A review of the application of canopy bridges in the conservation of primates and other arboreal animals across Brazil

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Abstract – Brazil is known as a high biodiversity country, but at the same time, it has an extensive road network that threatens its wildlife and ecosystems. The impacts of roads and railways on vertebrates have been documented extensively, and the discussion concerning the implementation of mitigation measures for terrestrial wildlife has increased in the last decade. Arboreal animals are especially affected by the direct loss of individuals due to animal-vehicle collisions and by the barrier effect, because most arboreal species, especially the strictly arboreal ones, avoid going down to the ground to move across the landscape. Here we summarize and review information on existing canopy bridges across Brazil, considering artificial and natural canopy bridge initiatives implemented mainly on road and railway projects. A total of 151 canopy bridges were identified across the country, 112 of which are human-made structures of different materials, while the remaining 39 are natural canopy bridges. We found canopy bridges in three of the six biomes, with higher numbers in the Atlantic Forest and Amazon, the most forested biomes. Most of the canopy bridges are in protected areas
(76%) and primates are the most common target taxa for canopy bridge implementation. Our study is the first biogeographic mapping and review of canopy bridges for arboreal wildlife conservation in a megadiverse country. We synthesize the available knowledge concerning canopy bridges in Brazil and highlight gaps that should be addressed by future research and monitoring projects.

**Keywords** – animal conservation, fragmentation, mammals, mitigation, road impacts, wildlife crossing structure.

**Introduction**

Highways are necessary for human displacement and social and economic development. However, at the same time, they are one of the main drivers of habitat fragmentation through the increase of urban and agricultural areas and exploitation of natural resources that result in new fragmented areas. Roads threaten ecosystems directly and indirectly by removing or disturbing natural vegetation, modifying water resources, soil and air quality, and consequently changing biological and geomorphological systems (Forman and Alexander, 1998; Laurance et al., 2009; Pinto et al., 2020).

For wildlife, roads and traffic can act as dispersal barriers, blocking access to resources and dividing populations (van der Ree et al., 2015). This is mainly due to road avoidance, which results in edge and barrier effects. On the other hand, animals that have the ability to cross highways have a high probability of being roadkilled. Roadkill is identified as the main human cause of direct mortality of many vertebrate species (Grilo et al., 2018), outpacing other natural pressures such as predation (Bujoczek et al., 2011) and anthropogenic impacts such as hunting (Laurance et al., 2008). Both barrier effects and road mortality can result in reduced population sizes and persistence (Jackson and Fahrig, 2011). Consequently, these impacts change the structure and dynamics of communities and ecosystems in the long term (Laurance et al., 2009; Taylor et al., 2011).

These impacts are especially dramatic for arboreal species that depend on canopy cover for displacement and foraging (Goosem, 2007; Taylor et al., 2011). Among arboreal taxa, there is variability in the level of arboreality, with some species never descending to the ground and others descending rarely or even regularly (Emmons and Feer, 1997; Soanes and van der Ree, 2015). Even those arboreal species that use the ground may stay close to trees to escape predation, if necessary (e.g., Martinez and Wallace, 2011). In this context, populations of strictly arboreal species tend to suffer from genetic isolation in fragmented habitats, further reducing their foraging areas for resource acquisition (Lancaster et al., 2016). When the main driver of fragmentation is a highway, the species that manage to descend to the ground and cross over it are still subject to being roadkilled, which can also lead to population isolation through the loss of genes from healthy individuals, in turn leading to reduced population abundance and persistence in the long term (Jackson and Fahrig, 2011). In other words, the highway becomes a problem both for strictly arboreal species and for those more tolerant to crossing open landscapes (Wilson et al., 2007; Laurance et al., 2009).

