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Research paper

Assessing the impact of human activities and land use change on livestock depredation by large carnivores in Mexico

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Abstract

Assessing the impact of human activities and land use change on livestock depredation by large carnivores in Mexico. Human-carnivore conflicts, arising from the predation of domestic animals, contribute to global declines in carnivore populations, primarily due to retaliatory and preventative killings. Understanding the contextual factors that commonly lead to such conflicts is crucial for developing policies and strategies that mitigate economic losses for individuals and reduce human-caused mortality of carnivores. In this study, we used livestock predation insurance claim records filed in Mexico from 2017 to 2020, alongside potentially significant anthropogenic and landscape variables, to explore the relationship between the occurrence of livestock predations and the degree of disturbance or transformation of natural habitats across the country. Our findings reveal that predation sites were widespread throughout Mexico, but their distribution varied in relation to the degree of anthropogenic transformation of habitats. The occurrences of predation by jaguar, puma, and black bear were associated with landscape attributes indicative of anthropogenic changes, including urbanization, deforestation, habitat conversion to intensive agriculture, roads, cultivated pastures, and *livestock density*. We propose that classified model of anthropic variables can serve as an effective planning tool to identify, prioritize, and address the vulnerability of livestock to carnivores, providing a strategic framework for managing and mitigating human-carnivore conflicts.

Key words: Anthropic variables, Conservation planning, Human-wildlife coexistence, *Panthera onca*, *Puma concolor*, *Ursus americanus*

Resumen

Evaluación del impacto de las actividades humanas y el cambio del uso del suelo en la depredación de ganado por grandes carnívoros en México. Los conflictos entre humanos y carnívoros, que surgen de la depredación de animales domésticos, contribuyen a la disminución global de las poblaciones de carnívoros, principalmente debido a matanzas preventivas y de represalia. Comprender los factores contextuales que comúnmente conducen a tales conflictos es crucial para elaborar políticas y estrategias que mitiguen las pérdidas económicas para las personas y reduzcan la mortalidad de carnívoros causada por el hombre. En este estudio, utilizamos los registros de reclamaciones de seguro por ataque de depredación de ganado presentados en México de 2017 a 2020, junto con variables antropogénicas y paisajísticas para estudiar la relación entre la frecuencia de los casos de depredación de ganado y el grado de perturbación o transformación de los hábitats naturales en todo el país. Nuestros resultados revelan que los sitios de depredación estaban extendidos por todo México, pero su distribución varía en función del grado de transformación antropogénica de los hábitats. La frecuencia de los casos de depredación protagonizados por jaguares, pumas y osos negros se relacionó con características del paisaje indicativas de cambios antropogénicos, como la urbanización, la deforestación, la conversión del hábitat a agricultura intensiva, las carreteras, los pastos cultivados y la densidad de ganado. Proponemos que el modelo clasificado de variables antrópicas que puede servir como una herramienta de planificación eficaz para identificar, priorizar y abordar la vulnerabilidad del ganado ante los carnívoros, y proporcionar un marco estratégico para gestionar y mitigar los conflictos entre humanos y carnívoros.

Palabras clave: Variables antrópicas, Planificación de la conservación, Coexistencia entre humanos y vida silvestre, *Panthera onca*, *Puma concolor*, *Ursus americanus*

Introduction

The predation of livestock by carnivores constitutes a significant source of conflict with humans globally, imposing considerable economic strain on smallholders and rural communities (Inskip and Zimmermann 2009, Amador-Alcalá et al 2013, Peña-Mondragón and Castillo 2013, Gervasi et al 2021, Krofel et al 2021). This conflict not only threatens carnivores but also increases the costs of their coexistence with humans (Kansky et al 2014, Flores-Armillas et al 2019, Torres-Romero et al 2023, Torres-Romero and Bender 2024). In response to such challenges, farmers and ranchers often resort to lethal measures to mitigate losses (e.g., Hoogesteijn et al 2016, Treves et al 2016, Chinchilla et al 2022, Torres-Romero et al 2023, Torres-Romero and Bender 2024), leading to the decline of local, regional, and global predator populations (Woodroffe et al 2005, Hoogesteijn et al 2016, Torres-Romero et al 2020).

