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Research paper

To cross or not to cross: patterns and predictability of vertebrate roadkill in three road corridors in the department of Cundinamarca, Colombia

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Abstract

To cross or not to cross: patterns and predictability of vertebrate roadkill in three road corridors in the department of Cundinamarca, Colombia. Roadkills are among the most important threats to wildlife worldwide. In Colombia, few studies have evaluated the impact or patterns of this threat and many aspects are yet to be evaluated. Bogotá and Cundinamarca are the most populated areas in the country, but no information is available regarding this threat in this area. Here we evaluated the incidence of roadkill in three main road corridors between August 2018 and November 2019, estimating its magnitude, patterns and influencing variables. All roadkill records were collected and characterized spatially, temporally, and taxonomically. We then modeled the effect of landscape variables on roadkill incidence. We surveyed 88 times, covering 12,120 km and obtaining 52 records of 15 species. Mammals were the most affected taxa (67.30 %), followed by reptiles (19.12 %). We identified 38 hotspots. Sinuosity was found to be the most influential variable in the probability of roadkill, with overall probabilities concentrated in the medium risk (60-70 %), and 20 % showing high probabilities (90-100 %). These findings lay the groundwork for long-term monitoring, promoting implementation of measures to reduce the effect of this threat to wildlife in the department.

Key words: Bogotá, Birds, Mammals, Reptiles, Amphibians, Roads, Road ecology

Resumen

Cruzar o no cruzar: patrones y predictibilidad de los atropellos en tres corredores viales del departamento de Cundinamarca (Colombia). Los atropellos son una de las amenazas más importantes para la fauna silvestre en todo el mundo. En Colombia, pocos estudios han evaluado el impacto o los patrones de esta amenaza y aún quedan muchos aspectos por estudiar. Bogotá y Cundinamarca son las zonas más pobladas del país, pero no se cuenta con información sobre esta amenaza. Evaluamos la incidencia de atropellos en tres principales corredores viales entre agosto de 2018 y noviembre de 2019, y estimamos la magnitud y los patrones de los atropellos, así como las variables influyentes. Para ello, se recopilaron todos los registros de atropello, que fueron caracterizados espacial, temporal y taxonómicamente, y se elaboró un modelo para determinar el efecto de las variables relacionadas con el territorio en la incidencia de atropellos. Se realizaron 88 recorridos que abarcaron un total de 12.120 km y se obtuvieron 52 registros de 15 especies, donde los mamíferos fueron el taxón más afectado (67,30 %), seguidos de los reptiles (19,12 %). Se detectaron un total de 38 puntos críticos y se encontró que la sinuosidad es la variable más influyente en la probabilidad de atropello, con probabilidades generales concentradas en el riesgo medio (60-70 %) y el 20 % con probabilidades altas (90-100 %). Este trabajo sienta las bases para hacer un seguimiento a largo plazo que permita adoptar medidas dirigidas a reducir el efecto de esta amenaza en la fauna silvestre en el departamento.

Palabras clave: Bogotá, Aves, Mamíferos, Reptiles, Anfibios, Carreteras, Ecología de carreteras

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Introduction

Roads are an artificial barrier for wildlife. They affect ecological dynamics of species and cause death by collision, consequently decreasing population densities at the local level (Heilman et al 2002, Clevenger and Huijser 2011, Van der Grift et al 2013, Monroy et al 2015). Roads fragment populations by acting as barriers for the mobility of many species, reducing their genetic diversity at the regional level and increasing factors such as fragmentation processes, loss of connectivity, and habitat destruction, that have a medium and long-term impact (Forman and Alexander 1998). Additionally, roadkill is a leading cause of mortality for terrestrial vertebrates worldwide, surpassing hunting (Forman and Alexander 1998), and often affecting healthy individuals (Bujoczek et al 2011, Hill et al 2019). Due to lack of planning, the continuous advance and development of human activity has significantly increased the problems affecting wildlife and biodiversity in general (González et al 2011, Castillo-Martínez et al 2016). For example, the ongoing expansion of agriculture and misguided policies have drastically transformed ecosystems (Lindenmayer and Fischer 2006, De la Ossa-Nadjar and De la Ossa-V 2015). These policies prioritize urban and rural development, aiming to enhance quality of life through expanded road networks, linking economic development to this infrastructure, and considering it essential for economic growth and trade (De la Ossa-Nadjar and De la Ossa-V 2013). The consequent growth of road networks has negatively impacted landscapes, fragmenting habitats and disrupting wildlife connectivity, creating the need for new conservation measures (Forman et al 2003, Teixeira et al 2013, Bauni et al 2017).

Due to the magnitude of the threat posed by roads, numerous recent studies have elucidated the impact of this infrastructure on wildlife population dynamics, indicating that roadkill is potentially the leading cause of loss of healthy vertebrates worldwide (Forman and Alexander 1998, Fahrig and Rytwinski 2009, Teixeira et al 2013). These events have been documented as determined by wildlife movement patterns, influenced also by seasonality and overall landscape characteristics (Keller and Yahner 2007, Alves da Rosa and Bager 2012). However, studies have shown that various factors influence the likelihood of roadkill occurrences. Collision probabilities vary among species and are shaped by landscape characteristics (Lopez-Herrera et al 2016). Numerous intrinsic and extrinsic factors also influence roadkill probabilities, such as animal behavior, vegetation type, landscape fragmentation, proximity to water bodies, road characteristics (sinuosity, straight sections, speed bumps), and traffic volume (Malo et al 2004, Brémond et al 2013).