Mitigation measures aimed at reducing the impact of roads on animals can be divided into two categories, those related to (1) changing vehicle driver behavior and (2) changing animal behavior (Glista et al., 2009). The first category involves measures such as speed reducers (e.g., speed bumps and speed traps), warning signs (e.g., standard animal crossing signs and animal detection systems), among others. The second category includes exclusion measures, such as fences aiming to block animal access to roads, and the combination of fences with safe crossing locations that allow animals to cross at predetermined locations over or under the road. Safe crossing locations aim primarily to recover or to increase structural and functional connectivity and secondarily to reduce road mortality (Rytwinski et al., 2016, Abra et al., 2020). The most common mitigation measures to guarantee safe passage of arboreal animals are natural and artificial canopy bridges (Soanes and van der Ree, 2015). In specific contexts, canopy bridges can also be combined with...
fences specifically designed to prevent arboreal animals from accessing the road and potentially decreasing road mortality (Linden et al., 2020).

Brazil has one of the greatest diversities of arboreal animals in the world, with 205 arboreal and semi-arboreal mammal species, almost a third of all mammals that occur in the country (Paglia et al., 2012). At the same time, Brazil has an extensive road network of more than 1.5 million kilometers and is identified as a priority region for mitigating the impacts of linear infrastructure on biodiversity, especially for primates (Valladares-Padua et al., 1995; Ascensão et al., 2021). Many arboreal and semi-arboreal mammals are among the most road-killed species reported in road mortality studies in different Brazilian biomes, such as the Amazon (Turci and Bernarde, 2009; Omena-Junior et al., 2012; Costa, 2018; Caires et al., 2019; Medeiros, 2019), the Pantanal (De Souza et al., 2015) and the Atlantic Forest (Coelho et al., 2008; Ferreguetti et al., 2020; Abra et al., 2021; Franceschi et al., 2022). Among arboreal mammals, primates are a group constantly affected by road mortality, with more than 60 species known to suffer from collisions with vehicles only on Brazilian roads (Secco et al., 2018). Although there are few published studies focused on the impact of roads on arboreal species or on associated mitigation measures in Brazil, there were pioneering studies in Brazil on canopy bridges installed in the late 1990s and early 2000s (Valladares-Padua et al., 1995; Lokschin et al., 2007; Teixeira et al., 2013). In recent years, these types of structures have become a more popular mitigation measure and have been installed to provide safe crossing opportunities for arboreal animals in different parts of the country.

Based on the need to mitigate the impacts of roads on a high diversity of arboreal species in Brazil, our study aimed to map the existing canopy bridges in the country. We assessed which of these structures are monitored, with which types of infrastructure they are present, which species were recorded using them, and we discuss how these structures can be useful as a conservation tool for Neotropical arboreal species. We provide the first review on this topic in Brazil, and therefore, present evidence on canopy bridge initiatives that can support future mitigation and conservation projects.

**Methods**

We analyzed all available data on existing canopy bridges in Brazil, encompassing the six terrestrial biomes that are represented in the national territory: Amazon, Atlantic Forest, Cerrado, Caatinga, Pantanal, and the Pampas. To construct our database, we compiled canopy bridge records (including geographic coordinates) from publications found in Web of Science, Google Scholar, Scielo, and Scopus (using ‘canopy bridge’ as a keyword in English and Portuguese). In addition, we included information provided by canopy bridge researchers, including co-authors of this study and their colleagues and monitoring projects available online that include methods and data from animal-crossing structures.

For each canopy bridge, we collected the following information, when available: location of bridges (geographic coordinates, city/state, inside/outside a protected area), date of installation, type of monitoring of the structures (e.g., camera traps, sand traps, or direct observation, including sporadic records from citizen scientists), and species recorded using the bridges. We also collected photographic records of canopy bridges when possible to better describe the design of each structure.

