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Research Letters

Immediate impact of fires on roadkilling of wild vertebrates on a highway in southeast Brazil

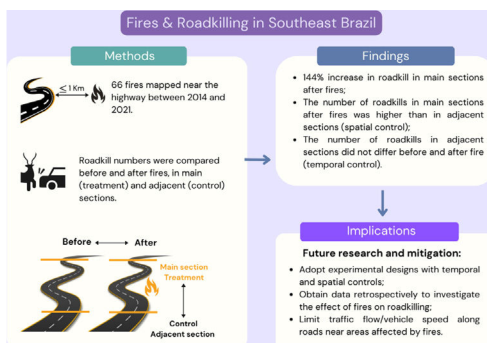
Cláudio Lacet[a], Natalie Olifiers[a,b,*], Cecília Bueno[a,b,c]

[a] Mestrado Profissional em Ciências do Meio Ambiente, Universidade Veiga de Almeida, CampusTijuca, R. Ibituruna, 108 - Maracanã, Rio de Janeiro, RJ, 20271-020, Brazil
[b] Núcleo de Estudos de Vertebrados Silvestres – NEVS, Universidade Veiga de Almeida, Campus Tijuca; R. Ibituruna, 108 - Maracanã, Rio de Janeiro, RJ, 20271-020, Brazil
[c] Departamento de Vertebrados Museu Nacional / Universidade Federal do Rio de Janeiro (MN/UFRJ) Quinta da Boa Vista s/n, São Cristovão, Rio de Janeiro, RJ CEP 20940-040

HIGHLIGHTS

- Wild vertebrate roadkills increased by about 144% after fires along the highway.
- Roadkills in sections affected by fires were higher than on neighboring sections.
- An experimental design with temporal and spatial controls should be adopted.
- Fires must be considered when formulating measures to mitigate wild vertebrate roadkilling.

GRAPHICAL ABSTRACT



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ABSTRACT

Fires cause wild vertebrates to try to escape, thereby leading to an increase in attempts to cross roads and consequently an increase in the number of roadkills. However, the study of the impact of fires on roadkilling of wild vertebrates is practically nonexistent. In this study, we analyzed the relationship between fires near a 180 km highway stretch in Southeast Brazil and wild vertebrate roadkills using a 7-year dataset on roadkills and satellite data on fires, hypothesizing that roadkills would increase after fires. We found that the number of roadkilled wild vertebrates increased by about 144% (P = 0.020) in highway sections up to 1 km from fires, within 7–8 days after the fires. The number of roadkills in highway sections affected by fires was also higher than that of neighboring (control) section (P = 0.028). Taken together, these results show there was a significant increase in the number of roadkills on road sections close to or within burned areas. This work emphasizes the importance of analyzing the synergistic effects of fires and roadkill of wild vertebrates and guides research on adopting an experimental design which allows for temporal and spatial controls using retrospective data on fires and roadkilling. We recommend decreasing traffic flow and/or vehicle speed near areas recently affected by fires, as a preventive management strategy.

* Corresponding author.
E-mail addresses: claudio.lac@gmail.com (C. Lacet), natolifiers@gmail.com (N. Olifiers), cecilia.bueno@uva.br (C. Bueno).

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Introduction

Roads are amongst the most visible, direct anthropic activity impacting natural systems. It is estimated that road length will increase to 4.7 million km by 2050 in the world, an increase of 14%–23% compared to current estimates, and much of this increase will happen in countries with high biodiversity and important natural ecosystems (Meijer et al., 2018). Brazil, for instance, has more than 1.7 million km of roads responsible for 56% of national transport, and the fourth largest road network in the world (CNT, 2021). The country's Southeast region has the largest road network, as well as the greatest number of vehicles (approximately 53,400,000) (IBGE, 2022). The nation's road network is expected to increase by 10% by 2050 (Meijer et al., 2018).

