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Wildlife roadkills in the Colombian Andes: Hotspots, causes, and most affected species

Atropellamientos de vida silvestre en los Andes colombianos: Puntos críticos, causas y especies más afectadas

Atropelamentos de vida selvagem nos Andes colombianos: Pontos críticos, causas e espécies mais afetadas

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Abstract

Background: Despite the improvements in connectivity and mobility of the national highways, road infrastructure of national highways still causes significant environmental disturbances, including wildlife-vehicle collisions. **Objective:** To estimate the direct road mortality of wildlife species during the construction of the two-lane Autopista al Mar 1 highway, in Antioquia (Colombia), from 2018 to 2021. **Methods:** A retrospective observational study was conducted using primary data sources. Descriptive statistics were used to estimate direct road mortality for each taxonomic group, and two roadkill rates were calculated (roadkills/day and roadkills/km/day). Events and month/year relationships were analyzed using ANOVA. Critical points were identified using cluster analysis and Ripley's K statistic. Logistic regression was performed to determine which environmental parameters best predicted wildlife roadkill along the road. **Results:** A total of 295 events were recorded, with *Didelphis marsupialis* (18.3%) and *Iguana iguana* (13.6%) being the most frequently roadkilled species in the study area. The roadkills/day rate was 0.7553, and the roadkills/km/day rate was 0.0218. At least 275.68 individuals are killed on this highway every year. A high spatial aggregation was found in eight critical points of the highway, but these were not associated with any of the environmental parameters explored. **Conclusion:** Opossums and iguanas accounted for more than a third of the animal mortality recorded on the road under study. Environmental and temporal factors did not explain this mortality, but explanatory factors related to the COVID-19 pandemic are hypothesized. The road mortality data presented can inform the management of road accidents, particularly the implementation of mitigation measures to reduce wildlife mortality on the road.

Keywords: *Boa imperator; Coragyps atratus; Didelphis marsupialis; epidemiology; fauna; roadkill; roadkills Iguana iguana; roadkill; wild animals; wildlife.*

Resumen

Antecedentes: A pesar de la mejora en la conectividad y movilidad de las carreteras nacionales, la infraestructura vial genera importantes perturbaciones ambientales, incluidas colisiones entre vehículos y fauna silvestre. **Objetivo:** Estimar la mortalidad vial directa de especies silvestres durante la construcción de la Autopista al Mar 1 de dos carriles, en Antioquia (Colombia), entre 2018 y 2021. **Métodos:** Se realizó un estudio observacional retrospectivo, utilizando fuentes primarias de información. Se utilizaron estadísticas descriptivas para estimar la mortalidad directa para cada grupo taxonómico, y se calcularon dos tasas de atropellos (atropellamientos/día y atropellamientos/km/día). Los eventos y las relaciones entre mes/año se exploraron usando ANAVA, los puntos críticos se identificaron mediante un análisis de conglomerados y la estadística K de Ripley, se realizó una regresión logística para determinar qué parámetros ambientales predijeron con mayor precisión los atropellamientos de vida silvestre a lo largo de la carretera. **Resultados:** Se registraron un total de 295 eventos, siendo *Didelphis marsupialis* (18,3%) e *Iguana iguana* (13,6%) las especies atropelladas con mayor frecuencia en el área de estudio. El número de atropellamientos/día fue de 0,7553 y el número de atropellamientos/km/día fue de 0,0218, lo que indica una mortalidad de al menos 275,68 animales silvestres cada año en esta carretera. Se encontró un mayor valor de agregación espacial en ocho puntos críticos de la carretera, pero estos no se asociaron con ninguno de los parámetros ambientales explorados. **Conclusión:** Zarigüeyas e iguanas representaron más de un tercio de la mortalidad animal registrada en la vía estudiada. Los factores ambientales y temporales no explicaron esta mortalidad, pero se plantea la hipótesis de factores explicativos asociados con la pandemia de COVID-19. Los datos de mortalidad vial presentados pueden contribuir a la gestión de los accidentes viales, principalmente en la implementación de medidas de mitigación que reduzcan la mortalidad de especies silvestres en la vía.

Palabras clave: *atropellamiento; atropellamiento de fauna; Boa imperator; Coragyps atratus; Didelphis marsupialis; epidemiología; fauna silvestre; Iguana iguana.*