**Results**

We obtained records of a total of 151 existing canopy bridges across Brazil (fig. 1, supplementary table S1), distributed over three of the six biomes (fig. 2). We identified canopy bridges installed in 15 states, with many more canopy bridge initiatives in the Atlantic Forest and in the Amazon than in the Cerrado (Figure 3). From the total number of canopy
bridges identified, 74.17% (n = 112) are artificial structures and 25.82% (n = 39) are natural canopy bridges, where the treetops naturally touch and were managed to be maintained, offering structural and functional connectivity for arboreal species. The design of the artificial bridges varied considerably, with more than eight different types (figs 4 and 5). Overall, 22 distinct taxa were confirmed using 69 of the canopy bridges in Brazil (fig. 6): 13 from the Order Primates, 5 from the Order Didelphimorphia, three from the Order Rodentia, and one from the Order Pilosa. Of the 22 species confirmed to use canopy bridges, six are nationally (MMA, 2022) and globally (IUCN 2020) endangered: the critically endangered pied tamarin (Saguinus bicolor), the endangered blonde capuchin (Sapajus flavius), black lion tamarin (Leontopithecus chrysopygus), and golden lion tamarin (Leontopithecus rosalia).
and the vulnerable southern brown howler monkey (*Alouatta guariba clamitans*) and maned three-toed sloth (*Bradypus torquatus*). Most of these threatened species are present in the Atlantic Forest, where a large proportion of bridges are installed. Most canopy bridges are located on roads inside protected areas (fig. 7).

**ATLANTIC FOREST BRIDGES**

In the Atlantic Forest of Southern Brazil, the Urban Monkeys Program (PMU/UFRGS) has been installing and monitoring rope canopy bridges since the early 2000s (Lokschin *et al.*, 2007; Teixeira *et al.*, 2013), targeting the brown howler monkeys (*Alouatta guariba clamitans*) surrounding the Lami Biological Reserve. The rope canopy bridges were installed to prevent injuries that impact local brown howler monkey populations, caused by electrocution, roadkill, and dog attacks (Printes, 1999; Lokschin *et al.*, 2007; Chaves *et al.*, 2022). The canopy bridges have been monitored with camera traps and with the support of the local community that recorded opportunistic sightings of animals crossing. These bridges have been shown to be used not only by howler monkeys, but also by other species such as the white-eared opossum (*Didelphis albiventris*) and the hairy dwarf porcupine (*Coendou spinosus*) (Teixeira *et al.*, 2013). Following this same canopy bridge design, other rope bridges were installed close to other protected areas and native vegetation remnants throughout the country with howler monkeys and other primates (e.g., Monticelli *et al.*, 2022). Currently, the Urban Monkeys...
Program team continues to monitor 10 existing canopy bridges and is testing different designs of canopy bridges both *ex situ* and *in situ*.

Highway BR-101 in Rio de Janeiro State provides an example of the bridges in the Atlantic Forest used by a species of conservation concern: golden lion tamarins (*Leontopithecus rosalia*), globally classified as ‘endangered’. Six of these bridges are similar to pedestrian passages, containing concrete support bases and a metallic structure over the road (fig. 6A), while the other four are formed by blocks of smooth concrete, forming a structure similar to a viaduct. Both of these bridge types are tunnel-like, with sides and overhead coverage to avoid exposing the tamarins to avian predators and to prevent the animals from falling off the structure while crossing it. Inside the tunnel formed by the canopy bridge structure, there are ropes intertwined and tied to the roof of the structure to facilitate different forms of arboreal locomotion. At both bridge ends, there are also ropes that connect the base of the structure to the nearest tree canopy. All 10 bridges are within the territory of the São João/Mico-Leão-Dourado River Basin Protected Area, and eight of them...
A review of canopy bridges in Brazil

Figure 6. Number of existing canopy bridges with confirmed use by each taxon in Brazil. Detailed information about the type of canopy bridges used by each species is described in supplementary table S1.

Figure 7. Proportion of A) species using canopy bridge according to extinction threat category (International Union for the Conservation of Nature) and (B) canopy bridges found inside vs. outside protected areas.
have been monitored with camera traps since the second half of 2021. Crossings of different species of arboreal mammals have been confirmed, including the endangered golden lion tamarins, which is a target species of this mitigation project, and the maned three-toed sloth (*Bradypus torquatus*), a species vulnerable to extinction at global and national levels.