Understanding the reasons behind the spatial patterns and variations in the impact of large carnivores on livestock farming is a complex issue due to its multidimensional nature (Gervasi et al 2021). This form of human-carnivore conflict involves various factors, both ecological and social, such as general mechanisms of predation ecology, local densities of large carnivores and their prey, landscape features influencing cover available for carnivores, their encounter rates with livestock, predation success, and livestock husbandry practices (Linnell et al 2012, Gervasi et al 2014, Ghoddousi et al 2016, Ciucci et al 2020).

Mexico is home to three large carnivore species known for preying on livestock: the American black bear *Ursus americanus*, puma *Puma concolor*, and jaguar *Panthera onca* (Oropeza-Hernández et al 2014, CNOG 2014, Flores-Armillas et al 2019). Previous studies have demonstrated that the populations of these three large carnivores can be impacted by human-caused habitat transformation. For example, jaguars and bears have disappeared across more than 60 % and 80 %, respectively, of their original distribution in Mexico, (Ceballos et al 2021, Delfín-Alfonso et al 2012). While the situation for pumas in Mexico is not extensively documented (Lopez-González and González-Romero 1998), there is a prevailing belief in their decline across large areas of the country (Chávez-Tovar 2005, Rosas-Rosas and Nuñez 2014). In Mexico, the puma has historically been reported in all states and practically all habitats, including pastures or agricultural fields (Chávez-Tovar and Ceballos 2014). However, habitat loss, hunting, and road density are significant drivers of puma population decline (LaRue and Nielsen 2011). For example, nearly 60 % of puma habitat remains across Latin America (Laundré and Hernandez 2010, LaRue and Nielsen 2011, Angelieri et al 2016).

Intensive landscape changes resulting from urbanization, deforestation, and intensive agriculture have led to the contraction of the geographic ranges of carnivore populations (Laliberte and Ripple 2004, Wolf and Ripple 2017, Torres-Romero et al 2020). Consequently, these populations are compelled to share space and resources with humans, potentially increasing human-carnivore conflicts, especially when natural prey and/or suitable habitats have been reduced (Azevedo and Murray 2007, Khanal et al 2020, Torres-Romero et al 2020, Naha et al 2021). Competition for limited resources, exacerbated by increased land use changes and poor livestock management often ignites conflicts, primarily in the form of predations on livestock and pets (Treves et al 2004, Ramesh et al 2020). These conflicts can be influenced by the overexploitation of local natural prey (Bradley and Pletscher 2005, Wolf and Ripple 2017), human population growth, unsustainable livestock ranching, and generally poor livestock management practices (Zarco-González et al 2013, Hoogesteijn et al 2016, Kuijper et al 2016, Rosas-Rosas et al 2020, Monter et al 2021).

Carnivore-induced livestock predation is often influenced by various ecological factors, including proximity to and extent of human settlements, densely forested areas, water sources, and roads (Bradley and Pletscher 2005, Chávez and Zarza 2009, Zarco-González et al 2013, Torres-Romero et al 2023, Torres-Romero and Bender 2024). These factors, along with poor livestock management and farming practices, must be considered potential drivers of livestock predation at local or regional scales (Kaartinen et al 2009, Torres-Romero and Bender 2024). Despite their significance, there remains a notable scarcity of investigation into the extent and magnitude of these conflicts across Mexico. In this study, we used livestock predation insurance claims from 2017 to 2020 to understand the extent of carnivore predation on livestock in Mexico and identify associated predation variables. Our aim was to deepen our understanding of how livestock predation, coupled with human-induced disturbances and biophysical factors, contributes to the likelihood of human-carnivore conflicts. We sought to identify the magnitude and scope of carnivore predation on livestock to develop strategies aimed at reducing risk and mitigating the vulnerability of livestock to predation (Miller 2015). While we anticipate an increase in the probability of livestock predation events in human-modified landscapes, uncertainties persist regarding which anthropogenic and landscape variables promote or reduce the likelihood of livestock attacks by carnivores.