Resumo

Antecedentes: A despeito da melhoria na conectividade e mobilidade das rodovias nacionais, , a infraestrutura rodoviária gera perturbações ambientais significativas, incluindo colisões entre veículos e animais selvagens. **Objetivo:** Este estudo teve como objetivo estimar a mortalidade rodoviária direta de espécies silvestres durante a construção da rodovia de duas pistas Autopista al Mar 1, em Antioquia (Colômbia), entre 2018 e 2021. **Métodos:** Foi realizado um estudo observacional retrospectivo, utilizando fontes primárias de informação. Estatísticas descritivas foram usadas para estimar a mortalidade rodoviária direta para cada grupo taxonômico, e duas taxas de atropelamentos foram calculadas (atropelamentos/dia e atropelamentos/km/dia). Os eventos e as relações entre mês/ano foram explorados usando ANOVA, os pontos críticos foram identificados por meio de uma análise de conglomerados e da estatística K de Ripley. Uma regressão logística foi realizada para determinar quais parâmetros ambientais melhor previram os atropelamentos de animais selvagens ao longo da estrada. **Resultados:** Foram registrados 295 eventos, sendo *Didelphis marsupialis* (18,3%) e *Iguana iguana* (13,6%) as espécies atropeladas com maior frequência na área de estudo. O número de atropelamentos/dia foi de 0,7553 e o número de atropelamentos/km/dia foi de 0,0218; pelo menos 275,68 animais selvagens morrem anualmente nesta rodovia. Os maiores valores de agregação espacial foram encontrados em oito pontos críticos da rodovia, mas estes não foram associados a nenhum dos parâmetros ambientais explorados. **Conclusão:** Gambás e iguanas representaram mais de um terço da mortalidade animal registrada na rodovia estudada. Fatores ambientais e temporais não explicaram esta mortalidade, mas se hipotetizam fatores explicativos associados à pandemia de COVID-19. Os dados de mortalidade rodoviária apresentados podem contribuir para a gestão de acidentes rodoviários, principalmente para a implementação de medidas de mitigação que possam reduzir a mortalidade de espécies selvagens nas rodovias.

Palavras-chave: *animais selvagens; atropelar; Boa imperator; Coragyps atratus; Didelphis marsupialis; epidemiologia; fauna silvestre; Iguana iguana; vida selvagem atropelada.*

Introduction

Roads promote urban development but also disconnect areas that are part of the species' distribution range (Carvalho and Mira, 2011). This lack of connectivity has drastic consequences for the dispersion and migration of animals, as it may reduce population size and genetic diversity (Riggio and Caro, 2017). Both invertebrates and vertebrates are vulnerable to these effects —irrespective of their dimensions, which can result in population declines (Fahrig and Rytwinski, 2009).

In Colombia, a new national program on road infrastructure has been implemented, involving the construction and operation of more than 8,000 km of highways. The objective of this program, known as the Fourth Generation Highways (4G), is to improve the country's competitiveness by reducing the cost and time of transportation of cargo and people, particularly from manufacturing points to export ports. The Autopista al Mar 1 highway is one of the 4G road infrastructure projects in the country. This project will expand an existing road into a two-lane highway, including the construction of a second tunnel and its accesses (Devimar, 2022).

Several Latin American countries have compiled databases documenting wildlife mortality on roads, which have contributed to the emerging field of road ecology (Gallina and Badillo, 2013; Morantes-Hernández, 2017). Medrano-Vizcaíno et al. (2022) conducted the first evaluation of roadkill impacts on birds and mammals in the region, while Medrano-Vizcaíno et al. (2023) provided the initial national assessment of wildlife mortality on Ecuadorian roads. In Colombia, however, data collection on wildlife road mortality is still incipient, and there is a need to develop studies that cover the different geographical regions in terms of vertebrate roadkill observation and patterns (Rojano-Bolaño and Ávila-Avilán, 2021). Therefore, given that the construction or improvement phase of a road has the greatest direct negative impact on wildlife (Parra and Rincón, 2016), in this study we aimed to characterize vertebrate road mortality during the construction of the two-lane Autopista al Mar 1 highway in the province of Antioquia, Colombia, between 2018 and 2021. Specifically, we quantified the vertebrate wildlife species affected and evaluated how mortality varied over time and space. Additionally, we analyzed landscape and road variables that may be associated with vertebrate roadkill in the area of interest.

Materials and Methods

Ethical considerations

This study was based on the wildlife roadkill records collected by Devimar S.A. concessionaire, contractor of Autopista al Mar 1 two-lane highway. Authorization of database use for research purposes was obtained from the concessionaire. Manipulation or direct intervention on animals was not conducted.

Study type and area

A retrospective observational study was conducted using primary sources of information (concessionaire's records). The study area was limited to the construction zone of the two-lane Autopista al Mar 1 highway, approximately 34.7 km long, and located between the municipalities of Santa Fe de Antioquia (6°30’44.8” N and 75°49’04.6” W) and Medellín (6°17’28.4” N and 75°38’59.9682” W) (Figure 1) in Antioquia province (Colombia). This highway is subdivided into five functional units (FU) of two-lane primary roads. The roads evaluated were FU 1, 2.1, and 3, locat--ed between the municipalities of Medellín, San Jerónimo, Sopetrán, and Santa Fe de Antioquia (Figure 1). The areas surrounding these roads correspond to a tropical dry forest biome, which is the predominant ecosystem. The altitude varies from 450 (Santa Fe de Antioquia) to 1,950 (Medellín) m.a.s.l., surrounded by grasslands, agriculture, dry forest, and urban settlements (Osorio, 2016; Arango-Lozano and Patiño-Siro, 2020) (Figure 2).