Another example in São Paulo State provides a solution for black lion tamarins (*Leontopithecus chrysopygus*), also globally classified as ‘endangered’, in the first study that compared different canopy bridge designs in Brazil. Crossings were monitored and compared between a wood pole bridge and a rope bridge. Six mammal species were shown to use the rope bridges, while seven mammal species and a lizard species used the wood pole bridge (García *et al.*, 2022).

The first mitigation project targeting anurans for Brazil was implemented in the Atlantic Forest (Zank *et al.*, 2019). In 2021, five fixed, large metal canopy bridges were installed over a road that crosses the Mata Paludosa Biological Reserve in Rio Grande do Sul, a location with high amphibian diversity, including four endangered species. The structures were installed at locations with high mortality rates of arboreal anurans, and the extremities of these canopy bridges are expected to be colonized by vegetation that is expected to attract tree frogs and then increase canopy connectivity over the road. Road mortality of anurans is being monitored in a before-after-control-impact design and a monitoring of bridge use with camera traps is being planned.

**AMAZON BRIDGES**

In the Brazilian Amazon there are 49 canopy bridges in the states of Amazonas (AM) and Roraima (RR). Thirty-nine (79.59%) are located in Amazonas and 10 (20.41%) in Roraima. A total of 10 (20.41%) are artificial and 39 (79.59%) are natural bridges formed by trees that were preserved during road maintenance to allow connectivity over the road. It is noteworthy that 73.47% (*n* = 36) of the natural canopy bridges (i.e., those formed by tree branches) in the Amazon are located on Highway BR-174 inside the Waimiri-Atroari Indigenous Territory (TIWA), some of which are already being used by primate species in the region, such as the black-capped capuchin (*Sapajus apella*), the guianan squirrel monkey (*Saimiri sciureus*), and the golden-handed tamarin (*Saguinus midas*). These natural canopy bridges resulted from a long-term project started in 2005 by one of the coauthors of this review (M. Gordo) and the indigenous community through the Waimiri Atroari Environmental Program. In this study, we defined natural canopy bridges as locations where tree branches either touch or nearly touch over the top of the road, with the understanding that only saltatory species, including most Neotropical monkeys, can cross where branches are not in full contact. On Highway BR-174, the local community worked with the highway maintenance company to avoid trimming of key branches, allowing them to grow and reconnect over the road. Now, there are several places where not only do the branches connect but tunnels of canopy connectivity have been restored over the road.

Among the most used artificial canopy bridges in the Amazon is one built only with braided stainless-steel cables supported by concrete posts (M. Gordo, pers. obs.). This bridge connects the trees at the edges of a forest fragment at the Federal University of Amazonas (UFAM) campus via lianas and has already been used by three primate species (e.g., the pied tamarin *Saguinus bicolor*, the golden-faced saki *Pithecia chrysocephala*, and the guianan squirrel monkey *Saimiri sciureus*), as well as by kinkajous (*Potos flavus*). In the same area, another artificial canopy bridge that was built with galvanized welded mesh and stainless-steel cables connected to a tree on one side and to a wooden pole on the other side has been used by *S. bicolor* and *S. sciureus*. Interestingly, the entrance portal structure of the UFAM campus, made of concrete and metal, has also been used by *S. bicolor* and has recently been better connected to the surrounding vegetation through steel cables and galvanized welded mesh. Another artificial canopy bridge type more recently built on the same campus uses a...
fire hose cable to connect trees on opposite sides of the street and is supported by a wooden pole on one side, but by the time of publication, no records were made of wildlife using it.

Outside the UFAM campus, in the Ponta Negra neighborhood of Manaus, there are two ladder-like fauna passages made of nylon rope, which are used by *S. bicolor* and *P. chryscephala* (confirmed by opportunistic observations), but these bridges have structural problems, as they strangle the trunks of the trees to which they are anchored and do not comply with the legislation regarding the minimum bridge height of 5.5 meters (they are ∼4 m from the street below).

