip width = 27 m), Fazenda Iguapê (IG) (-22.505720°, -42.326960°) (average pipeline strip width = 20 m) and Fazenda Dois Irmãos (DI) (-22.512860°, -42.337680°) (average pipeline strip width = 23 m) (Figure 2), all areas separated by a distance of about 1.5 km. The APA was instituted in 2002 and has an extension of 150,700 ha, located in the municipalities of Silva Jardim and Casimiro de Abreu. About 50% of the area is covered by secondary forests in different successional stages, predominantly on scarps or on hilltops. Within these areas, the occurrence of human habitation is frequently witnessed principally in FL, wherein the pipeline corridor serves as a traversing route for machinery and individuals engaged in various undertakings such as afforestation, game hunting, and livestock management, among other pursuits (Lima et al., 2006).

The other three areas were located within a strictly legally protected area, which does not allow almost any anthropic intervention, the Reserva Biológica União (hereafter REBIO): REBIO União A (UA) (average pipeline strip width = 22 m) (-22.422637°, -42.018349°), REBIO União B (UB) (-22.443004°, -42.050378°) (average pipeline strip width = 22 m), and REBIO União C (UC) (-22.462706°, -42.093187°) (average pipeline strip width = 29 m), all separated by a distance of about 4.2 km. The last area (UC) was a farm until 2017 when it was bought by the REBIO and added to the reserve. This reserve has more than 7,000 ha of preserved forest (Lucas et al., 2019). The area UC presents a higher degree of human intervention compared to UA and UB, owing to intense farming activities in its surroundings, similar to the conditions found in the APA areas. All the areas are traversed by the same pipeline, and in all these areas, the forest connectivity is greater on the northern side of the duct, where the forest fragments are larger (Figure 2).

Sampling design

In each area, we created four live-trapping parallel linear transects. We placed two transects at the forest edge adjacent to the corridor, one on each side of the pipeline strip, and the other two in the forest interior, at a distance equivalent to the width of the pipeline, and parallel to the edge transects. The equivalence in distance between transects aimed at assessing whether a natural environment devoid of physical barriers would exhibit a higher frequency of movements within the same distance compared to areas influenced by the presence of the pipeline. Each transect was composed of 15 sampling stations, 10 m apart from each other, with a Sherman (30 cm x 8 cm x 9 cm) and a Tomahawk (45 cm x 16 6 cm x 16 cm) trap (Log Materiais e Ferramentas Ltda, Belo Horizonte-Minas Gerais, Brazil) (according to Voss and Emmons, 1996), totalizing 60 stations and 120 traps per area. At each station, we installed one trap on the ground and one on the understory, 1-2 meters high, and tied to branches and lianas. We alternated the types of traps between the ground and the understory at every station. Traps were checked daily and baited with a mixture of banana, sardine, cornmeal, and ground peanuts.

We carried out samplings quarterly, from October-2018 to December-2019. Each sampling campaign lasted seven nights, the traps remained active 24 hours/day and were checked every morning between 7 a.m. and noon. REBIO and APA areas were sampled in separate campaigns. The sampling effort was 840 traps-nights in each area per campaign, totalizing an effort of 10,080 traps-nights for REBIO and 12,600 traps-nights for APA.

Animal handling

At each capture, we carefully immobilized and handled the animals. The animals were marked with numbered earrings (National Band Tag Inc. number 1), sexed, aged according to the pattern of teeth eruption (Macedo et al., 2006), and inspected for signs of reproductive activity (lactating mammae or suckling young). Lastly, they were released in the same station where captured. This method allowed us to use the capture-recapture history of an individual to infer its movements. The study was authorized by license No. 64807-2 issued by The Institute for Conservation of Biodiversity “Chico Mendes” (ICMBio) and the Ministry of the Environment of Brazil (MMA). following the ASM guidelines (Sikes, 2016).

Movements

The classes of movements and the distances travelled by each individual were inferred from its capture/recapture history and from the coordinates of the sampling stations where the animal was captured. We classified the recorded movements into three classes:

1) Same-side transect switching (ST): recapture on the same side of the forest, but in a different transect (edge or interior) than that of the previous capture.