Field registration methods and database

Two surveys were conducted weekly by the concessionaire between January 2018 and December 2021. Two people in a vehicle (at 60 km/h) searched for vertebrate wildlife roadkill events, carrying out a total of 400 field surveys. All mortality events were registered in an Excel database, according to the environmental license guidelines granted to the concessionaire by the national environmental licensing authority (Autoridad Nacional de Licencias Ambientales, ANLA). When possible, the following information was collected for each wildlife roadkill event: date (day, month, year), geographic coordinates (latitude, longitude), taxonomic classification (class —Amphibia, Reptilia, Aves, Mammalia), scientific name, common name, stage of development (juvenile, subadult, adult), and type of vegetation cover (forest, cultivation, wetland, paddock, river/stream, urbanized). Carcasses were removed from the road and buried to avoid sampling duplicates (Parra and Rincón, 2016) and to reduce the probability of new roadkill due to scavenging animals (Carvalho-Roel et al., 2019; De Araújo et al., 2019; Medrano-Vizcaíno et al., 2022). When the identification of the wildlife individual was not possible, it was recorded as unidentified.

Statistical analysis

The number of roadkilled amphibians, reptiles, birds, and mammals was summarized by month and year using descriptive statistics in Stata v.16.1 (StataCorp, 2020, College Station, Texas, USA). Roadkill rates were calculated (roadkills/day, roadkills/km/day, roadkills/year) using Siriema® Road Mortality Software v. 2.0 (NERF UFRGS, 2014, Porto Alegre, BR), following previous reports (McNish, 2007; Santos et al., 2011). This software automatically adjusts raw data on the observed number of roadkilled individuals to consider the probability of detection. This adjustment was performed for each group of vertebrates using the following mathematical model:

$$N = \sum_{i=0}^{n-1} N_i = \lambda T_R p \sum_{i=0}^{n-1} \left(1 - \sum_{j=1}^{i} e^{-\frac{jT_S}{T_R}} p (1-p)^{j-1} \right)$$

N = total number of carcasses recorded during the study (295), λ = the number of carcasses per day, p = probability of detection (where the upper limit for each group was 0.59; Teixeira et al., 2013), TR = time that elapses from the moment of the collision until the complete disappearance of the carcass (in days; Santos et al., 2011), resulting in 1 day for amphibians, birds, and reptiles (<500 g of average weight), bats, and squirrels; 2 days for reptiles (>500 g of average weight); 3 days for birds (>500 g of average weight), turtles, skunks, and mammals (400-900 g of average weight); and 4 days for mammals (1,000-5,000 g of average weight). TS = sampling interval between surveys set at 3.5 (representing an approximate range of 3 to 4 days among samplings), totaling 400 surveys in the 4-year period. i = a given point on the road, and J = represents each roadkill event.

To understand whether mortality events varied over time (month or year), estimated mortality rate data was set for the most representative species, replacing TS with the number of weeks in each month of sampling. Transformed data were used to carry out mixed linear (additive) and bilinear (multiplicative) models, using time by month (for the 12 months) and by year (2018, 2019, 2020, 2021) as independent variables. Each analysis was performed independently after normal distribution was assessed, using Shapiro-Wilk test. Statistical differences were detected with ANOVA (analysis of variance) in the R® environment, v. 2023.03.0 (R Foundation for Statistical Computing, 2023), considering a significance level of $P < 0.05$.

Spatial analysis

A conglomerate analysis of the roadkill events was carried out. A 2-D Ripley's K statistic was performed to test for a non-random spatial distribution of the events, considering the sinuosity of the road through multiple scales (Coelho et al., 2008; Arango-Lozano and Patiño-Siro, 2020). In addition, a 2-D hotspot analysis was carried out to differentiate the spatial aggregation of vertebrate roadkill events with statistical significance, which also made it possible to generate graphic descriptions of the results (Coelho et al., 2008; Magioli et al., 2019), following a radius of 100 m, 1,000 simulations, and 95% confidence limits (CL). The Siriema® Road Mortality Software v. 2.0 (NERF UFRGS, 2014, Porto Alegre, BR) was used (Coelho et al., 2014).

Landscape and road variables analysis

A logistic regression was carried out to identify environmental parameters best predicting wildlife roadkill events along the road, using R® software, v. 2023.03.0 (R Foundation for Statistical Computing, 2023), considering a significance level of $P < 0.05$. The explanatory variables corresponded to spatial information from cartographic data supplied by Devimar S.A.S. company, consisting of (1) the surrounding land cover (forests/natural areas, watercourses—rivers, lakes, streams, croplands, modified terrain—urban, extraction lands), and (2) the road geometry (curved or straight road segments). In addition, the road was divided into 1-km segments and spatially aggregated (hotspots) for each km (hotspot presence = 1 and no hotspot presence = 0). Land cover parameters were determined as the number of square meters surrounding a 1-linear-km road segment (1 km buffer). In addition, road geometry was summarized as the total length of curved and straight segments, as previously defined by Rojano-Bolaño and Ávila-Avilán (2021).