Roads cause several negative impacts on the environment and biodiversity (for a review, see Bennett, 2017). The most obvious direct and immediate impact of roads on vertebrate biodiversity is through wild animal collision with vehicles. In Brazil, it is estimated that 475 million wild vertebrates are killed by vehicles every year (CBEE, 2015), although estimates vary substantially (e.g., for mammals, Pinto et al., 2022; González-Suárez et al., 2018) and may be underestimated (Slater, 2002; Teixeira et al., 2013) .

Another factor that significantly impacts wild animals is fire. Fires can occur naturally due to lightning strikes and it is an important process in certain ecosystems, such as in the Cerrado biome (Mistry, 1998; Fidelis and Pivello, 2011); however, the frequency and magnitude of fires caused by human activities are increasing worldwide, thereby negatively impacting native ecosystems (Keeley and Pausas, 2019; Kelly et al., 2020), and this can also be observed in Brazil (Pivello et al., 2021). Brazil is the country with the highest frequency of fires in South America (Li et al., 2020). Between 1985 and 2020, 19.6% of the Brazilian territory had been directly affected by fires at least once (Mapbiomas, 2021). Whether intentional or accidental, fires are responsible for the death of many wild animals every year. In 2020, for instance, an estimated 17 million animals died in the Pantanal biome due to fires (Tomas et al., 2021).

Considering the negative impacts that both fires and road networks can have on biodiversity, an aspect that has practically not been investigated is the synergistic effects of these factors on wildlife. Apart from the fact that roads are places where fires can start more frequently (Ricotta et al., 2018), an immediate effect of fires on wildlife might be the killing of animals due to collision with vehicles on roads running through or near areas affected by fires. Fires trigger a range of movements, both within, away from, and towards the burned (or burning) area (Nimmo et al., 2019). While small terrestrial animals may not be able to flee in response to fires, instead finding refuge underground or elsewhere locally (Ford et al., 1999; Engstrom, 2010) or dying *in situ*, larger animals and volant species are able to escape more easily by moving farther away from the fire site (Singer and Schullery, 1989; Engstrom, 2010; Silveira et al., 1999). However, in escaping from fires and moving more, animals may be more frequently killed while crossing roads, thereby leading to an increase in the number of roadkills during and soon after fires, particularly if fire severity is not high enough to cause large animal mortality (Jolly et al., 2022). Even when the fire is over, behavioral changes in animal movement may cause animals to move more frequently. For instance, bison and other grazers are attracted to burned areas (Shaw and Carter, 1990). Likewise, salamanders on burned areas move more, probably to find better habitats (O'Donnell et al., 2016), and some predators are attracted to burned areas due to increased detection of prey in the recently formed open areas (McGregor et al., 2015; Leahy et al., 2016; Doherty et al., 2022). In sum, while fire causes an immediate increase in species movement, roadkilling is expected to increase during and shortly after fires, at least when fires are not of high intensity. However, to the best of our knowledge, only four studies have been published reporting the effect of fires on roadkills (Coombs, 2015; Vujović et al., 2015; Bernardo, 2021; Cruz et al., 2021). Three of these found an increase in roadkilling of avian and mammal* species (Cruz et al., 2021; *marginally significant) and small reptiles (Coombs, 2015; Vujović et al., 2015) due to fires, while the fourth one found a decrease in roadkills except for some species of mammals (Bernardo, 2021).

In this study, we investigated whether there is a relationship between fires and the number of roadkilled wild vertebrates on a highway in Southeast Brazil. We hypothesized that there would be an immediate increase in roadkills during and after nearby fires.

Material and methods

Study area

The study was performed on a 180.4 km stretch of the BR-040 highway (Fig. 1) that passes through nine municipalities, from Juiz de Fora – MG (21°41’20S̈; 43° 20’40Ẅ) to Rio de Janeiro - RJ (21°41’20S̈; 43°20’40Ẅ) in the Atlantic Forest biome. The highway has double (2–7) lanes of concrete or asphalt, with altitude varying between 25 m and 1000 m. At a 20Km stretch on Serra do Mar, it splits into two separate lanes that passes through three Conservation Units (Fig. 1). The highway stretch has been managed by concession to a private company (CONCER) since 1996. In 2021, more than 37 thousand vehicles passed over this highway stretch per day (CONCER, 2021).