Research from Europe, North America, and South America has underscored the alarming consequences of roadkill for wildlife populations (Hawbaker and Radeloff 2004, Arezco 2005, Rosa and Mahus 2005, Monroy et al 2015, Carvalho-Roel et al 2019). In Colombia, comprehensive studies have been conducted in specific landscapes in the Pacific, Caribbean, and Andean regions (Vargas-Salinas et al 2011, De la Ossa-Nadjar and De la Ossa-V 2013, 2015, Castillo et al 2015, De la Ossa-V and Galván-Guevara 2015, Monroy et al 2015, López-Herrera et al 2016). However, information on roadkill is scarce for many regions of Colombia, including Cundinamarca. While there is only one study on roadkill management exists for the jurisdiction (Rincón and Parra 2016), and the department has invested heavily in industry, housing, and road development (Decree 435, 2018). It also hosts major road corridors such as Bogotá-Honda and Bogotá-Girardot, where traffic volumes (Gobernación de Cundinamarca 2020) are high alongside natural reserves, protected areas, and crucial ecological corridors (González-Maya et al 2019b).

A lack of understanding about the magnitude, patterns, and causes of roadkill in biologically and socially important regions like Cundinamarca hinders effective mitigation strategies and conservation efforts (Ceballos et al 2011). The development of adequate policies to mitigate this threat is hindered by the lack of information for the department, the country's primary economic region and area of influence for the capital. Cundinamarca is already affected by numerous transformations, such as deforestation, cattle ranching, and indiscriminate mountain land use, which account for 49 % of the department's total area (Gobernación de Cundinamarca 2016). To establish effective conservation strategies, we here assessed the extent and patterns of wildlife roadkill along three major road corridors in Cundinamarca. By characterizing affected species and identifying associated infrastructure and landscape factors, we aimed to determine high-probability roadkill hotspots. The findings may serve as a foundation to develop targeted mitigation measures to reduce wildlife-vehicle collisions in the region.

Materials and methods

Study area

The department of Cundinamarca is located in the Andes (Andean) region (5° 5 l' 00''-3° 42' 00'' N and 74° 54' 00''-73° 03' 00'' W) and has an extension of 24,210 km^2, covering 116 municipalities (Gobernación de Cundinamarca 2016). Although not part of its political division, Cundinamarca nearly encircles Bogotá DC, serving as the capital's connection to the rest of the country (Morales-Cely et al 2014) and hosting some of the nation's most vital transportation corridors. With a population of 2,762,800 (DANE 2018), Cundinamarca, combined with Bogotá's 7,181,569 residents, accounts for approximately 23 % of the national population (DANE 2018). The department has a road network of 23,945 km, 890 km of which correspond to first order roads, 4,997 km to secondary roads, and 18,058 km to tertiary roads (Gobernación de Cundinamarca 2016).

The present study was developed in the three main road corridors or principal highways of the department: Bogotá- Girardot corridor (B-G), Bogotá-Puerto Salgar corridor (B-PS) and Bogotá- Chiquinquirá corridor (B-C). The B-G corridor runs an approximate length of 119 km of paved road. It is currently divided into 2-4 lanes (ANI 2015), and runs through the department between 4° 35' 46.6'' N, 74° 11' 04.3'' W and 4° 18' 04.4'' N, 74° 47' 48.3''. This highway is part of National Route

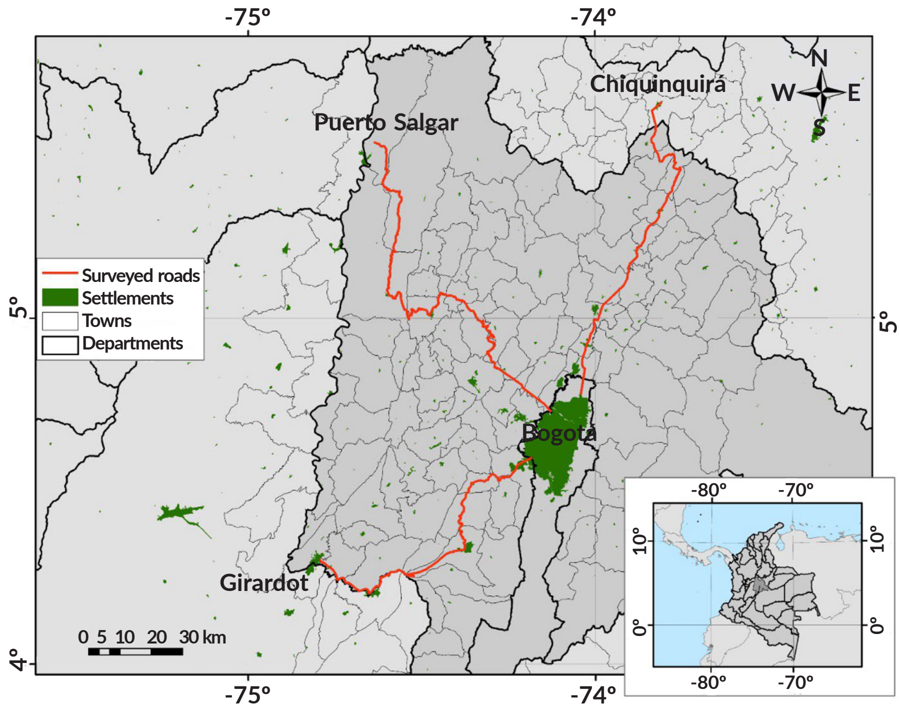

Fig. 1. Study area in the department of Cundinamarca, Colombia, showing roads surveyed to assess roadkill. The map includes the Bogotá-Girardot, Bogotá-Puerto Salgar, and Bogotá-Chiquinquirá corridors.