Methods

Study area

Mexico, a country with rich ecological diversity spanning nearly two million km^2 in southern North America (fig. 1) (INEGI 2017), showcases a varied topography, with over 65 % of its landmass situated above 1,000 m. This diversity extends to various climates, including tropical rainy, dry/xeric (inland and coastal), temperate, cold, and other climatic zones (García 2004). The country's vegetation is equally diverse, encompassing tropical forests, temperate forests, coastal dry forests, coastal plains, deserts, and alpine ecosystems (Rzedowski 2006). Agriculture plays a crucial role in Mexico, contributing approximately 3.5 % to the country's GDP (World Bank 2015). About 63.5 % of Mexico's land is dedicated to agricultural production, with around

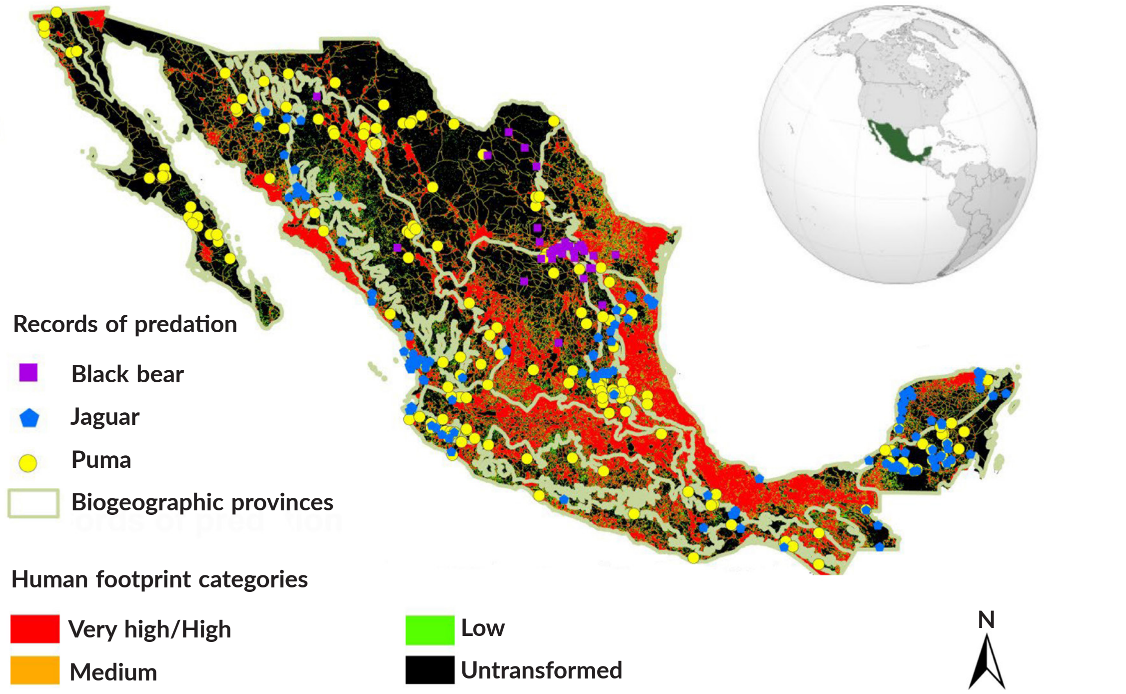

Fig. 1. Locations of sites of livestock predation by black bears, jaguars, and pumas in Mexico, as well as human footprint impact related to highest occurrence of predation risk along biogeographic provinces grouped into categories (i.e., untransformed, low, medium, and high/very high human footprint, respectively; see González-Abraham et al (2015) for further details about human footprint).