2) Pipeline crossings (PC): recapture occurred on the opposite side of the pipeline strip than the previous capture.

3) Transect movements (TM): recapture at a different station along the same transect of the previous capture.

To obtain the rate of pipeline crossings (PCr), we divided the total number of pipeline crossings by the sum of forest and pipeline crossings (PCr = PC/(PC+ST)). To obtain the rate of forest crossings (STr), we divided the ST by the sum of forest and pipeline crossings (STr = ST/(PC+ST)).

Using a Chi-square test ($\chi2$) ($\alpha = 0.05$), we evaluated whether there were fewer PCs than STs based on the hypothesis that the pipeline acts as a barrier restricting movements of *M. paraguayana* between fragments. We also used a Chi-squared test to assess the effect of sex on the number of pipeline crossings.

Edge effect

We considered the number of captures at the edge and interior transects as a surrogate of habitat use (Braga et al., 2015; Carmignotto et al., 2014; Geier and Best, 1980). Therefore, we built a generalized linear mixed model (GLMM) in which the number of captures was the response variable, the transect position (two levels: edge or interior) was the explanatory variable, and "area" and "sampling session" as random effects. The poisson distribution of the model was assessed by calculating the overdispersion parameter (Zuur et al., 2009).

Distances of movement

We inferred the movements and the distances travelled by each individual based on its capture-recapture history and the geographic coordinates of the trap stations where it was successively captured. The distance of movement was the smaller linear distance between the stations of consecutive captures. We tested if there were differences in the distances travelled by males and females with a Mann-Whitney test. For this analysis, we included only adults, since they represented 65.3% of the captures, and comparisons including other age classes would include ontogenetic variation in size and behaviour that could affect movement distance.

To explore if unaccounted disparities between the studied areas affected the distances travelled by *M. paraguayana*, we carried out a Kruskal-Wallis test where the movement distance was taken as a dependent variable and the study area as a predictive variable. We tested if there were significant differences ($\alpha = 0.05$) between distances travelled in each area. Movement distances can also be affected by the climatic season since the availability of food resources tend to vary between seasons and the animals may need to cover larger areas to find enough food in the dry season. Therefore, we conducted a Mann-Whitney test to evaluate the variation in movement distances between climatic seasons (wet, and dry). For this analysis, we considered the movement distance as a dependent variable and season (two levels: wet or dry) as an explanatory variable.

Results

We recorded a total of 185 captures of 72 individuals of *M. paraguayana*, 38 males and 34 females. Most of the captured individuals (n = 47; 65.28%) were adults. The species was more abundant in the REBIO (n = 45) than in the APA (n = 27) areas, and in both cases, the abundance of captured males and females was similar (Table 1). We also observed a variation in the number of captures of males and females throughout the year, tending to register more captures of females in the first semester, and then an increase in the frequency of male captures in the second semester (Appendix 1). Additionally, we registered females in reproductive stage (females with newborn pups attached) (Appendix 2).

Movements - We recorded 105 movements, of which only eight consisted of pipeline strip crossings (7.41% of all movements) performed by only four individuals (5.56% of all individuals).

The remaining 97 movements were performed within the same forest side, with similar proportions between transect movements and forest crossings (46 TM and 51 ST).

For the "APA" we registered 33 movements, of which two (6.06%) were pipeline strip crossings performed by only two individuals. On the REBIO, we registered 72 movements, of which six (8.33%) were pipeline crossings performed by four individuals (Table 1). Despite the variation in the number of captures and recaptures, the rates of pipeline strip crossings and forest movements were similar between REBIO (PCr = 13.63% and STr = 86.36%) and APA (PCr = 13.33% and STr = 86.66%).

We recorded a total of 64 movements for females (60.09% of the total movements) and 41 movements for males (39.04%). Among the eight pipeline crossings recorded, five were performed by males (12.19% of the total male movements) and three by females (4.69% of the total female movements). Among the 51 forest crossings, 30 were performed by females (46.87% of the total female movements) and 21 by males (51.22% of the total male movements). Females also performed 31 of the 46 transect movements (48.44%) and the other 15 were made by males (36.58% of the total male movements).