***Fig. 1.** Zona de estudio en el departamento de Cundinamarca (Colombia) con las carreteras en las que se estudiaron los atropellos. El mapa comprende los corredores de Bogotá-Girardot, Bogotá-Puerto Salgar y Bogotá-Chiquinquirá.*

40 that connects the country transversely from west to east, from the municipality of Buenaventura (department of Valle del Cauca, Pacific region, western part of the country) to Puerto Carreño (department of Vichada, eastern border of the country), and connects the country's capital and the department with the southern and western regions of Colombia. The road does not cross any protected areas but presents an ecosystem characterized by an interrupted mosaic where tropical rainforest predominates (González-Maya et al 2019b). B-PS is a road corridor that has an approximate length of 173 km, with a variation by sections between 2-6 paved lanes between 4° 43' 43.9'' N, 74° 07' 36.6'' W and 5° 28' 26.6'' N, 74° 38' 49.9'' W. This highway is part of National Route 45, or Troncal del Magdalena, which connects the country longitudinally from south to north, from the San Miguel bridge (department of Nariño, southern border with Ecuador) to the municipality of Ciénaga (department of Magdalena, northern border with the Caribbean Sea) and connects the country's capital and the department with the northern region of Colombia. This highway also crosses the eastern mountain range that has a predominance of tropical rainforest interrupted by anthropogenic activities (González-Maya et al 2019b). B-C has an approximate length of 122 km and presents a variation by sections between 2-6 paved lanes between 4° 49' 31.7'' N, 74° 02' 03.2'' W and 5° 36' 39.4'' N, 73° 49' 36.4'' W. This highway is part of the National Route 45A, or Troncal Central, which connects the capital, Bogotá DC, with the municipality of San Alberto (department of Cesar) and from there it connects with the Troncal del Magdalena, connecting the capital with the northwestern part of the country (departments of Cundinamarca, Boyacá, Santander and Cesar). This corridor starts in the north of the country and crosses areas dominated by agricultural crops, livestock and remnants of secondary Andean forests of reduced extension (fig. 1) (González-Maya et al 2019b).

The three corridors have a high flow of private, public and cargo vehicles, being part of the most important economic routes in the region as they directly connect the center with the north, south and west of the country, and the capital. It is estimated that 35 % of cargo transportation (Rodríguez-Cano and Cano Torres 2018) and 31 % of passengers in the country (Mintransporte 2005) are mobilized in the main highways of the department.

Field sampling and species characterization

We conducted a total of 88 surveys, distributed in 30 for corridor B-PS, 30 for corridor B-G and 28 for corridor B-C for 14 months, from August 2018 to November 2019, surveying all corridors (round trip) at least once in the sampling week alternately. Each run started at 5:30 am, ending at 7:00 pm, at an average speed of 40 km/h (Artavia-Rodriguez 2015). In total, 12,176 km were traveled in the three corridors: 3,570 km in B-G, 5,190 km in B-PS, and 3,416 km in B-C.

To facilitate comprehensive carcass identification and secure roadway clearance, vehicular stops were

Table 1. Variables used to identify the sites with the highest probability of vertebrate roadkills in three road corridors of the Cundinamarca department, Colombia.

Tabla 1. Variables utilizadas para determinar los lugares con la mayor probabilidad de atropellos de vertebrados en los tres corredores viales del departamento de Cundinamarca (Colombia).

Variable	Description of the variable	Source	Other studies
Biomass	Biomas of aerial vegetation (mg/ha)	Avitabile et al (2016)	Brémond et al (2013)
Natural coverage buffer 1 km	Natural coverage (ha)	IDEAM et al (2017)	Meza-Joya et al (2019)
Natural coverage buffer 5 km	Natural coverage (ha)	IDEAM et al (2017)	Meza-Joya et al (2019)
Distance to rivers	Double rivers (m)	IGAC (2016)	Meza-Joya et al (2019)
Distance to streams	Simple rivers (m)	IGAC (2016)	Meza-Joya et al (2019)
Distance to towns	Towns (m)	IGAC (2016)	Meza-Joya et al (2019)
Distance to natural coverage	Natural coverage (m)	IDEAM et al (2017)	Smith and Dood (2003)
Elevation	Digital elevation (m)		Meza-Joya et al (2019)
Sinuosity	Continue (índice 0-1)	IGAC (2016)	Delgado-Trejo et al (2018)

implemented at suspected roadkill sites after detection. Adherence to roadside parking regulations (ART.77. CNTT.2002) mandated off-road vehicle placement with the deployment of safety cones and hazard lights. Subsequent to these actions, a spatial data collection protocol was initiated, encompassing georeferencing, photographic documentation, and temporal recording. Carcasses were handled using personal protective equipment (PPE), including surgical gloves, face masks, and shovels. To decrease the risk of duplicate counts, bodies were staged in vegetated areas adjacent to the roadway. For species identification, we consulted the guide of terrestrial and semi-aquatic continental carnivores of Colombia (Suárez et al 2015), the catalog of amphibians and reptiles of Colombia (ACH, Asociación Colombiana de Herpetología 2022-2024, available online: https://www.acherpetologia.org/), the guide of birds of Colombia (McMullan et al 2010), and the practical necropsy guide for wild animals (Uhart and Rago 2010), among other consultation sources. Roadkill frequency was calculated as the number of roadkill individuals per kilometer traveled on each road, following the method of Zanzini et al (2018).