Fig. 1. Ubicación de los lugares donde se producen casos de depredación por osos negros, jaguares y pumas en México, así como la relación entre el impacto de la huella humana y el máximo riesgo de depredación en las provincias biogeográficas agrupadas en categorías (por ejemplo, sin transformar, huella humana baja, media y alta o muy alta, respectivamente; véase González-Abraham et al (2015) para obtener más información sobre la huella humana).

13.5 % allocated to intensive agriculture, such as row cropping, cultivated pastures, and livestock feedlots, and 43–50 % to extensive native grazed rangeland (Peel et al 2010, Ibarrola-Rivas and Nonhebel 2019). Ejidos, which are communal lands managed primarily for agriculture by local communities, constitute 43.4 % of Mexico's land, while small rural agrarian communities account for 9.1 % (CEDRSSA 2019). Due to its vast diversity, Mexico is divided into 19 biogeographic provinces based on the known distribution of vascular plants, amphibians, reptiles, mammals, and major morphotectonic features (Arriaga et al 1997). This division reflects the complexity and richness of Mexico's ecological and agricultural landscapes.

Livestock predation records

The database containing records of livestock predation by pumas, jaguars, and black bears from 2017 to 2020 was provided by the National Agricultural and Rural Assurance Fund (FanCampo https://fancampoyvida.com.mx; formerly the National Confederation of Livestock Organizations - CNOG, https://cnog.org.mx/articulos-revista/fancampo-y-fanvida; for further reference see FanCampo and CNOG; permission to use this livestock predation database was obtained from the compilers and authors at FanCampo/CNOG). This union group, authorized by the relevant authorities, offers specialized risk coverage and various services, including 'insurance for livestock losses', which compensates producers for losses caused by predators (CNOG 2014). FanCampo's livestock insurance peoples are highly skilled in identifying the carnivore species responsible for predation events, utilizing diverse forensic methodologies (Torres-Romero et al 2023; Torres-Romero and Bender 2024). Since not all livestock producers, especially small-scale or subsistence farmers, opt for livestock insurance, the predation records from FanCampo likely underestimate the true extent of predation. The exact degree of this bias is unknown but is presumed to be considerable. Nonetheless, given the extensive dataset on livestock predation, it likely provides a relatively representative survey of the impact of carnivores and the relative vulnerability of livestock.

Occurrence records

Including variables that might elevate the probability of livestock predation based solely on the spatial occurrence of reported attacks can yield misleading results as records of attacks may be confounded with general occurrence records for the carnivore species. Therefore, the detected effect of variables explaining the spatial occurrence of predation records might merely reflect those explaining species occurrence. To mitigate this, we used species occurrence records as the baseline for subsequent comparisons with livestock predation records (see below). All presence records, along with associated geographical coordinates, were sourced from free online databases, including REMIB (http://www.conabio.gob.mx/remib), UNIBIO (http://unibio.unam.mx/), Global Biodiversity Information Facility (GBIF, https://www.gbif.org), and iNaturalist (www.iNaturalist.com.mx). We gathered 1,062 occurrences for jaguar, 1,015, for puma and 137 for black bear.