Data collection and analysis

Data on roadkills were collected by employees of CONCER and provided to the project "Caminhos da Fauna". The survey was carried out by car several times every day (day and night) by trained employees, who were also performing other duties during the survey. However, a biologist assisted in the monitoring from 7 a.m. to 5 p.m. on weekdays.

Information on species, roadkill dates and locations were recorded. Exotic (but not domestic) species were considered in the analysis. Data collection was performed under SISBIO license number: 30727−9, operation license number 1187/2013 and authorization for capture, collection and transport of biological material - Abio (1st Renewal and 3rd Rectification) number 514/2014.

Fire data were obtained from the website of the National Institute for Space Research (INPE; https://queimadas.dgi.inpe.br/queimadas/bdqueimadas#exportar-dados) in shapefile format. The Aqua satellite (Source link: http://www.dgi.inpe.br/documentacao/satelites/aqua; resolution 500–1000 m) was used to obtain fire records from October 1, 2014 to September 30, 2021. We considered only fires within 1 km from the highway. To investigate whether the fires influenced the number of roadkilled wild vertebrates, we employed a paired before–after control-impact (BACIP) design, in which we added the roadkills in the 7 days prior to each fire and compared it to the number of roadkills in the 7 days after the fire in the affected (main) section of the highway. The same procedure was repeated for the two neighboring sections of equal length, from which one was selected randomly as control for comparison with the paired main section. We hypothesized that the main section, that is, the one closer to the fire (or directly affected by it) would show an increase in roadkills after the fire, while the neighboring section (control) would maintain the same rates of roadkills before and after the fires, functioning in this case as temporal controls. Since the data were not normally distributed, we performed aligned rank transformation (Wobbrock