Identification of sites with high incidence of roadkill

The three study corridors were delineated using the official Colombian road map (IGAC 2018) and each recorded roadkill location was georeferenced (Saranholi et al 2016). Segments of 300 m were generated along the three highways, proposed as an appropriate resolution for cluster identification (Ramp et al 2006) and based on visibility and scale aspects (see spatial modeling and sinuosity, Ózcan and Ózkazanç 2017, Chen and Koprowski 2016), and the number of events in each segment was counted. K Ripley spatial distribution analysis was performed at 95 % confidence level to identify whether the distribution of these points was homogeneous (Boots and Getis 1988). To identify roadkill hotspots, we conducted a hotspot analysis using the Getis-Ord Gi* statistic (Getis and Ord 1992). This method statistically identifies significant clusters of roadkill events by examining the spatial distribution of points relative to their neighbors (Langen et al 2009, Saranholi et al 2016, Bedoya-V et al 2018). To define the threshold distance for the search of significant units, we performed an incremental spatial autocorrelation analysis to identify the threshold where the spatial correlation of the events was maximized, and thus where underlying geographic processes could explain the clusters (Zhang et al 2015, Siabato and Guzmán-Manrique 2019). All analyses were performed using ArcGIS 10. 5 (ESRI 2016)

Spatial modeling

To estimate the probability of occurrence of roadkill events and the effect of variables on this probability (Imam and Kushwaha 2013) we used a generalized linear model based on binary distribution with *logit* link (King and Langche 2001, Pearce and Ferrier 2001, González-Maya et al 2019a). Each roadkill record was characterized using nine variables. Eight of these were landscape-related (anthropogenic and natural), including distance to the nearest natural vegetation, rivers, streams, and towns. Additionally, we calculated road sinuosity. To assess landscape context, 1 km and 5 km buffers were created around each event (Meza-Joya et al 2019), within which, total natural cover was estimated using data from IDEAM et al (2017) (table 1). We also calculated elevation and biomass for each record (Brémond et al 2013, Meza-Joya et al 2019, González-Maya et al 2019a, table 1). Finally, we used the division by segments already established (300 m; Ozcan and Ózkazanç 2017, Chen and Koprowski 2016), and for each one we estimated the sinuosity index, which estimates the difference between the shortest distance between the start and end point, and the total distance traveled by the segment (Rautela and Pant 2007, Medrano-Vizcaíno 2015, Carvalho- Roel et al 2019); with index ranges from 0 to 1, with 1 representing a straight line and lower values indicating greater sinuosity (Rautela and Pant 2007, Delgado-Trejo et

Table 2. Species and number of road killed vertebrate individuals in three road corridors of the Cundinamarca department, Colombia. The total number of roadkills by species and the percentage by higher taxon (PHT, n = 51) are presented: B-PS, Bogotá-Puerto Salgar; B-G, Bogotá-Girardot; B-C, Bogotá Chiquinquirá.

Tabla 2. Especies y número de ejemplares de vertebrados atropellados en los tres corredores viales del departamento de Cundinamarca (Colombia). Se presentan el número total de atropellos por especie y el porcentaje por taxón mayor (PHT, n = 51): B-PS, Bogotá-Puerto Salgar; B-G, Bogotá-Girardot; B-C, Bogotá Chiquinquirá.

Class	Species	B-PS	B-G	B-C	Total	PHT (%)
Mammalia	*Didelphis marsupialis*	12	11	4	27	67.30
	Cerdocyon thous	1	2	0	3	
	Sciurus granatensis	1	0	1	2	
	Tamandua tetradactyla	0	1	0	1	
	Leopardus tigrinus	0	0	1	1	
	Leopardus pardalis	0	1	0	1	
Reptilia	*Iguana iguana*	1	3	0	4	19.12
	Boa constrictor	0	2	0	2	
	Epicrates cenchria	0	2	0	2	
	Spilotes pullatus	0	2	0	1	
Aves	*Turdus fuscater*	1	0	0	1	11.53
	Penelope montagnii	3	0	0	3	
	Tyrannus melancholicus	1	1	0	2	
Amphibia	*Rhinella marina*	0	1	0	1	1.92
Total		20	26	6		

a1 2018). Subsequently, 156 additional record points were generated randomly (three times the number of records) (González-Maya et al 2019a), equally distributed for each of the roads, and the same variables were calculated for these (González-Maya et al 2019a). To avoid including highly correlated variables, a Pearson correlation was performed between all variables for all data, and those with a significant correlation coefficient greater than 0.7 were excluded (Schober et al 2018).

Models were generated and evaluated using the *best subset* method, which consists of estimating all possible combinations of explanatory variables to then select the most competitive models using the Akaike Information Criterion corrected for small samples (AICc), and choosing the most competitive models from among all possible candidates as those with $\Delta < 2$ (Bozdogan 1987, White 1982, Zhang 2016). As more than one competitive model was found, the maximum likelihood method based on AIC weights (AICw) was used to weight the final model (Burnham and Anderson 2004). Once the best explanatory model was obtained, the model value was estimated for each road segment and was standardized and weighted to a 0-100 scale, indicating the sites with the highest roadkill risk percentage, which was extrapolated to the three corridors (González-Maya et al 2019a). Additionally, contingency tables were used to see the relationship between climatic season and roadkill. A χ^2-test was applied to contrast whether the observed data of roadkills by class did not depend on the climatic seasons (rainy and sunny) (Castillo-R et al 2015).

All analyses were performed using ArcGIS 10.5 software (ESRI 2016), R statistical software (R Team Development Core 2019) and Infostat (Di Rienzo et al 2017).

Results

A total of 154 animal roadkill records were collected with 51 involving wild species across the three study corridors (table 2). Mammals were the most frequently affected group, accounting for 67.3 % of all collisions (15, 14, and 6 events for corridors B-G, B-PS, and B-C, respectively), followed by reptiles, birds, and amphibians. These records represent 15 species: six mammals, four birds, four reptiles, and one amphibian (table 2). No other group approached the mammal collision rate, with all other vertebrates combined accounting for 32.6 % of the total roadkill incidents. Corridor B-G showed the highest number of collisions (26) and species diversity (10), followed by B-PS with 20 individuals and seven species. Corridor B-C had the lowest number of collisions (6) and species (3). The lowest roadkill rate occurred on B-C (0.002 indiv./km), followed by B-PS (0.004 indiv./km) and B-G (0.007 indiv./km). *Didelphis marsupialis* was the most frequently recorded roadkill species with 27 individuals, while eight other species were represented by a single record (table 2). All individuals recorded on each of the roads were in a moderate state of decomposition, facilitating their identification to the lowest possible taxonomic level (fig. 2).