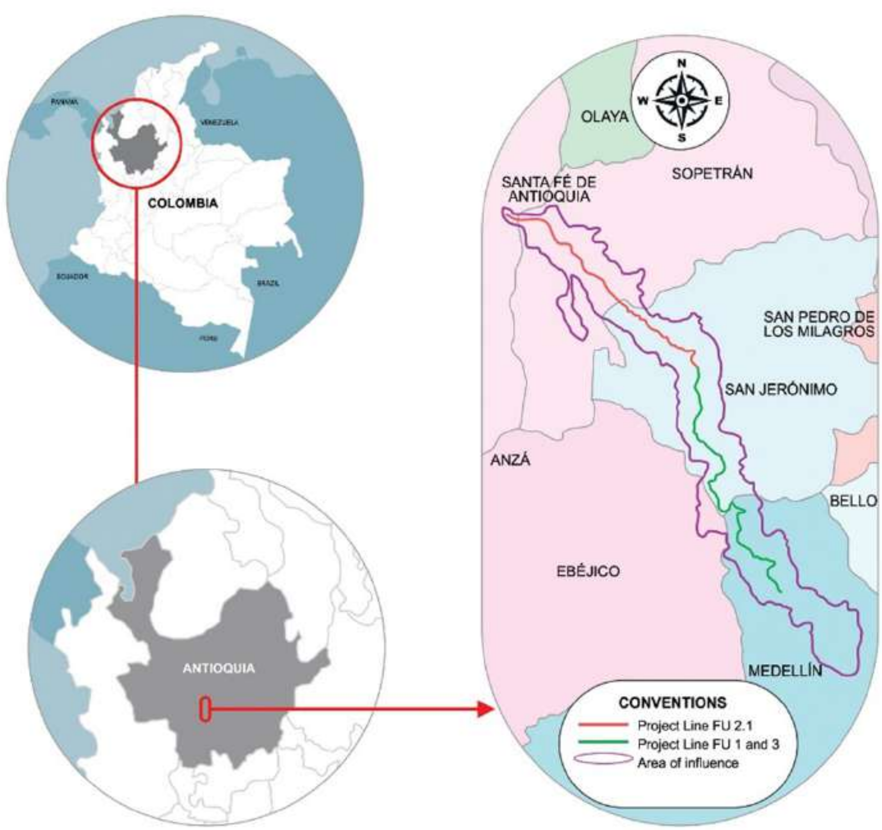

Figure 1. Study location: Autopista al Mar 1 Highway, between the municipalities of Santa Fe de Antioquia and Medellín, Central Andean Region of Colombia.

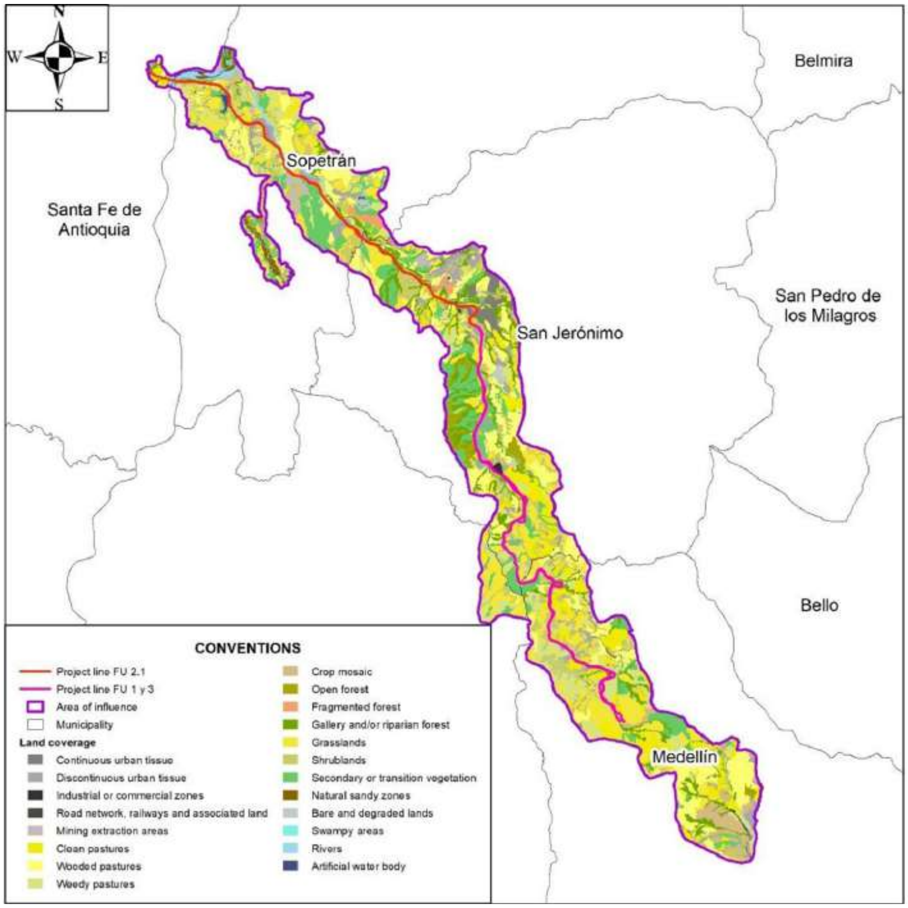

Figure 2. Vegetation cover in the Autopista al Mar 1 highway influence area (Antioquia, Colombia), 2021.