Independent variables

We formulated a model to predict the probability of livestock attacks by large carnivores based on three proxies of human-induced disturbances and biophysical factors within human-altered landscapes (see table 1). First, we used human population density (HPD), road Density (RD) (Meijer et al 2018), and human footprint (HFP) to assess human impact on the landscape. Following González-Abraham et al (2015), we categorized HFP into three impact levels, high, medium, and low/untransformed. This layer spatially represents various sources of direct human modification of the land surface, including human settlements, cultivated land (i.e., agriculture, forestry plantations, and cultivated grasslands), cultivated coasts (i.e., related to marine aquaculture), and roads (González-Abraham et al 2015). We used some of the variables grouped by HFP such RD and HPD to investigate potential detailed effects not captured by the synthetic variable. Secondly, since the occurrence of livestock attacks might be expected to rise with the availability of livestock, we integrated spatial data compiled by Gilbert et al (2018) on cattle, pigs, sheep, goats, horses, and chickens. These livestock species are the most abundant species in Mexico and play an important economic role for local producers and rural communities. To prevent over-parameterization of subsequent models while accounting for the availability of all livestock species, we created a synthetic variable by summing the densities of each species. Lastly, we included landscape attribute variables such as natural protected areas (NPA) and forest canopy height (FCH), both serving as potential proxies for more intact or densely forested areas, acting as refuges for carnivores (see table 1, CONANP 2022, Simard et al 2011). A Spearman correlation was used to examine the associations among variables at occurrence records for each species and flagged those (if any) with correlations of $P \geq 0.7$. Additionally, we evaluated collinearity between variables using the variance inflation factor (VIF), with a threshold of four indicating low collinearity (Hair et al 2014).

Macroecological analyses

We evaluated the effects of landscape and human-related variables on the prevalence of predation records given the spatial distribution of each species. For each species, we first constructed a binomial variable set, where 1 indicated the occurrence of a predation event for one of the three carnivore species, and 0 represented the occurrence of a species without a recorded predation event. This approach allowed us to distinguish locations where a predation event occurred within the known distribution of each species from locations where the species occurred but without a recorded predation. Species occurrence records falling within the buffer of a predation occurrence record were excluded because it was plausible that the individuals recorded in these occurrences might also be responsible for the livestock predation. Our analysis focused on the results derived from a 10 km buffer; although alternative buffers yielded similar outcomes (see table 1s). The selection of a 10 km buffer size was informed by the understanding that the home ranges of carnivores can vary significantly due to factors such as region, season, or the presence of highly productive sites. We chose this buffer size based on findings from other studies: the minimum average home range of female black bears in Vancouver, approximately 7.83 km² (Davis et al, 2006); the home-range dynamics of female black bears in a recovering population in Western Maryland, approximately 8.9 km² (Jones et al 2015); and the observed movement patterns of female jaguars, typically encompassing a minimum area of 10 km² in a Central American tropical forest habitat (Rabinowitz and Nottingham 1986). We then fitted logistic regression models (i.e., generalized linear models with a logit link and binomial error family) as a function of each of the prospective predictor variables described above, and did so independently for each species. Next, we used a backward model selection based on AICc, a corrected measure for selecting and comparing models based on the log-likelihood-2 (restricted) (Cavanaugh and Neath 2019). We identified the best models, computing the total explained deviance for the best models (pseudo R^2) and the partial deviance explained for each predictor independently. The partial deviance was computed as the full model pseudo R^2 -pseudo R^2 of a model excluding the targeted predictor (see Calatayud et al 2019 for more details). The partial deviance explained for each predictor independently indicates the fraction of deviance attributable to each predictor alone. Finally, for categorical variables (e.g., Human Footprint and Natural Protected Areas), we explored the effects of each categorical level using least squared means via the *emmeans* R package (Lenth 2021). All analyses were conducted in R software 3.4.1 (R Core Team 2021), using the AICcmodavg (Mazerolle 2020) to compute AICc.

Results

We collected 339 predation occurrence sites for all species, and 179, 121, and 39 livestock predation records attributable to pumas, jaguars, and black bears, respectively (fig. 1). The variables selected for the best model explaining the predation events for each carnivore species varied slightly (tables 2s to 4s). Our models show that HFP, FCH, and HPD appeared to be important for all three species. Conversely, RD was only included in the best model for puma-caused predation, whereas NPAs was only important in the best model for jaguar. The deviance explained by the best models ranged widely, likely due to the differences in sample size: ~5 % for puma, ~7 % for jaguar, and ~31 % for black bear (fig. 2). Looking at partially

Table 1. Set of variables and sources used to predict the occurrence of predation by large carnivores in Mexico.