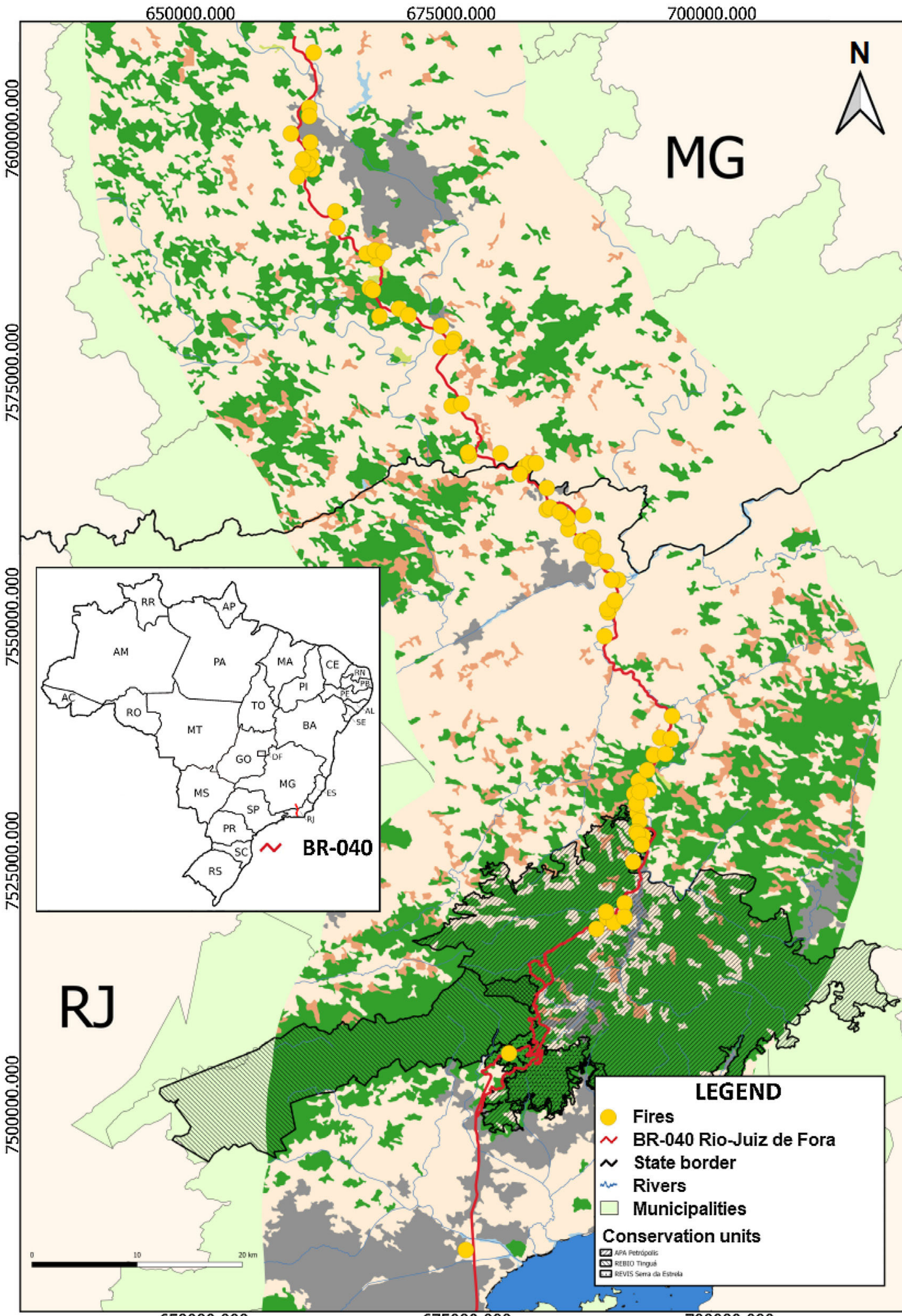

Fig. 1. The stretch of highway BR-040 analyzed between 2014 and 2021, showing fire events near (≤ 1Km) the highway.

et al., 2011) followed by two-way repeated measures ANOVA to investigate whether there was an interaction between before-after and control-treatment, which is the main statistic of interest in a BACI analysis and would be significant when a change occurs at the impact site but not at the control site (Smokorowski and Randall, 2017). The Wilcoxon rank test was then performed using the original data; for all comparisons, $\alpha = 0.05$. Finally, we calculated the effect size for roadkills in the before-after fire comparisons in the main sections applying the matched-pairs rank biserial correlation coefficient (*rc*) using the Wilcoxon rank test output,

Table 1
Wild vertebrate species roadkilled before and after fires in the study area, between October 2014 and September 2021.

Taxon	Species	Common name	Before fires	After fires
Mammals	*Cerdocyon thous*	Crab-eating Fox	3	1
	Coendou spinosus	Paraguaian Hairy Dwarf Porcupine	2	6
	Didelphis aurita	Brazilian Common Opossum	1	3
	Hydrochoerus hydrochaeris	Capybara	1	2
	Mus musculus	House Mouse	1	0
	Myotis sp.	Bat	0	1
	Rattus norvegicus	Brown Rat	0	1
Reptiles	*Crotalus durissus*	Cascabel Rattlesnake	0	1
	Ophiodes sp.	Fragile Worm Lizard	1	3
	Oxyrhopus clathratus	Duméril's False Coral Snake	0	1
	Philodryas patagoniensis	Patagonia Green Racer	0	1
	Salvator merianae	Black-and-White Tegu	1	0
	Sibynomorphus neuwiedi	Neuwied's Tree Snake	0	1
Amphibian	*Rhinella icterica*	Yellow Cururu Toad	0	2
Aves	*Caracara plancus*	Carcara	1	0
	Chiroxiphia caudata	Swallow-tailed Manakin	1	0
	Colaptes campestris	Campo Flicker	1	0
	Coragyps atratus	Black Vulture	0	3
	Crotophaga ani	Smooth-billed Ani	1	3
	Guira guira	Guira Cuckoo	0	1
	Leptotila verreauxi	White-tipped Dove	0	1
	Lophornis magnificus	Frilled Coquette	0	1
	Megascops choliba	Tropical Screech Owl	0	1
	Nyctidromus albicollis	Pauraque	0	1
	Nystalus chacuru	White-eared Puffbird	0	1
	Patagioenas picazuro	Picazuro Pigeon	0	3
	Phaethornis pretrei	Planalto Hermit	1	0
	Rupornis magnirostris	Roadside Hawk	0	1
	Tersina viridis	Swallow Tanager	0	2
	Turdus leucomelas	Pale-breasted Thrush	1	0
	Tyrannus melancholicus	Tropical Kingbird	1	0
	Vanellus chilensis	Southern Lapwing	0	1

as suggested by Kerby (2014). Since fires varied in extent, road sections analyzed ranged from 2 km to 6 km, but most of them were 1 km long.