Pipeline strip crossings were significantly less frequent than forest crossings (χ^2 (1, N = 59) = 29.49; *p* = <0.001). We did not detect differences between the frequencies of crossings expected and the observed for each sex (χ^2 (1, N = 8) = 2.00; *p* = 0.16).

The history of movements over time showed that pipeline strip crossings occurred only during the wet season between October and January. In October 2019 we recorded the highest number of STs (n = 17) and PCs (n = 5) while in December 2019 we did not record any PCs. We did not record movements in February 2019 (Figure 3).

Edge effect – We recorded a higher number of captures of *M. paraguayana* in the forest interior (n = 107, mean = 3.96, SD = 3.81) than in the edge (n = 78, mean = 2.89, SD = 2.97), suggesting that animals tended to avoid forest edges ($\beta = 0.31 \pm 0.14$; z = 2.14; *p* = 0.03).

Movement distances - Males moved longer distances than females (Z = 2.35, *p* = 0.01) (Figure 4). Movement distances also differed among areas, with longer distances being recorded in "FL" (H (5, N = 93) =15.03; p = 0.01) (Appendix 2). There was no significant variation in movement distance between climatic seasons (Z = 1.22, *p* = 0.22).

Discussion

Our results highlighted the significant effects of oil and gas pipeline strips on movement, habitat use, and population connectivity of an arboreal Neotropical small mammal. We demonstrated that the unforested strip above pipelines limits the movements of *M. paraguayana* between opposite forest fragments and that the individuals avoid the forest edge. We also observed that females presented shorter movement distances than males and that pipeline crossings were more likely to occur during the wet season.

Despite the lower pipeline crossing rate compared to the forest crossing rate, the pipeline strip does not constitute a "hard barrier" for *M. paraguayana* movements, as 5.56% of the individuals we monitored were able to cross the pipeline strip. Instead, the pipeline strip functions as a partial or semipermeable barrier to inter-fragment movements, limiting the rate of this type of movement but not completely preventing individuals from moving from one forest fragment to the other. In previous studies of *M. paraguayana* crossing rates in a nearby fragmented landscape, Pires et al. (2002) recorded a crossing rate of 1.2% among small fragments (1.4 to 15 ha) separated by 145 to 800 m of a non-forested matrix. They hypothesized that despite the significant barrier effect caused by the matrix of open habitats, the limited number of observed movements of *M. paraguayana* would be sufficient for the subpopulations to maintain a metapopulation structure. Our study estimated a higher frequency of pipeline crossing movements (7.61%), but the distance traversed between opposite sides was considerably smaller (20-30 m) and the fragments were larger than those studied by Pires et al. (2002). Our results thus suggest that the barrier effect is still perceptible for *M. paraguayana* even under conditions of narrower matrices and larger forest fragments.

The loss in landscape connectivity and forest cover is considered the most detrimental effect of deforestation on the genetic diversity of the species (Almeida-Rocha et al., 2020). Brito (2009) simulated the population viability of *M. paraguayana* under various fragmentation scenarios and showed that migration rates as high as 5% (close to the one observed in this study) are insufficient to prevent the loss of genetic diversity in subdivided small metapopulations (N = 100 individuals). Likewise, empirical studies on other forest small mammals show that migration rates of about 5% might not be high enough to reverse genetic divergence among populations separated by linear infrastructures (Galantinho et al., 2022, Ascensão et al., 2016). Nonetheless, genetic analyses of the local *M. paraguayana* populations of this study are still necessary to evaluate whether the proportion of migrating individuals observed is sufficient to prevent loss of genetic variation. Given the overall reduced number of migrating individuals in all areas monitored, if most migrants were not successful at reproducing, the pipeline strips might exert a much stronger barrier effect than the one estimated by our analyses of individual movements.