Three other canopy bridges were built with steel cables, ropes, and wooden steps, supported on concrete posts on both sides and connected to the forest. These were designed by a partnership between one of the authors of this article (M. Gordo) and the Manaus Refinery (REMAN), owned by PETROBRAS Company. This was an initiative that installed the bridges in 2011 along the REMAN access road, and since then, they have been used by several *S. bicolor* groups, a species that had been roadkilled on this road in the past.

Discussion

The impacts caused by roads on wildlife are seldom considered and not properly mitigated along transportation networks (Rosa *et al.*, 2020). However, the financial costs of mitigation measures can be offset by the long-term return on investment via reduced accidents, which benefits both people and wildlife, maintaining biodiversity and ecosystem services (Balbuena *et al.*, 2019; Rosa *et al.*, 2020). Many arboreal and semi-arboreal animals benefit from the existence of canopy bridges, but species with small populations and/or species threatened with extinction, such as *S. bicolor* and *Leontopithecus* spp., are still the most affected by vehicle collisions, significantly increasing the probability of local extinctions (Gordo, 2012; Campos *et al.*, 2017; Lucas *et al.*, 2019). In the case of these endangered species, canopy bridges have been used successfully and have the potential of promoting long-term population persistence, which must be assessed with long-term monitoring.

Our review demonstrates that Brazil has a large number of canopy bridge projects. Along with other countries such as Australia (Weston *et al.*, 2011; Goldingay *et al.*, 2013; Soanes *et al.*, 2013) and Costa Rica (Azofeifa and Gregory, 2022; Flatt *et al.*, 2022), Brazil is taking the lead in the implementation of mitigation measures for arboreal animals. In general, a large number of the canopy bridges span two-lane roads with low traffic volume and are composed of low-cost materials. However, it is interesting to note that more substantial canopy bridges made of concrete and metal and installed on high-traffic roads were built in places where there are endangered species, such as the ones on Highway BR-101, Rio de Janeiro State and the ones on the Highway BA-099 in Bahia State, both in the Atlantic Forest. Mammals tend to be the main target group for canopy bridge projects, however, there are new initiatives in the Atlantic Forest focused on other taxa such as amphibians, with new bridges recently installed on RS-486 in Rio Grande do Sul State in the Mata Paludosa Biological Reserve being an example (Zank *et al.*, 2019).

A significant number of canopy bridges have been installed by community groups, researchers, and conservation NGOs, such as the examples mentioned from the two geographic extremes of the country, Rio Grande do Sul (Lokschin *et al.*, 2007; Teixeira *et al.*, 2013) and Amazonas/Roraima. Although these are seminal projects in Brazil, of critical importance both locally and by influencing similar initiatives, canopy bridges are yet to be upscaled and mainstreamed in road mitigation plans. Government initiatives, such as the canopy bridges built in the Northeast by the National Center of Research and Conservation of Brazilian Primates (CPB-ICMBio), are extremely important, but they are not yet part of federal public policy within the necessary ministries, such as the Ministries of Environment and Infrastructure. Large roads continue to lack mitigation measures to reduce collisions with fauna and to restore connectivity. For example, the BR-319 cuts through a long stretch of the Amazon, has

Vol. 93(3-6), 2022
been under scrutiny for major environmental impacts and has only recently added wildlife crossings under pressure from the Federal Public Ministry (Andrade et al., 2021). The same lack of public policies extends to most state governments and municipalities.

In the Brazilian Amazon, canopy bridges are found in two distinct contexts related to different biodiversity pressures and needs. In the urban perimeter of Manaus, the implementation of bridges was strongly motivated by a drive to mitigate roadkills of the pied tamarin (Saginus bicolor) (Gordo et al., 2013; Gordo et al., 2017; Secco et al., 2018), classified as Critically Endangered by the Brazilian Red List of Threatened Species (Vidal et al., 2018) and by the IUCN Red List (Gordo et al., 2019). However, there is still strong resistance from companies to comply with requirements made by environmental licensing agencies, which often require the installation of canopy bridges as a mitigation measure to reduce impacts. The urban context in Manaus includes an array of small roads that require simple bridge designs to multi-lane freeways that involve complex bridge installation programs (Coelho et al., 2018). For this reason, we feel that bridges that are as simple in terms of design, access to materials, construction, financial costs, safety, and landscape-level evaluations to ensure long-term connectivity are critical for new initiatives.