Fig. 2. Main species affected by roadkill in three road corridors of Cundinamarca department, Colombia: A, *Tamandua tetradactyla;* B, *Leopardus tigrinus;* C, *Boa constrictor;* D, *Sciurus granatensis;* E, *Didelphis marsupialis;* F, *Penelope montagnii*.

Fig. 2. *Principales especies afectadas por los atropellos en los tres corredores viales del departamento de Cundinamarca (Colombia): A,* Tamandua tetradactyla*; B,* Leopardus tigrinus*; C,* Boa constrictor*; D,* Sciurus granatensis*; E,* Didelphis marsupialis*; F,* Penelope montagnii.

Sites with high incidence of roadkill

Incremental spatial autocorrelation analysis revealed a maximum correlation distance of 7.5 km (annex 1), indicating that spatial processes influence data variability within this distance. Consequently, 25 segments were analyzed to identify significant roadkill concentrations within each segment. The K-Ripley analysis showed distribution of the points was not homogeneous, with higher accumulations of frequencies towards certain segments ($p < 0.05$). Hotspot analysis revealed distinct clusters of roadkill events with statistically significant concentrations ($p < 0.01$). We identified a total of 38 significant 300-meter hotspots: 25 on corridor B-G and 13 on B-PS. In corridor B-G, the hotspots were located in the municipalities of Ricaurte, Nilo and Melgar (Tolima department), concentrated between the area of the Tolemaida military base and the Piscilago Aquatic and Conservation Park, where 19 of the 26 total records for this route were concentrated. In the B-PS corridor, hotspots were concentrated in the municipalities of Villeta, Nimaima and Nocaima, where 9 of the 20 total records were detected. No hotspots were identified for B-C (fig. 3).

Spatial modeling

Although some variables were correlated, none exceeded the proposed threshold (< 0.70). It is worth mentioning the correlation between distance to rivers and elevation (Pearson = 0.67, $p < 0.001$) and between natural cover in the 1 and 5 km buffers (Pearson = 0.65, $p < 0.001$). After estimating all possible combinations and using all selected variables, we chose two models according to the AICc. Model 1 indicated that roadkill probability was influenced by elevation and sinuosity. Model 2 expanded on this by incorporating natural cover (within a 5 km radius) as an additional predictor (table 3). The final weighted model (table 3) identified sinuosity as the primary predictor of roadkill probability, with higher values associated with increased risk. Elevation had a negative influence, meaning higher probabilities occurred at lower elevations while natural cover within a 5 km radius positively correlated with roadkill probability, indicating a higher likelihood in areas with more natural habitat (table 3).

Model extrapolation to the three corridors showed that the majority of segments (> 60 %) had medium to high roadkill probabilities (fig. 4A, 4B). Notably, approximately 20 % of segments had an extremely high probability (90-100 %) of roadkill occurrence (fig. 4B). The B-G corridor exhibited the highest average roadkill probability for all segments (81.60 ± 14.19), followed by B-PS (77.05 ± 15.39) and B-C (65.44 ± 5.03; fig. 4B). For the B-G corridor, the highest roadkill probability segments were concentrated between Fusagasuga and Girardot (fig. 4A). On B-PS, high-probability segments clustered in lowland areas, primarily within the municipalities of Villeta, Guaduas, Caparrapí, and Puerto Salgar (fig. 4A). In contrast, B-C showed lower overall probabilities, with 80 % of segments falling between 60 and 70 %, and no segments exceeding 80 % (fig. 4B).

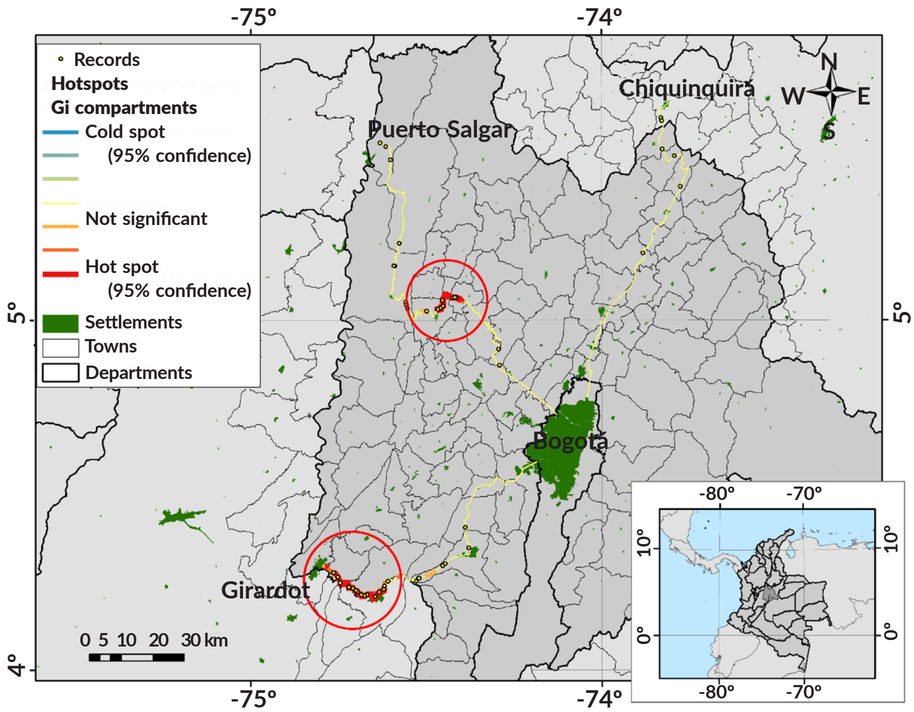

Fig. 3. Hotspot analysis showing the areas with the highest significant concentrations of vertebrate roadkills in three road corridors in the department of Cundinamarca, Colombia. The red circles indicate the hotspot concentration zones.