Results

A total of 295 wildlife roadkill events were reported over 4 years (from January 2018 to December 2021). The class with the highest mortality was mammals (n = 94), followed by reptiles and birds (n = 89 each), amphibians (n = 9), and 14 roadkilled individuals were unidentified. The mortality corresponded to 76 different species distributed among amphibians (3%), reptiles (32.9%), birds (31.9%), and mammals (32.2%). The species with the highest incidence of roadkill events were *Didelphis marsupialis* (n = 54; 18.3%), *Iguana iguana* (n = 40; 13.6%), *Boa imperator* (n = 16; 5.4%), *Coragyps atratus* (n = 15; 5.1%), *Cerdocyon thous* (n = 12; 4.1%), *Megascops choliba* (n = 10; 3.4%), and 15 individuals were classified as unidentified at the genus and/or species level. The highest number of events occurred in 2021 (39.7%), followed by 2018 (24.1%), 2019 (20%), and 2020 (16.3%) (Table 1).

The total number of roadkills per day was 0.7553, the total number of roadkills per km per day was 0.0218, and the annual average was 275.68 roadkills. Table 2 presents the roadkill rates by taxonomic group, with reptiles being the class with the highest roadkill probability per day and per km per day.

Table 1. Frequency and distribution of vertebrate wildlife roadkill events by taxonomic group on the Autopista al Mar 1 highway (Antioquia, Colombia), 2018-2021.

Family	Scientific name	Common name (in Spanish)	Red list category (IUCN)	Frequency (% for the 4 years)
		Class Amphibia		
Bufonidae	*Rhinella horribilis*	Sapo común	LC	7 (2.37)
Leptodactylinae	*Leptodactylus* sp.	Rana terrestre	LC	2 (0.68)
		Class Reptilia		
Alligatoridae	*Caiman crocodilus*	Babilla	LC	2 (0.68)
Boidae	*Boa imperator*	Boa cazadora	LC	16 (5.42)
	Atractus sp.	Serpiente tierrera	DD	2 (0.68)
	Clelia equatoriana	Cazadora negra	LC	1 (0.34)
	Dendrophidion bivittatus	Guardacaminos corredora	LC	1 (0.34)
	Dipsadinae sp.	Culebra	LC	1 (0.34)
	Lampropeltis micropholis	Falsa coral	LC	1 (0.34)
Colubridae	*Mastigodryas pleii*	Guardacaminos	LC	7 (2.37)
	Mastigodryas sp.	Culebra guardacaminos	LC	1 (0.34)
	Oxyrhopus petolarius	Falsa rabo de ají	NE	5 (1.69)
	Pliocercus euryzonus	Falsa coralilla	LC	1 (0.34)
	Pseudoboa neuwiedii	Candelilla	LC	4 (1.35)
	Spilotes pullatus	Serpiente toche	LC	1 (0.34)
Dactyloidae	*Anolis* sp.	Lagartija	DD	1 (0.34)
Emydidae	*Trachemys* sp.	Hicotea	DD	1 (0.34)
Iguanidae	*Iguana iguana*	Iguana verde	LC	40 (13.56)
	Polychrus gutturosus	Camaleón andino	LC	1 (0.34)
Kinosternidae	*Kinosternon leucostomum*	Tortuga tapaculo	DD	1 (0.34)
	Ameiva ameiva	Lagarto terrestre	LC	1 (0.34)
Teiidae	*Ameiva* sp.	Lagarto	LC	1 (0.34)
	Holcosus festivus	Lobito	LC	1 (0.34)
Scincidae	*Mabuya mabouya*	Lagarto mabuya	NE	1 (0.34)
Unidentified				6 (2.03)
		Class Aves		
Accipitridae	*Rupornis magnirostris*	Gavilán caminero	LC	1 (0.34)
Ardeidae	*Bubulcus ibis*	Garza garrapatera	LC	1 (0.34)
Cathartidae	*Coragyps atratus*	Gallinazo común	LC	15 (5.08)