Tabla 1. Conjunto de variables y fuentes utilizadas para predecir la frecuencia de los casos de depredación por grandes carnívoros en México.

Class	Variables, type, and original spatial resolution	Source
Human impacts	Human population density/continuous/1 km^2	CIESIN (2015)
	Road density/ continuous/8 km^2	Meijer et al (2018)
	Human footprint/categorical	González-Abraham et al (2015)
Livestock density	Cattle/ continuous/10 km^2	Gilbert et al (2018)
	Horses/ continuous/10 km^2	
	Goats / continuous/10 km^2	
	Sheep / continuous/10 km^2	
	Hogs/ continuous/10 km^2	
	Chickens/ continuous/10 km^2	
Landscape attributes	Natural protected areas/categorical	CONANP (2022)
	Forest canopy height /continuous/1 km^2	Simard et al (2011)

explained deviances, HFP was the predictor explaining the greatest deviance for pumas and black bears (pseudo R^2 = 3.7 and 26.2 %, respectively, fig. 2). For jaguars, HPD explained the greatest deviance alone (pseudo R^2 = 3.6 %) closely followed by HFP (pseudo R^2 = 2.8 %, see fig. 2). HPD was the second most important variable, explaining more of the deviance for pumas and black bears (pseudo R^2 = 12.8 %, fig. 2). FCH was the second best variable (pseudo R^2 = 1.1 %) for pumas, closely followed by HPD (pseudo R^2 = 0.8 %).

Our least squared mean regression on categorical predictors highlighted that predation events were lower in regions with a lower HFP, but became more frequent in regions where the impact of the HFP increased (least squared mean coefficients for high HFP = 0.39, 0.18, and 0.92; medium HFP = 0.30, 0.16, and 0.33; low HFP = 0.16, 0.07, and 0.08; respectively for puma, jaguar, and black bear; fig. 3). For jaguars, the probability of livestock predation was lower inside natural protected areas than outside such areas(least squared mean coefficients inside NPAs = 0.10 and outside NPAs = 0.17; fig. 3).

Regression coefficients for continuous predictors showed that the probability of predation declined as HPD increased for all carnivore species (regression coefficient were 0.39, 0.14, and 0.01 for puma, jaguar, and black bear, respectively; fig. 3), likely due to the swamping effect of urbanization. However, the probability of livestock predation for all species increased as the amount of FCH increased (regression coefficient were 0.60, 0.72, and 0.60 for puma, jaguar, and black bear, respectively; fig. 3).

Finally, we found that the zones with the greatest predation events occurred along the coastal plains of the Gulf of Mexico, and inland from there along an east-to-west corridor that follows the Mexican transversal volcanic belt and the associated upland plateau (fig. 1).

Discussion

Carnivores face endangerment and population declines due to hunting and various forms of persecution (Inskip and Zimmerman 2009, Packer et al 2013, Wolf and Ripple 2017, Torres-Romero et al 2023, Torres-Romero and Bender 2024). This study addresses the scarcity of coarse-scale knowledge concerning the macroecological drivers of human-carnivore conflicts. Our findings underscore those three large carnivores –black bears, jaguars, and pumas– more frequently prey on livestock in areas of high anthropogenic disturbance (table 3). One might argue that the observed result could be attributed to the variability in the availability of livestock in regions with varying levels of human transformation of habitats (Marchini and Macdonald 2012, Dickman et al 2014, Ramesh et al 2020). However, it is plausible that this nuanced aspect is not fully captured by our results and synthetic measures in the analysis of livestock density (fig. 2). Despite our efforts, there may be limitations in comprehensively capturing the intricate relationship between human footprint impacts and livestock distribution. Nevertheless, it is worth noting that even when we examined the density of each livestock species independently, we consistently observed similar effects of the human footprint variable (table 5s).