***Fig. 3.** Análisis de los puntos críticos donde se muestran las zonas con mayor concentración de atropellos de vertebrados de los tres corredores viales del departamento de Cundinamarca (Colombia). Los círculos rojos indican las zonas en las que se concentra el mayor número de atropellos.*

Climatic seasons were found to significantly influence the number of roadkills for the three corridors (χ^2 = 9.7, gl = 3, p = -0.05).

Discussion

Although Colombia is a leader in Latin American roadkill research, comprehensive data remain scarce across much of the country (Monge-Nájera, 2018), limiting the comparability result within the study area. Despite extensive sampling, insufficient data prevented detailed subgroup analyses due to unreliable estimates. Nevertheless, the information collected allowed us to establish that mammals are the most frequent victims of roadkill on the sampled highways. While medium-sized mammals were those most highly represented, factors such as body size and carcass removal rates may also influence our results (table 2). Our findings align with previous studies in Antioquia, Sucre, and Magdalena, which reported mammals as the most impacted group due to their ecological traits (Delgado-Vélez 2007, 2009, De la Ossa and Galván-Guevara 2015). Despite this, the roadkill rate for all four vertebrate groups across the three corridors (B-G = 0.007 indiv./km; B-PS = 0.004 indiv./km; B-C = 0.002 indiv./km) was lower than rates reported in other studies (0.21-0.32 indiv./km), even though those studies used smaller sample sizes (De la Ossa-Nadjar and De la Ossa-V 2015, Monroy et al 2015, Bedoya-V et al 2018). Climatic season significantly influenced roadkill patterns. Bird, reptile, and amphibian roadkill rates were higher than expected during the rainy season, while mammal rates were unexpectedly higher during the dry season. While our one-year dataset limits conclusive findings, Gumier and Sperber (2009) reported reduced vertebrate activity and road use during the rainy season. Although Castillo et al (2015) confirmed this pattern for mammals, our results suggest potential variations for other vertebrate groups (table 4). Continued monitoring is necessary to clarify these discrepancies.

It is also of note that the relatively low number of roadkill records in this study may reflect the barrier effect of roads, which impedes organismal movement, dispersal, and colonization (Arroyave et al 2006). This fragmentation can lead to metapopulation dynamics, characterized by population fluctuations and increased extinction risk: while fencing and underpasses can mitigate these impacts, their effectiveness varies and requires further investigation (McCollister and Van Manen 2010). In some localities in North America, for instance, it has been reported that only 3 % of the individuals of two small mammal populations cross a road (Gossemn 2002), and it has even been suggested that this effect would have a greater impact than roadkills (Arroyave et al 2006). Another potential factor influencing roadkill rates is the roadside effect, characterized by changes in biotic and abiotic conditions near roads. These alterations can affect verte-

Table 3. Competitive models and selected variables, including the weighted model coefficients (Coef.), to estimate the probability of vertebrate roadkills in three road corridors of the Cundinamarca department, Colombia: M, model; SE, standard error; AICc, Akaike's information criterion corrected for small samples, AICw, AIC weights; Wv, weighted variable; Wc, Weighted coefficient.

Tabla 3. Modelos competitivos y variables seleccionadas, incluidos los coeficientes ponderados (Coef.) de los modelos para estimar la probabilidad de que se produzca el atropello de un vertebrado en los tres corredores viales del departamento de Cundinamarca (Colombia): M, modelo; SE, error estándar; AICc, criterio de información de Akaike corregido para muestras pequeñas; AICw, pesos de Akaike; Wv, variable ponderada; Wc, coeficiente ponderado.

M	Variable	Coef.	SE	N	AICc	ΔAICc	Likelihood	AICw	Wv	Wc
1	Intercept	-6.660	3.960	207	221.080	0.000	1.000	0.440	Intercept	-6.6648
	Elevation	-0.001	0.000						Elevation	-0.0007
	Sinuosity	6.580	4.060							
2	Intercept	-6.678	39.715	207	223.070	1.990	0.370	0.160		
	Sinuosity	6.587	4.062						Sinuosity	6.5819
	Natural cover (5 km)	3.50E-09	3.20E-08							
	Elevation	-0.001	2.00E-04						Natural cover (5 km)	3.50E-09

brate distribution and abundance, with some groups, such as birds, being particularly sensitive (Reijnen et al 1996). While the lower abundance of roadkill on lane B-C than on lane B-G might be partly explained by the different landscape characteristics (tropical rainforest vs. agricultural crops), overall animal abundance could also influence these results. Further research on animal distribution and population density within these corridors is needed to disentangle the relative importance of roadside effects and habitat suitability in respect to roadkill rates. Additionally, carcass removal rates might have impacted the recorded number of roadkill incidents, potentially influencing the observed patterns.

Mammals were the group most affected by roadkills in our study, with some interesting specific cases. We documented 27 roadkills involving *Didelphis marsupialis* (table 2), consistent with findings from northwestern Colombia and other tropical regions. This species' scavenging and generalist ecological habits likely contribute to its high roadkill rate (De la Ossa-Nadjar and De la Ossa-V, 2013, 2015, Castillo-R et al 2015). The finding of three *Cerdocyon thous* individuals is noteworthy, aligning with prevalence rates in Colombia's Caribbean region (De la Ossa and Galván-Guevara 2015). Additionally, single records were obtained for *Leopardus pardalis* and *Leopardus tigrinus*, both considered ecologically important felids (Delgado-Vélez 2007, 2009, González-Maya et al 2022). Of note, *L. tigrinus* is classified as Vulnerable by the IUCN Red List (Payán and de Oliveira 2016) and it was detected in high roadkill probability segments (fig. 4).