We also detected a negative edge effect of pipeline strips on the capture success of *M. paraguayana*. Assuming that capture success is a proxy of habitat use (Braga et al., 2015; Carmignotto et al., 2014; Geier and Best, 1980), the higher capture success in the forest interior indicates that individuals avoid using the forest edge. By avoiding the edges, most individuals would seldom reach and cross the unforested pipeline strip. Therefore, the negative edge effect probably contributes to the low rate of pipeline crossings observed. Numerous variables can influence species habitat selection (e.g., wind intensity, food availability, perceived predation risk, and composition of the neighbouring matrix), and the diverging condition of the forest edge might attract or repel different species (Lidicker, 1999). de la Sancha et al. (2023) found that the forest edge areas of the Paraguayan Atlantic Forest are dominated by generalist, open-habitat, or exotic species of small mammals. Mazzamuto et al. (2018) pointed out that the presence of small mammals at the edge could depend more on factors that reduce the perceived risk of predation (e.g., refugees, visibility of the landscape, and cover) than the actual presence of predators. Thus, the lower abundance of *M. paraguayana* in the edge areas may be related both to the fact that this species is a forest specialist (Prevedello et al., 2009; Emmons, 1999), and to the perceived risk due to habitat changes and frequent human presence in the pipeline strips for maintenance, generally performed using noisy machinery (lawnmowers, tractors). The presence of humans and noise produced by machinery have previously been described as generators of edge effects for small mammals (Chen and Koprowski, 2015; Villaseñor et al., 2014; Lacerda et al., 2009).

Our results agree with other studies (Gregory et al., 2017; Thurber and Ayarza, 2005) highlighting the negative effects of linear constructions on arboreal mammals. Pires et al. (2002) also working on the Atlantic Forest reported that the Cursor Grass Mouse (*Akodon cursor)*, a rodent present also in our study area, presented crossing rates even smaller than *M. paraguayana* and that the bare-tailed woolly opossum (*Caluromys philander*), an arboreal marsupial, never crossed the matrix of open vegetation during their study. This suggests that our results can be extrapolated to other non-social arboreal mammals of similar body size. However, the results obtained for *M. paraguayana* may not be generalizable to larger arboreal species in the region. In a study of movements and home ranges of Golden Lion Tamarins (*Leontopithecus rosalia*, Linnaeus, 1766) in the same landscape as the present study, Lucas et al. (2019) did not find barrier effects of the pipeline strip, as tamarin group home ranges showed core areas on both sides of the pipeline. This difference could be due to the larger size of *L. rosalia* when compared to *M. paraguayana*, which would allow it to move greater distances and cross larger matrices. *Leontopithecus rosalia* is also a social species and could have a better perception of risk than solitary species such as *M. paraguayana* (Lehtonen and Jaatinen, 2016). *Marmosa paraguayana* faces a higher predation pressure as they are prey to a larger number of vertebrates (Voss and Jansa, 2021) and might have evolved a stronger avoidance behaviour towards the non-forest matrix formed by linear infrastructures.

Although no variation was found between the rates of crossing and movements within the forest in crossing rates of REBIO (PCr = 13.63% and STr = 86.36%) and APA (PCr = 13.33% and STr = 86.66%), we observed more captures, movements, and pipeline crossings in the REBIO areas than in the APA areas. The areas in the APA present higher anthropic intervention due to activities such as cattle grazing, and agriculture occurring on the proximities of the pipeline strips (Lucas et al., 2019; Carvalho et al., 2004). The type of anthropogenic use of the landscape where the pipeline strips are located could be a determining factor in the abundance and behaviour of small mammals, modifying their perception of risk, orientation, and foraging behaviour (Fahrig, 2017; Vieira et al., 2009; Brown and Kotler, 2004), and these changes could act synergically with the pipeline to decrease species abundance and movement. For Atlantic Forest small mammals, anthropic activities in the matrix, such as agriculture or urban settlements, influence the local composition of species inhabiting the fragments (Vieira et al., 2009). Those authors observed that forest fragments near urban areas surrounded by highly disturbed matrices had lower abundances of *M. paraguayana* compared to fragments near small rural properties. Our results suggest that in addition to the abundance, the movements of *M. paraguayana* are conditioned to the kind and the use of the landscape where the individual lives. Fragments surrounded by matrices with higher anthropic intervention may also offer a higher resistance to the movements of this species.