Corvidae	*Cyanocorax affinis*	Carriquí pechiblanco	LC	1 (0.34)
	Crotophaga ani	Garrapatero ani	LC	2 (0.68)
Cuculidae	*Crotophaga* sp.	Garrapatero	LC	1 (0.34)
	Piaya cayana	Cuco ardilla	LC	1 (0.34)
Fringillidae	*Euphonia laniirostris*	Eufonia gorgiamarilla	LC	4 (1.35)
Galliformes	*Ortalis columbiana*	Guacharaca común	LC	7 (2.37)
Icteridae	*Psaracolius decumanus*	Oropéndola crestada	LC	1 (0.34)
Hirundinidae	*Stelgidopteryx ruficollis*	Golondrina gorgirrufa	LC	1 (0.34)
Strigidae	*Megascops choliba*	Búho currucutú	LC	10 (3.39)
Picidae	*Colaptes puntigula*	Carpintero moteado	LC	1 (0.34)
Psitacidae	*Forpus conspicillatus*	Perico de anteojos	LC	1 (0.34)
	Ramphocelus dimidiatus	Toche pico de plata	LC	1 (0.34)
	Ramphocelus flammigerus	Tángara flamiguera	LC	1 (0.34)
	Sporophilla sp.	Arrocero	LC	1 (0.34)
Thraupidae	*Stilpnia vitriolina*	Tángara rastrojera	LC	1 (0.34)
	Tangara gyrola	Tángara cabecibaya	LC	1 (0.34)
	Thraupis episcopus	Azulejo	LC	4 (1.35)
	Thraupis palmarum	Azulejo de palmeras	LC	2 (0.68)
Trochilidae	*Amazilia* sp.	Colibrí	LC	2 (0.68)
	Amazilia tzacalt	Amazilia de cola rufa	LC	1 (0.34)
Troglodytidae	*Campylorhynchus griseus*	Cucarachero común	LC	1 (0.34)
	Catharus ustulatus	Zorzal	LC	1 (0.34)
Turdidae	*Turdus ignobilis*	Mirla común	LC	4 (1.35)
	Turdus sp.	Mirla	LC	3 (1.02)
	Elaenia flavogaster	Fiofío ventriamarillo	LC	1 (0.34)
	Machetornis rixosa	Picabuey	LC	1 (0.34)
	Myiodynastes maculatus	Bienteveo rayado	LC	1 (0.34)
Tyrannidae	*Myiozetetes similis*	Benteveo mediano	LC	1 (0.34)
	Tyrannus melancholicus	Sirirí común	LC	9 (3.05)
	Tyrannidae sp.	Atrapamoscas	-	1 (0.34)
Vireonidae	*Vireo flavoviridis*	Vireo verdeamarillo	LC	1 (0.34)
	Vireo olivaceus	Vireo ojirrojo	LC	1 (0.34)
Unidentified				8 (2.71)
		Class Mammalia		
Aotidae	*Aotus cf lemurinus*	Marteja	VU	2 (0.68)
Canidae	*Cerdocyon thous*	Zorro perro	LC	12 (0.04)
Not reported	*Chiroptera* sp.	Murciélago	-	1 (0.34)
Dasyproctidae	*Dasyprocta punctata*	Ñeque	LC	1 (0.34)

	Caluromys lanatus	Chucha lanuda	LC	1 (0.34)
Didelphidae	*Didelphis marsupialis*	Zarigüeya común	LC	54 (18.30)
	Didelphis sp.	Zarigüeya	LC	8 (2.71)
Myrmecophagidae	*Tamandua mexicana*	Oso hormiguero	LC	6 (2.03)
Sciuridae	*Syntheosciurus granatensis*	Ardilla roja	LC	2 (0.68)
Phyllostomidae	-	Murciélago	-	3 (1.02)
Procyonidae	*Potos flavus*	Perro de monte	LC	1 (0.34)
	Procyon cancrivorus	Mapache	LC	2 (0.68)
Vespertilionidae	*Myotis* sp.	Murciélago negro	LC	1 (0.34)
Unidentified				1 (0.34)

NE = Not evaluated; DD = Data deficient; LC = Least concern; VU = Vulnerable; - = Unidentified species.

The mortality of *D. marsupialis* was similar across all four years (P = 0.56) and months (P = 0.26). Similarly, the mortality of *I. iguana* was similar across all years and months (P = 0.61 and P = 0.19, respectively); however, we found a significant month-by-year interaction (P = 0.006), which corresponded to a higher mortality recorded in January 2021 (n = 16).

The 2-D Ripley's K statistic (300 m radius and 95% CL) showed a greater value of spatial aggregation with L(r) > 6.5 between km 15.5 and km 17.9 of the highway. This section corresponds to a curved segment at the main entrance of San Jerónimo municipality (6°26'42.2698" N, 75°43'51.9356" W). The 2-D hotspots analysis identified eight road segments with statistically significant spatial aggregation (i.e., K1+8, K3+5, K6+2, K7+1, K13+5, K15+5, K9+5, and K26). There was no statistical relationship between the aggregation of roadkill events and the environmental parameters associated with the road (Table 3).

Table 2. Vertebrate roadkill rates by taxonomic group on the Autopista al Mar 1 highway (Antioquia, Colombia), 2018-2021.

Taxonomic group	Roadkilled individuals (n)	Roadkill rates in 34.7 km-long route				
		p (detectability)	TR (days)	Roadkills/ day	Roadkills/ km/day	Roadkills/ km/year
Amphibia	*9*	0.59	1.1378	0.0344	0.0009	0.3957
Reptilia	97	0.59	1.3318	0.3260	0.0094	3.7970
Aves	94	0.59	2.7147	0.1795	0.0051	2.3752
Mammalia	*95*	0.59	19.1436	0.0819	0.0023	1.3769
Total	*295*	0.59	24.3279	0.6220	0.0258	9.4389

p = probability of detection (where the upper limit for each group was 0.59) (Teixeira et al., 2013); TR = time that elapses from the moment of the roadkill until the complete disappearance of the carcass.