Reptiles were the second most frequently recorded group. Previous studies in Colombia have linked reptile roadkill to daylight hours, suggesting that warm asphalt attracts these ectothermic animals for thermoregulation (De la Ossa-Nadjar and De la Ossa-V 2013, López-Herrera et al 2016). However, due to their size, reptile carcasses may be visible on the road for less time as their decomposition is faster, and consequently, the frequency of roadkill may be underestimated (De la Ossa-Nadjar and de la Ossa-V 2013, López-Herrera et al 2016). Regarding birds, previous research found

Table 4. χ^2-test (contingency table) of association between climatic season and roadkill occurrence by taxonomic class (χ^2 = 9.7, gl = 3, p = 0.05).

Tabla 4. Prueba de la χ^2 (tabla de contingencia) de la asociación entre la estación del año y el número de atropellos por clase taxonómica (χ^2 = 9,7; gl = 3; p = 0,05).

		Class				
Season		Mammalia	Aves	Reptilia	Amphibia	Total
Rainy	Observed	13	6	4	1	22
	Expected	15.1	2.6	3.9	0.4	22.0
Dry	Observed	22	0	5	0	29
	Expected	19.9	3.4	5.1	0.6	29.0
Total		35	6	9	1	51
		35.0	6.0	9.0	1.0	51.0

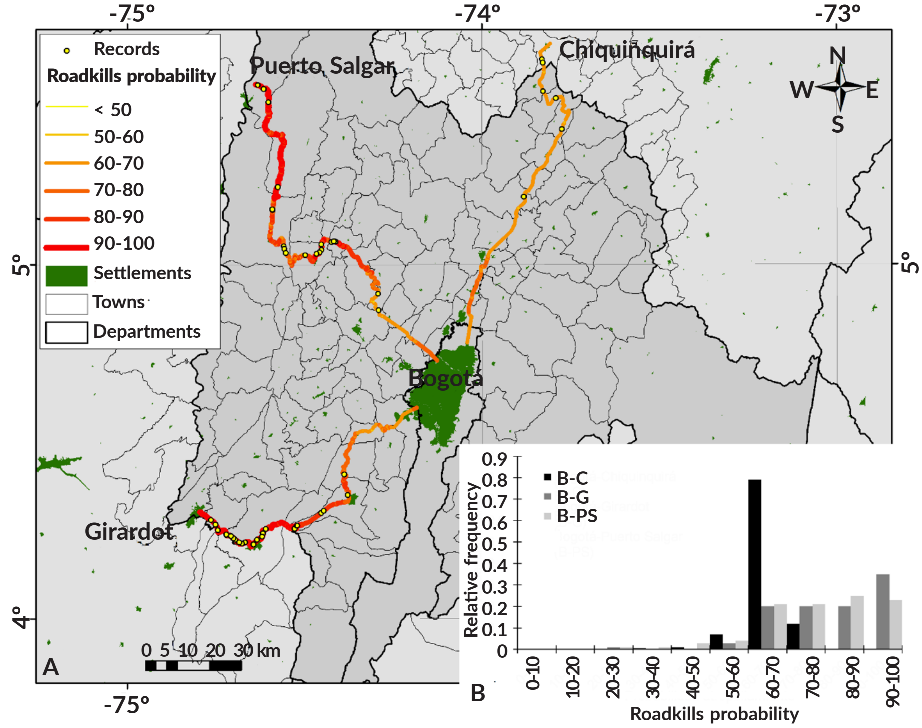

Fig. 4. Distribution of (A) the spatial probability of roadkills and (B) the frequency of roadkills in three road corridors in the department of Cundinamarca, Colombia: BC, Bogotá-Chiquinquirá; BG, Bogotá-Girardot; B-PS, Bogotá-Puerto Salgar.

Fig. 4. Distribución de (A) la probabilidad espacial de los atropellos y (B) la frecuencia de atropellos en los tres corredores viales del departamento de Cundinamarca (Colombia): BC, Bogotá-Chiquinquirá; BG, Bogotá-Girardot; B-PS, Bogotá-Puerto Salgar.

this group was that most affected by roadkills, suggesting their abundance, feeding, and flight habits as the proximal causes of their vulnerability (Florido-Cuellar 2015, Bedoya-V et al 2018). However, this was not the case in our study as they were the third most affected group. Interestingly, despite infrequent roadkill records, *Penelope montagnii* may be particularly vulnerable to vehicle collisions due to its limited flight capabilities and ground-dwelling behavior (Sua-Becerra et al 2012). In general, carcass detectability is a primary consideration in roadkill surveys (Santos et al 2016). Our methodology likely underestimated the total number of roadkill incidents, especially for non-mammalian groups due to the potential to overlook smaller or decomposed carcasses. This possibility could introduce a bias towards larger, more visible species, highlighting the need to consider these factors when interpreting our results and designing future studies.