Most of the fires detected up to 1 km from the highway lasted one day (98.5%), but in cases in which the fire lasted more than a day, an additional day was counted in the analysis. Since we performed statistical tests for dependent samples (paired tests), variations in highway length or time interval did not bias the analyses because the tests are based on differences between groups within dependent sample units.

Results

There were 66 fires recorded between 2014 and 2021 along the analyzed highway stretch. The intensity of roadkills in the entire study area was 0.018 roadkills/km/day (8,318 roadkills in 2,557 days; Table 1). There was a significant interaction between before-after and treatment-control sections (F = 5.232; df = 1; p = 0.025), but no main effects of before-after (F = 0.771; df = 1; P = 0.383) or treatment-control (F = 0.612; df = 1; P = 0.437). The Wilcoxon rank test showed a significant increase in the number of roadkills after the fires in the (main) affected highway sections in comparison with before the fires (Z= −2.33; N = 66; P = 0.020), with an effect size of *rc* = 0.53. There were 17 roadkills recorded up to 7 days before the fires in the affected sections (Table 1), which corresponds to an intensity of 0.016 roadkills/km/day. The total number of roadkills in the 7 days after the fires was 42 (Table 1), which represents an intensity of 0.039 roadkills/km/day, 2.44 times or 144% higher than that before the fires and 2.17 times, or 117% higher than the roadkills over the entire highway stretch analyzed.

In addition, there was also an increase in the number of roadkills on the affected sections in comparison with paired, neighboring (control) sections after the fires (Z = −2.204; N = 66; P = 0.028). Taken together, these results show there was a significant increase in the number of roadkills after fires only in the main sections of the highway, that is, those closer to the fires or directly affected by them.

Discussion

Since both fires and roadkilling are processes responsible for a significant number of wild animal deaths worldwide, it is essential to investigate how these two processes can act together to increase the number of vertebrate deaths, particularly in megadiverse countries with high projected road construction, such as Brazil. In this context, this is one of a very few studies that has investigated the synergistic effect of fires and roadkilling of wild vertebrates. We found an increase of 144% in roadkills in highway sections affected by fires, which we consider an intermediate to high effect size (*rc* = 0.53) that should not be disregarded. We believe this pattern of roadkill increase due to fires is common, at least for fires of relatively small magnitude and duration, but it is underestimated due to the lack of studies.

The very few studies on the effect of fire on roadkilling have reported contrasting results depending on the taxonomic group, which is probably explained by the distinct species ability to escape fires as well as fire intensity. For instance, in the study of Cruz et al. (2021) carried out in Mira (Portugal), they found an increase of around 54% in roadkills after fires, with higher mortality of avian and mammal* species (*marginally significant). They argued that this was probably because most species of these taxa move more rapidly and farther away while looking for refuge and food during/after fires. Reptiles and amphibians, in turn, showed lower numbers of roadkills after the fires, probably because most of them died burned or asphyxiated before reaching roads (Cruz et al., 2021). In South Africa, in turn, 32 lizards (*Chamaesaura anguina*) were roadkilled after a fire, although the species is rarely found dead along roadways in other situations (Coombs, 2015). The author argued that this species moves relatively fast and was therefore able to escape the fire (Coombs, 2015), which apparently was not of high magnitude. In a study carried out in Montenegro, there was a considerable increase in deaths of Hermann's tortoises (*Testudo hermanni*), both burned and roadkilled, after a large fire nearby a road (Vujović et al., 2015). Finally, in a study with mammals on highway BR-163, Mato Grosso state, Brazil, there was an overall reduction in roadkills after fires, except for capybaras (*Hydrochoerus hydrochaeris*) and other semiaquatic mammals, which were subject to an increase in roadkills up to 6 months after the fires. The author argued that the fire was of high intensity and probably caused the death of most animals (Bernardo, 2021). As highlighted before, most of the fires recorded in this study were relatively small, being extinguished within a day, and all of them were 1 km or closer to the highway. However, we could not statistically verify how the number of roadkills varied per taxon.