The pipeline crossings were not evenly distributed throughout the trapping sessions, occurring only in October and January. These months also coincided with our first records of reproductive females (Appendix 2), suggesting that the crossing movements of *M. paraguayana* might be related to the mating season. Males also travelled longer distances than females even when females were more captured. These results can be explained by the fact that male home ranges tend to be larger than female home ranges, as they travel higher distances searching for partners, whereas females tend to present philopatric behaviour, presumably due to parental care (Pires and Fernandez, 1999). Several other studies showed how movement distance in mammals varies according to sex or mating season (Wauters et al., 2021; Allan et al., 2019; Carmignotto et al., 2014; Goosem, 2001; Manson et al., 1999; Diffendorfer et al., 1995; Gaines and Mcclenaghan, 1980). Allan et al. (2019), working with an Australian marsupial species (*Trichosurus cunninghami*), obtained similar results, where males of this species tended to cover greater distances than females in linearly fragmented landscapes. They inferred that this behaviour is also due to the search for females for reproduction, while females only moved enough to secure foraging resources, resulting in smaller home ranges. Diffendorfer et al. (1995) also showed that most crosses between forest fragments were performed by males in three species of rodents (cotton rats *Sigmodon hispidus*, deer mice *Peromyscus maniculatus*, and prairie voles *Microtus ochrogaster*), attributing this variation to the reproductive behaviour of the species.

We detected differences in the distance of the movements in each area. The individuals of *M. paraguayana* in FL, moved larger distances than those in the other areas, even considering the number of captures. FL is the only sampling area with a completely flat topography. In all other areas, a large extent of the transects is in slopes and foothills. Assuming that small mammals are more susceptible to the topographic variations observed in our study areas (Jeanson et al., 2003), it is probably less costly for the individuals of *M. paraguayana* to move longer at FL than in the other areas. As we mentioned before, FL also exhibits the highest anthropogenic presence within our project, with cultivated areas near the study site frequented by workers operating machinery such as tractors for ploughing tasks. Additionally, there appears to be limited connectivity within the canopy of this area, which could explain the greater distances travelled. It is plausible that animals perceive increased risks and therefore seek points where crossings can be more easily accomplished (Xu et al., 2021; Rico et al., 2007). Contrary to our expectations, we did not detect differences in movement distance between dry and rainy seasons, suggesting that the availability of the food resource consumed by this species did not vary sufficiently to cause changes in the movement distance.

Conclusions

The fragmentation produced by the pipeline strip significantly restricts the movements of *M. paraguayana* between forest fragments. All the forest crosses occurred during the wet season, probably due to reproductive activities. Our results support the hypothesis that the pipeline strip also generates a negative edge effect for *M. paraguayana* populations. The distances of movements of this opossum seem to be affected by the topography of the area but are unaffected by the climatic season. If *M. paraguayana*, which is relatively tolerant to habitat loss and fragmentation, are impacted negatively by linear pipeline corridors, other Brazilian Atlantic Forest arboreal small mammals might experience similar or stronger barrier effects caused by these linear infrastructures. Therefore, the design and implementation of measures to mitigate the impact of gas and oil pipeline strips in forested areas should include specific considerations to improve arboreal small mammals' movements and gene flow, such as *M. paraguayana*. Canopy bridges have emerged as a promising solution to address the issue of connectivity for arboreal small and medium-sized mammals moving between forests fragmented by linear structures (Mitchell et al., 2022; Nekaris et al., 2020; Weston et al., 2011). These bridges are structures that span gaps between tree canopies, providing a safe passage for arboreal mammals to move across otherwise discontinuous habitats (Balbuena et al., 2019). Canopy bridges are constructed using various materials, including ropes, cables, and bridges made of wood or metal, and can be designed to mimic natural tree branches or vines to facilitate their use by arboreal mammals (Weston et al., 2011). *Marmosa paraguayana* and other arboreal and scansorial mammals could benefit from the installation of this type of structure by increasing the number of crosses between the fragments.

As mentioned, this study belongs to a bigger project of landscape connectivity, and it contemplates the construction of canopy bridges as a way to mitigate the impacts produced by the pipeline. After their construction, we will evaluate the effectiveness of these structures.