Road characteristics, such as sinuosity and proximity to natural vegetation, have been identified as key factors influencing road traffic crashes and increasing the likelihood of wildlife-vehicle collisions (Forman and Alexander 1998, Gunson et al 2011). Most studies have linked road sinuosity to increased vehicle speeds and higher roadkill rates across terrestrial vertebrates (Delgado-Trejo et al 2018). However, our findings suggest the opposite: greater sinuosity was associated with a lower probability of roadkill. This discrepancy might be attributed to improved driver visibility on curved roads (Grilo et al 2009), rather than increased speeds as proposed by Barthelmess (2014). Additionally, the ability of different species to react to potential collisions (Mazerolle et al 2005) could influence this relationship, also with differential response by different taxonomic groups. On the other hand, variables such as elevation have been widely identified in previous studies as potential drivers of the likelihood of roadkill (Canal et al 2018), but also in the context of Cundinamarca, it implies an increase in species diversity and the presence of ecosystems that offer larger habitat areas for species towards lower areas, probably indicating a higher probability of roadkill (Andrade-C 2011, González-Maya et al 2019b). It is important to consider that there may also be a synergistic effect between sinuosity and elevation, although the data did not reflect this in terms of correlation between these two variables. It is also noteworthy that proximity, context, and composition of natural habitats available in roadside areas are considered among the main factors that increase the occurrence of vertebrate roadkill (Smith and Dood 2003, Attademo et al 2011). In this study, natural cover within a 5 km radius significantly increased the probability of roadkill, particularly for mammals and reptiles. These groups were more prevalent in segments with higher roadkill rates, likely due to the presence of food, shelter, and connectivity provided by these areas (Forman and Alexander 1998, Attademo et al 2011, Gunson et al 2011).

While the hotspot analysis and modeling approach aligns with common practices in this field, more specific methods tailored to individual study groups (Ramp et al 2005) are warranted for deeper insight. This study establishes a crucial foundation for addressing roadkill in the study area. High-probability roadkill segments identified in this study should provide prime locations for wildlife crossings, such as overpasses and ecoducts. However, these interventions should be integrated into a comprehensive highway strategy to effectively mitigate the overall impact of road infrastructure. When feasible, future studies should consider additional infrastructure and landscape variables,such as road width, number of lanes, traffic volume, and average speed. Incorporating habitat type surrounding study segments, as suggested by Santos et al (2018), could also provide valuable insights into the relationship between habitat and roadkill rates for different species groups. Moreover, considering species-specific factors such as population density, behavior, and ecology will enhance the precision of future research.

Finally, the diversity of species affected in this study highlights the wide range of groups threatened by the phenomenon of roadkills, reinforcing the importance of considering vehicle collisions as a significant threat to the department's biodiversity. Although this is one of the first systematic studies of road ecology in Cundinamarca and lays the foundation for long-term monitoring, it is crucial to recognize the dynamic nature of wildlife roadkill. As the hotspots identified in this study could change over time, caution is advised when implementing highly specific prevention measures in specific locations. Instead, we suggest that focus should be placed on general measures along road sections, especially for the most affected groups. This would enable greater adaptability of wildlife to changes in road use patterns. Additionally, future studies with a higher sampling frequency could provide a more detailed view of the spatial and temporal dynamics of roadkill, allowing more precise adjustment of mitigation measures.

Given the substantial pressures on biodiversity in densely populated regions such as Cundinamarca and the critical importance of this biodiversity hotspot, detailed assessment of threats is crucial. This study not only provides a foundation for addressing and mitigating one of these threats but also underscores the urgent need for systematic and adaptive approaches to biodiversity conservation in critical tropical areas.

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Author contributions
Camilo A. Paredes-Casas, **Diego A. Zárrate-Charry**, **Ginna P. Gómez-Junco, José F. González-Maya** conceived the study design. **Camilo A. Paredes-Casas** performed the fieldwork. All authors analyzed the data, wrote the manuscript, edited and review the final document.

Conflicts of interest
No conflicts declared.

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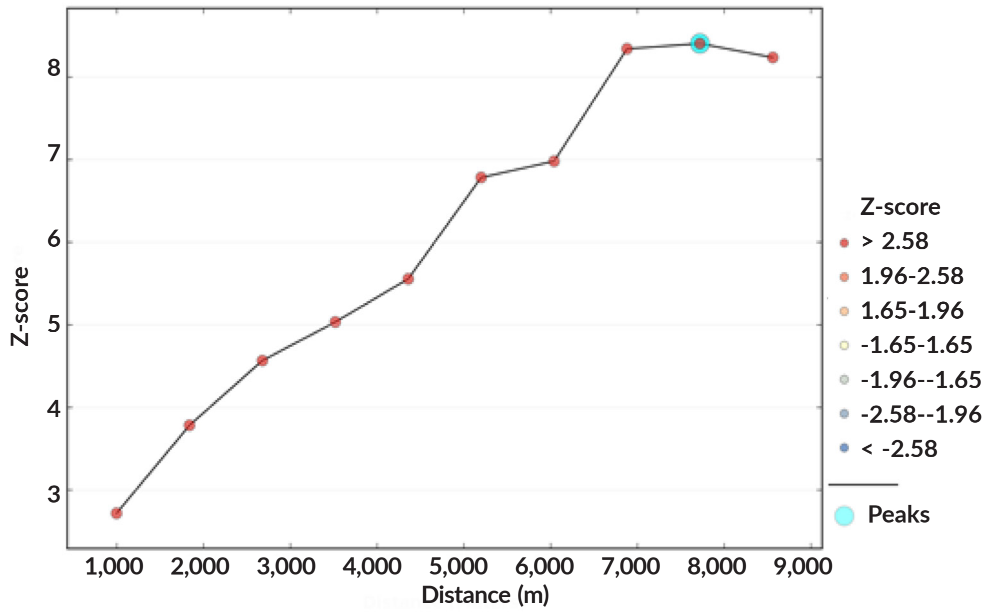
Supplementary material



Annex 1. Incremental spatial autocorrelation analysis indicating a maximum correlation distance of 7.5 km.

Anexo 1. *Análisis de la autocorrelación espacial incremental que indica una distancia de correlación máxima de 7,5 km.*