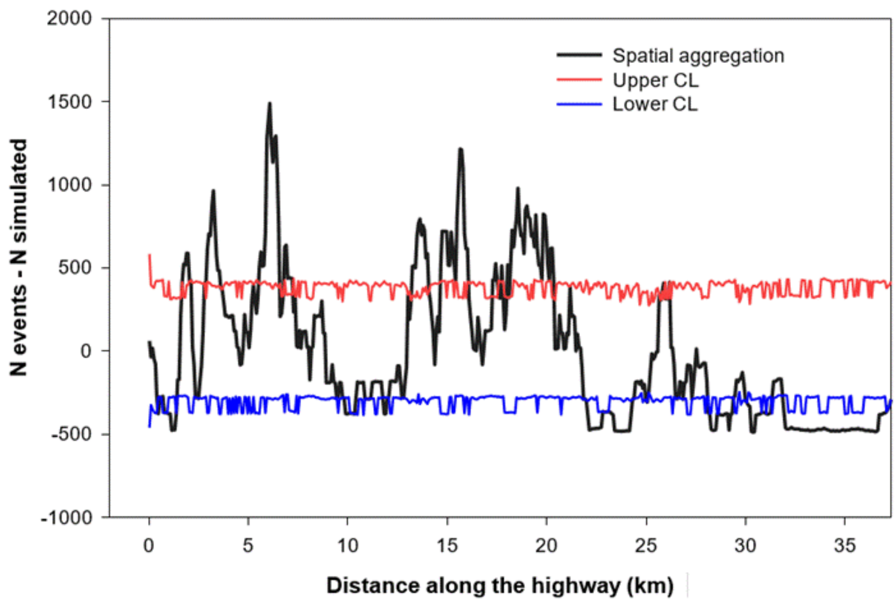

Figure 3. Spatial aggregation of vertebrate wildlife roadkill events (black line) on the Autopista al Mar 1 highway (Antioquia, Colombia), 2018-2021. The blue and red lines represent the lower and upper 95% CL, respectively.

Table 3. Odds estimated from surrounding land cover and road geometry to explain the spatial aggregation of vertebrate wildlife roadkill events on the Autopista al Mar 1 highway (Antioquia, Colombia), 2018-2021.

Environmental parameters	*Coefficients*	Estimate	SE	Z-value	P-value
	Intercept	**-3.954**	**2.071**	**-1.909**	**0.056**
Surrounding land cover (1 km radius)	Forest/natural areas	0.001	0.001	1.445	0.148
	Watercourse	0.0006	0.006	0.097	0.922
	Agriculture	0.001	0.001	0.912	0.362
	Modified lands	0.001	0.001	1.375	0.169
Road geometry	Curve	-0.001	0.002	-0.482	0.630
	Straight	NA	NA	NA	NA

SE = Standard error; NA = Not applicable.

Discussion

This study aimed to estimate the direct road mortality of wildlife species during the construction of the two-lane highway Autopista al Mar 1 (2018-2021).

The common black-eared opossum (*D. marsupialis*) and the green iguana (*I. iguana*) were the species with the highest roadkill incidence, representing more than 18% and 13% of the total cases, respectively. These species adapt easily to urbanized habitats and are frequently reported as road mortality events in Colombia (Rodda and Grajal, 1990; Delgado-Vélez, 2014; Castillo et al., 2015; De La Ossa and Galván-Guevara, 2015; Arango-Lozano and Patiño-Siro, 2020). These findings could also be associated with higher population densities in natural and modified habitats compared to other species (Rodda and Grajal, 1990; Pinowski, 2005; Castillo et al., 2015;

Arango-Lozano and Patiño-Siro, 2020).

The higher mortality of opossums and iguanas was observed uniformly throughout the years and months, with only a peak in iguana mortality observed in January 2021. That year marked the final phase of highway construction, during which many new roadways (approx. 200 km) were opened to the public, potentially contributing to an increased vehicle flow, as previously reported (Clevenger et al., 2003; de Freitas et al., 2015). By January 2021, the COVID-19 confinement had ended in Colombia, and January coincides with a national holiday period (Oxley et al., 1974; Arévalo et al., 2017). No association was found for the other months, years, or their combinations, which may be due in part to the limited observation time.

The roadkill rates observed here are low compared to other reports from different regions of Colombia (Payan et al., 2013; Pallares and Joya, 2018; Rojano-Bolaño and Ávila-Avilán, 2021; Arana-Rivera and Gutiérrez-Quintero, 2022). Regarding mammals, a characterization conducted by Meza et al. (2019) in Barrancabermeja (Santander, Colombia) reported a higher roadkill rate but agreed that the opossum was the most affected species. On the other hand, Quintero-Ángel et al. (2012) reported a lower roadkill rate for reptiles (78.8/year) over a five-month period. The differences among these studies can be attributed to various factors, such as vehicular traffic, road geometry, adjacent vegetation, weather conditions, and elevation (Rincón-Aranguri et al., 2015). This underscores the importance of segmenting wildlife roadkill characterization to develop strategic solutions that account for these factors.