Although the roadkill data used were not corrected for the bias generated by carcass persistence and searcher efficiency and taxonomic/body size groups, which are sources of error recognized in the literature (Santos et al., 2016; Teixeira et al., 2013), we do not believe our results are biased by these factors since the highway stretch was surveyed 24 h a day, 7 days a week by trained employees, including a biologist who helped during weekdays. Moreover, we do not think carcass persistence and searcher efficiency varied before and after fires, or in control and affected sections, therefore not affecting the analyses performed here.

The scientific research of road impacts on vertebrates rarely focuses on multifactor or synergistic impacts on wild vertebrates (Jaeger and Torres, 2021), although in some cases data can be obtained for such purposes. We believe this work can be used as a model to guide future research into the synergistic effect of fires and roadkills worldwide, and that such effect should be considered in environmental impact assessments (Jaeger and Torres, 2021), since roads not only cause roadkilling and increase the probability of human-induced fires (Ricotta et al., 2018), but also the fires themselves may increase roadkilling even more, as shown by this study.

In this study, we adopted an experimental design which allowed for temporal and spatial controls. The BACI/BACIP designs provide less biased results (Smith, 2002; Smokorowski and Randall, 2017; Christie et al., 2020) but has not been used to evaluate the impact of fire on roadkilling. Considering that data on fires can be obtained through satellite images and that long-term projects to monitor vertebrate roadkilling are performed routinely in many places around the world, it is relatively straightforward to investigate the effect of fires on roadkilling using this approach. Data on fires can be obtained retrospectively, as done in this study, thereby allowing such investigations. It is clear, however, that long-term data are usually needed to obtain adequate statistical power for analysis at lower taxonomic levels.

Future studies should disentangle how distinct species respond to fires and at which specific spatial and temporal scales such responses are significant. In the short term, some species may move to avoid being burnt during fire (Geluso and Bragg, 1986; Grafe et al., 2002; Pausas and Parr, 2018), while in the longer term researchers may need to track shifts in resources that emerge during post-fire vegetation succession. The studies of Cruz et al. (2021) and Bernardo (2021) found higher roadkills for some species several months after the fires had been extinguished, and Bernardo (2021) found distinct roadkill patterns depending on the scale analyzed. In addition, in Southeastern Brazil, Hilário et al. (2021) found that the number of rescued wild vertebrates involved in traffic collisions increased with the number of fires two months before in the studied region. Moreover, an additional variable that might be worth investigating is fire direction, that is, whether it spread towards the road or away from it, and fire magnitude. Fires of high magnitude that last for several days/weeks and burn large areas may simply kill most of the animals, decreasing roadkill numbers at least just after the fire.

Regarding roadkill mitigation strategies and considering the specificities of the highway stretch analyzed here, we recommend that traffic velocity should be reduced in areas recently affected by fires, in order to decrease roadkilling probability. As proposed by Coombs (2015), limiting traffic flow and/or vehicle speed on roads nearby areas affected by fires and/or installing corridors beneath roads can also be applied in some situations to facilitate migration of species to fire-free areas.

Finally, it is important to note that both fire susceptibility and roads have increased over the last decades in Brazil and worldwide (Meijer et al., 2018; Singh and Huang, 2022; CNT, 2021; Oliveira et al., 2022). We therefore anticipate that the synergistic effect of fires on roadkilling will increase worldwide in the next decades, which highlights once more the need to investigate the combined effect of such anthropic impacts on wild vertebrates. Recently, Nimmo et al. (2019) called attention to the need for integration between movement ecology and fire ecology. We propose including road ecology in such integration whenever roads are present.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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