Our analysis reveals significant geographic and spatial variations in carnivore livestock predation records across Mexico, documenting 339 incidents by FanCampo. However, this likely underrepresents the total livestock predations occurring nationwide, as indicated by other sources (CNOG 2020, Oropeza-Hernández et al 2014, Torres-Romero et al 2023, Torres-Romero and Bender 2024). Despite this limitation, there is a notable and widespread risk of human-carnivore conflict throughout the country, with

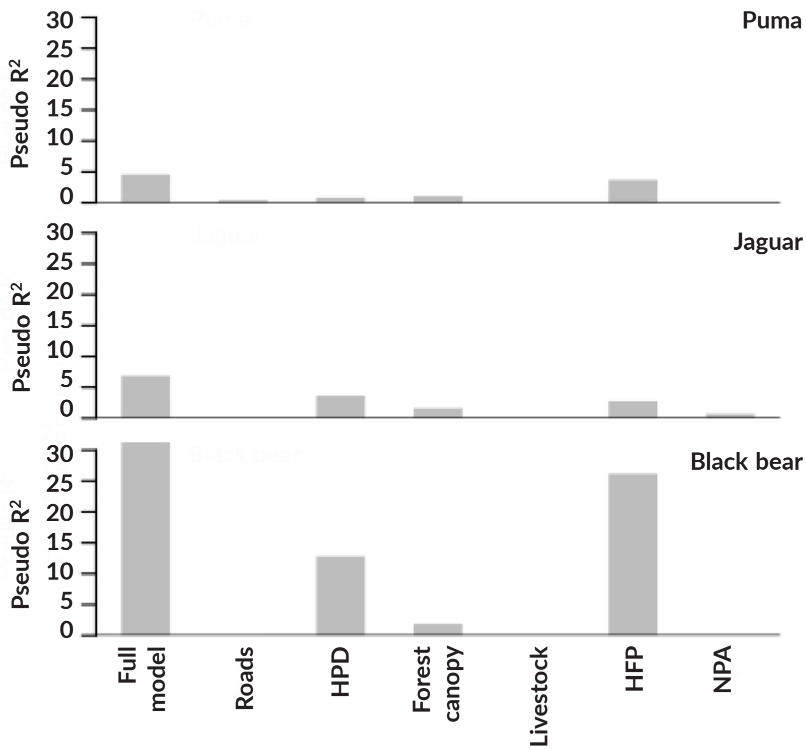

Fig. 2. Explained deviance (%) for the best models and each predictor independently: HPD, human population density; HFP, human footprint; and NPA, natural protected areas.

Fig. 2. *Desviación explicada (%) de los mejores modelos y cada uno de los indicadores independientemente; HPD, densidad de población humana; HFP, huella humana; NPA, áreas naturales protegidas.*

our analysis supporting a positive nationwide relationship between the occurrence of livestock predations and the degree of disturbance or transformation of natural habitats. This observation aligns with the broader context of Mexico, where approximately 55 % of the land area is now under significant medium to high human impacts (González-Abraham et al 2015). These impacts stem from factors such as increased human population growth, urbanization, agricultural expansion and intensification, and transportation infrastructure development (González-Abraham et al 2015). Anticipated future acceleration of these land use changes across Mexico suggests that their adverse effects on the remaining natural vegetation cover of the country will persist (González-Abraham et al 2015). As Mexico continues to undergo these transformations, the challenges of mitigating human-carnivore conflict and preserving natural habitats for wildlife are likely to intensify despite poor livestock management and farming practices.