The second canopy bridge project context in the Amazon involves the community-based establishment of canopy bridges along Highway BR-174, in the Waimiri Atroari Indigenous Territory. This is a great example of how an indigenous community was able to achieve a conservation solution through managed cutting of vegetation by road maintenance companies, despite some resistance from truck drivers. This initiative occurred in partnership with the Federal University of Amazonas, in negotiation with the Federal Transportation Agency (DNIT) and was aimed to enable connectivity for arboREAL animals over long road stretches at very low cost via natural bridges. Since the paving of this road in 1993, indigenous people have been troubled by high roadkill rates in their territory on BR-174 (Costa, 2018; Medeiros, 2019). Natural canopy bridges have been shown to be preferred by arboreal species to crossing on the ground (Gregory et al., 2017), however, studies are still needed to assess the effectiveness of these bridges in reducing the impact of roadkill on the target species. Taking advantage of the indigenous initiative, for the same stretch within the indigenous land, a new project in partnership with the Center of Conservation and Sustainability of the Smithsonian Institution (Washington, DC, USA) aims to install 30 artificial canopy bridges of two designs atop concrete posts and also to monitor natural bridges. This initiative is being implemented in 2022 and has the potential to bring relevant information to drive the installation of canopy bridges in other regions of the Amazon.

There is great difficulty in measuring the barrier effect of roads and railways on arboreal species, especially primates and other strictly arboreal species that use very high forest canopies (e.g., spider monkeys (Ateles spp.), Aureli et al., 2022). As these animals are rarely recorded being roadkilled on highways/railways, both public opinion and environmental and transport agencies do not see the need to install mitigation such as canopy bridges. However, the absence of roadkill records cannot be interpreted as evidence of low impact on wildlife, as it may mask past massive mortality or strong barrier effects due to the inability or reluctance of individuals to cross roads (Ascensão et al., 2019). Mitigation measures for these species are highly necessary, as 65% of primate species globally are threatened with extinction, mainly by habitat loss and fragmentation, largely caused by linear infrastructure (Ascensão, 2021).

Knowledge of canopy bridge design is increasing, but there is still a lack of knowledge regarding the best designs for different target species. In our review, we aimed to synthesize the available knowledge concerning canopy bridges in Brazil. We were able to gather information on which species were recorded using the canopy bridges only for a few projects, as most projects do not monitor the bridges or this information was not accessible. Moreover, there
may be canopy bridge projects that our literature review did not detect or that were not known by the authors, and therefore, not included in our manuscript. There are also bridges that are in the process of being implemented. Our review shows that canopy bridges are being used for a large set of arboreal species in different biomes throughout Brazil. However, as only a few canopy bridge projects encompassed systematic monitoring, there is still much to learn. There is a demand for more research on canopy bridge effectiveness, and quantitative comparisons based on robust study designs are urgently needed.

Conclusions

The implementation of canopy bridges has been a strategy to promote structural and functional connectivity of habitats and reduce road mortality of arboreal species, and these initiatives have been substantially growing in Brazil in recent years. Currently, Brazil faces some challenges such as implementing long-term monitoring with robust study designs to assess the use of the structures by different species and the suitability of different bridge designs for distinct locomotion types. While wildlife underpasses and fences are being widely discussed and implemented in road and railway projects across Brazil, initiatives to scale up the deployment of canopy bridges to benefit arboreal species, especially endangered arboreal primates, are still incipient in this megadiverse country.

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Author contributions

LGS and HS framed the overall scope for the manuscript analyzed the first version of the dataset and wrote the first article draft. FZT led the revisions, reanalyzed the final dataset, and reworked the final version of the manuscript. All authors contributed with field data sourcing, writing specific sections of the text, and revisions.

Supplementary material

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A review of canopy bridges in Brazil