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Table 1. Number of captures and recaptures (Recaps) of *Marmosa paraguayana* in the Área de Proteção Ambiental da Bacia do Rio São João (APA) and in the Reserva Biológica União (REBIO União). M = males, F = females, ST = same side transect switching, TM = transect movement, PC = pipeline crossing, Total mov = Total movements.

Area	Sex	Captures	Recaps	ST	TM	PC	Total Mov
APA	M	15	17	7	7	1	15
	F	12	20	6	11	1	18
	Total	*27*	*37*	*13*	*18*	*2*	*33*
REBIO União	M	23	27	14	8	4	26
	F	22	49	24	20	2	46
	Total	*45*	*76*	*38*	*28*	*6*	*72*

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Figure 1. A. Corridor of open vegetation formed by pipeline right of ways. B. Long-furred woolly mouse opossum (Marmosa paraguayana) in Rio de Janeiro state, Southeastern Brazil.

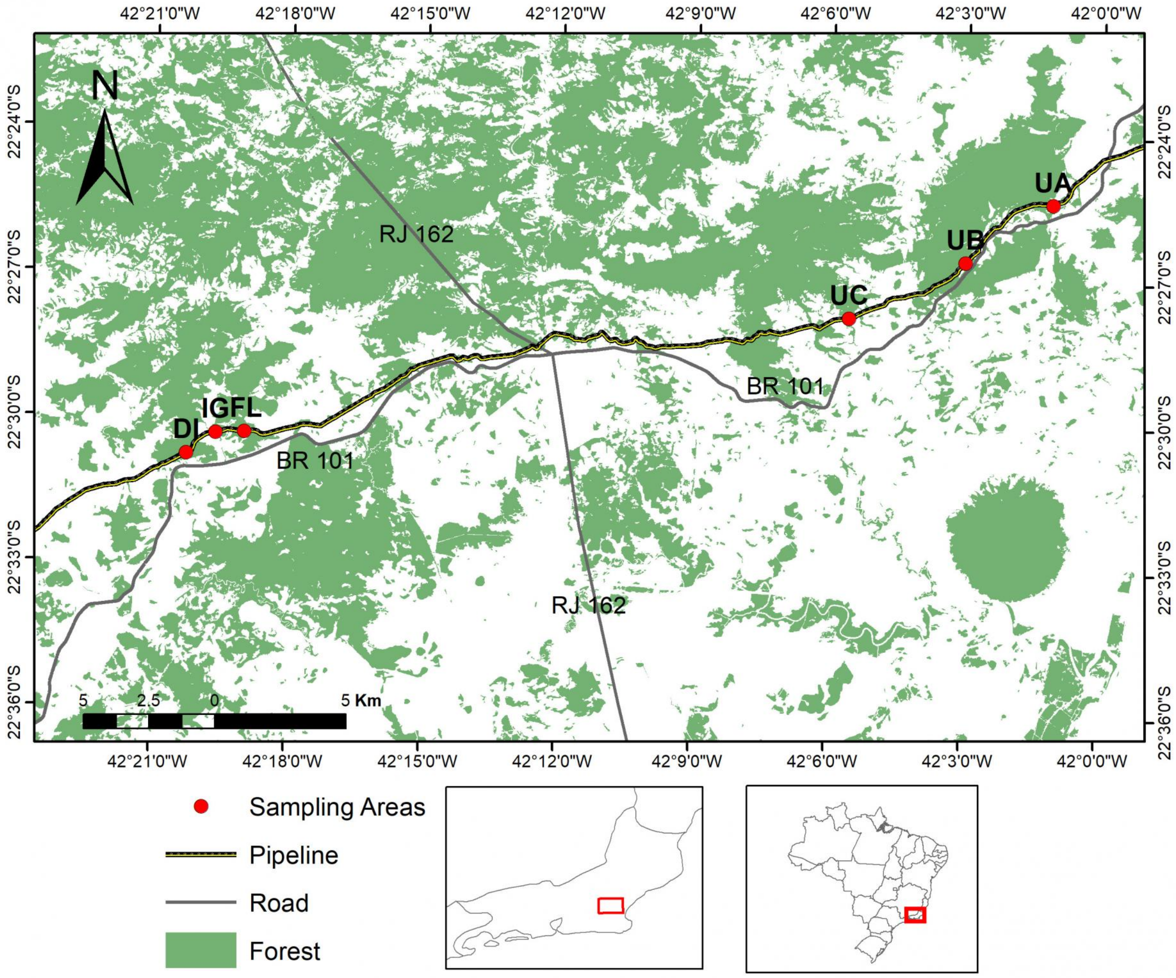

Figure 2. Sampling areas in the São João River Basin, Rio de Janeiro state, Southeastern Brazil. Areas UA, UB and UC are within the limits of the Reserva Biológica União (REBIO), while areas DI, IG and FL are within the Área de Proteção Ambiental da Bacia do Rio São João (APA).

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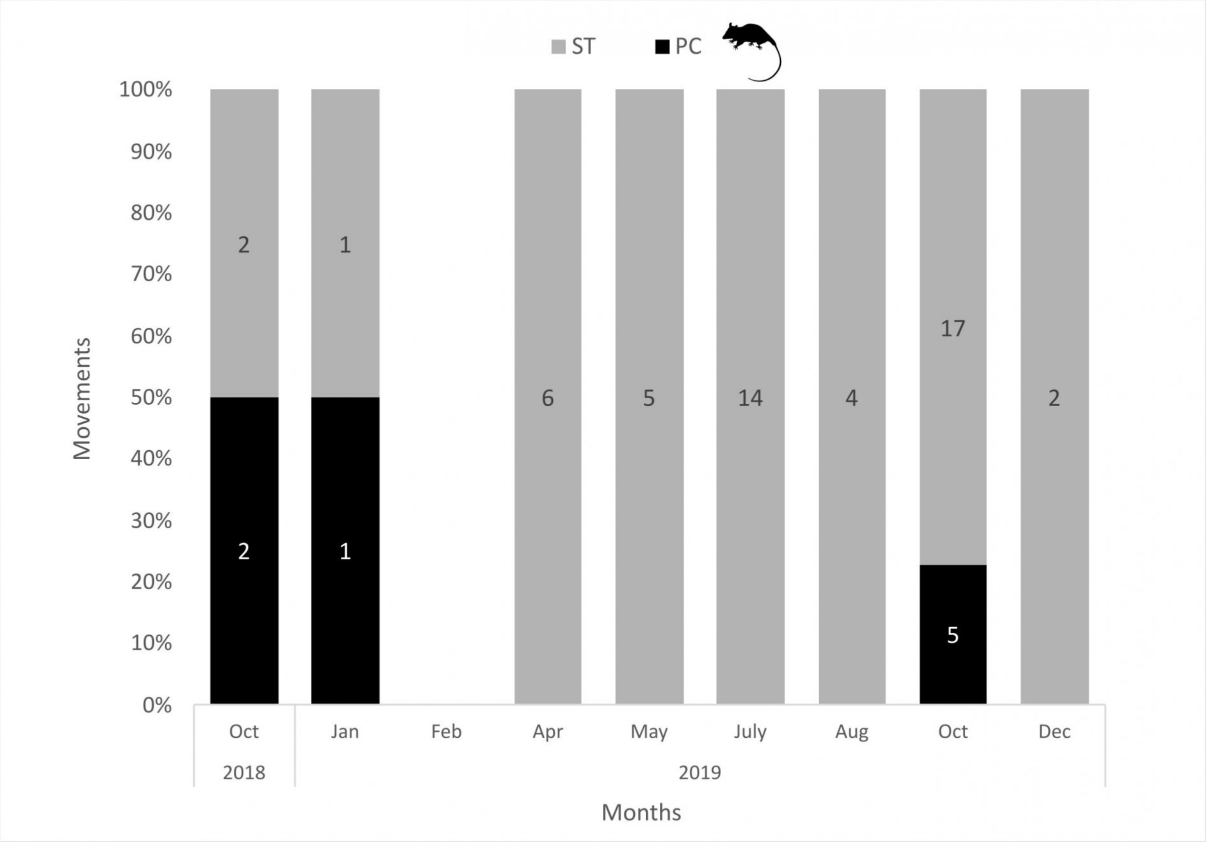

Figure 3. Percentage of crossing movements (ST: (forest strip crossing; PC: pipeline crossing) performed by Marmosa parguayana in each sampling month. Number of crossing events reported within bars.