Eight roadkill hotspots were identified along the 34.7-km Autopista al Mar 1 highway. Despite the apparent lack of influence of land cover types and road geometries on roadkill aggregations—possibly due to the high variation in land use within the 1-km-wide spatial matrix surrounding the road—all roadkill hotspots were found in curved road segments. This suggests that such geometry may pose a greater risk to wildlife in these specific circumstances, as previously reported (Arango-Lozano and Patiño-Siro, 2020).

The 2-D Ripley's K statistic showed a greater spatial aggregation value in a curved segment at the main entrance of the touristic municipality of San Jerónimo. In this context, it is important to highlight that regional social dynamics also play a crucial role in road ecology. Tourism activity in this area has grown in recent years, as evidenced by the construction of inns, hotels, urbanizations, and recreational facilities (Alcaldía de San Jerónimo, 2022). In such cases, public awareness and traffic control measures could be effective in mitigating wildlife road mortality (Fernández-López et al., 2022).

In this study, no statistically significant relationship was found between environmental parameters and wildlife roadkill. Nevertheless, addressing the ecology and biology of each species may be relevant for understanding wildlife mortality on this road (Cáceres, 2011). Ecological factors, such as the presence of natural and modified green covers along roads and human infrastructures, the use of roads as heat sources for thermoregulation and basking by iguanas (Townsend et al., 2003; Colino-Rabanal and Lizana, 2012), and the attraction of scavengers to roadkill, as seen in opossums, could contribute to species-specific mortality patterns. Additionally, biological and behavioral traits, such as the large body size of iguanas when crossing roads and the tendency of opossums to remain still when approached by a vehicle, make these species more vulnerable to collisions (Delgado-Vélez, 2007; Castillo et al., 2015).

Our results showed that iguana roadkill rates peaked between November and January, which coincides with their breeding season (Campos and Desbiez, 2013). In addition, their nesting season in Colombia has been reported between January and June (Muñoz et al., 2003). It is well established that during the breeding season, many species increase their activity as they search for mates and suitable territories. This heightened mobility exposes them to a greater risk of being struck by vehicles (Ritchie and

Johnson, 2009; Fernández-López et al., 2022). Regarding opossums, anthropogenic effects such as deforestation and urbanization in rural areas have increased direct contact between these animals and peri-urban and urban populations (Delgado-Vélez, 2007; Jaramillo et al., 2017). These observations highlight a possible relationship between the species' ecological traits and the timing of roadkill events.

This study had some limitations, including a relatively short sampling period, incomplete morphometric data of the roadkill specimens, and limited availability of census data due to the global pandemic confinement. However, it also had certain strengths, such as a thorough analysis of the data, allowing the proposal of strategic mitigation measures based on species biology and ecology. Additionally, data on wildlife that survived vehicle collisions and long-term monitoring of such cases were not available in the database, which limits the understanding of the broader impact on wildlife health and survival. To date, no study in Colombia has incorporated this type of information.

Road ecology is still an emerging field in Colombia, and more research is needed to develop effective strategies for wildlife conservation in road construction projects. Future studies should expand scientific knowledge on strategic interventions, considering factors such as elevation, topography, and human cultural influences.

This study highlights the impact of road construction on wildlife. A total of 295 wildlife roadkill cases were recorded over four years along Autopista al Mar 1 (Antioquia, Colombia). Opossums and iguanas were the most affected species. The overall mortality rate was 275.68 roadkills/year across all vertebrate classes. Additionally, an interaction was found between month and year in iguana mortality, with a peak in January 2021. This study also identified eight road segments with statistically significant roadkill clusters, including the entrance to San Jerónimo municipality. Finally, none of the environmental parameters evaluated were significant predictors of roadkill, emphasizing the need to explore ecological and biological factors as potential indicators of vertebrate wildlife road mortality.

Our methodology can be applied to national and international highways, adapting the tools as needed. Implementation of preventive vertical traffic signs indicating wildlife crossings, as well as electronic vertical and horizontal signs, should be prioritized—especially during breeding seasons or periods of increased wildlife movement.

From the perspective of environmental impact assessment, the present results could significantly contribute to the design of measures to prevent and minimize the environmental impact on fauna during both the construction and operation phases of highways. In the construction phase, our findings can guide the strategic placement of wildlife crossing structures, such as underpasses or overpasses, in identified hotspots to facilitate safe animal movement and reduce roadkill incidents. During the operation phase, the continuous monitoring of wildlife roadkill and the adaptive management of signage and other mitigation measures can help maintain the effectiveness of these interventions. Implementing these measures can not only enhance road safety by reducing wildlife roadkill but also conserve biodiversity by protecting wildlife populations from the adverse effects of road networks.

Declarations

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Conflicts of interest

The authors declare that no known competing financial interests or personal relationships are present that could have influenced the work reported in this paper.

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Author contributions

The authors confirm contribution to the paper as follows: study conception and design: KA and NC; data collection: KA; analysis and interpretation of results: KA, CC, and CR; draft manuscript preparation: KA and NC. All authors reviewed the results and approved the final version of the manuscript.

Use of AI

No AI or AI-assisted technologies were used during the preparation of this work.

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