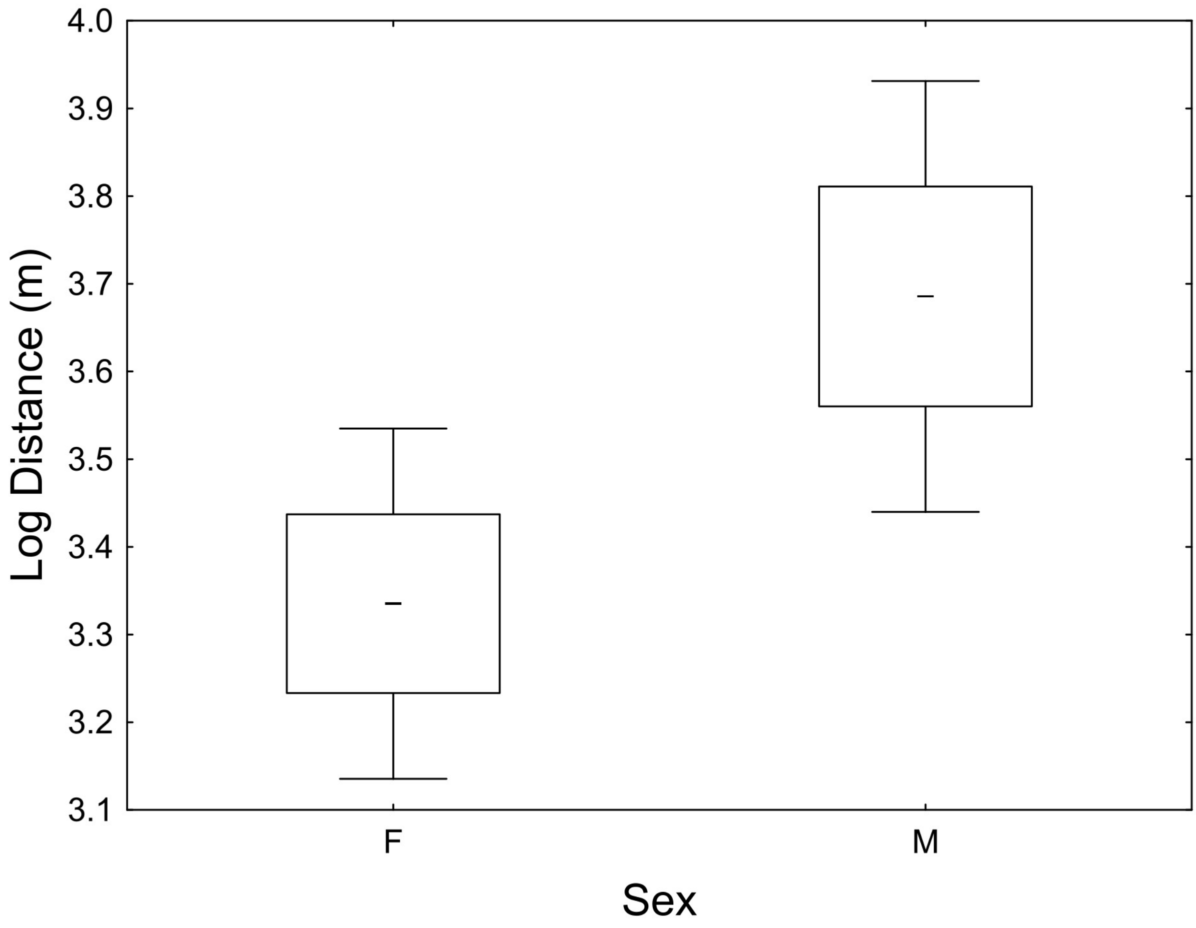

Figure 4. Variation of the distance travelled by males (M) and females (F) of M. paraguayana. The boxes represent the values of the mean and standard error of the logarithm of distances travelled by each sex. The line within the boxes is the mean of the logarithm of distances, and the whiskers are the mean ±1.96* the standard error.