Several key factors were associated with elevated livestock predation events by large Mexican carnivores. These included a greater extent of canopy cover, a relatively high population of humans, and high anthropogenic transformation or conversion of the land, findings similar to those identified by Zarco-González et al (2013) and Reyna-Saenz et al (2019). Additionally, our findings underscore the importance of proximity to protected areas, where local carnivore populations may have increased access to livestock within agricultural landscapes while still occupying some of the best habitats in the region, or likely due to the greater availability of both domestic animals and natural prey. These natural landscapes may also serve as prime territory for ranging livestock, as the positive association between the areas used for livestock grazing and large carnivores may be due to more intense competition in productive habitats, which host higher-quality food sources for many herbivores (Torres-Romero et al 2020). This association may also be due to humans replacing wild ungulates with cattle, thereby supplementing potential prey for large carnivores and facilitating prey switching (Torres-Romero et al 2020). Furthermore, we observed that the probability of predation increased as urbanization (i.e., HPD) decreased, likely because both high human population densities and infrastructural thresholds (e.g., towns and cities) prevent the presence of carnivores and their prey.

Our results also suggest that livestock predation by pumas and jaguars specifically seemed to escalate in environments with a high percentage of forest cover. While this pattern is notably observed in the tropical forests of southeast Mexico (Zarco-González et al 2013), such conflict hotspots were not exclusive to this region. Dense forest coverage likely serves as a refuge and crucial cover for carnivores, acting

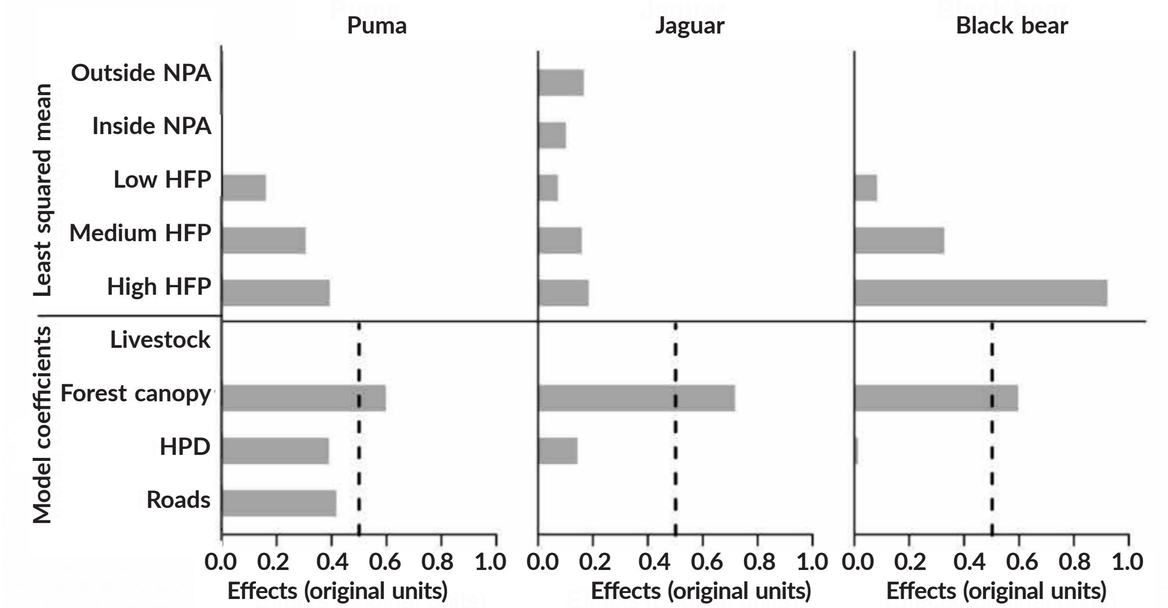

Fig. 3. Least squared mean effects for levels of categorical variables (HFP, human footprint; NPA, natural protected areas) and regression coefficients for quantitative predictors (i.e. road density; livestock density; forest canopy height; human population density [HPD]). Mean effects and regression coefficients are provided in original units after inverse logit transformation. The dotted lines represent 0.5 probability. Quantitative variables with regression coefficients smaller than 0.5 have negative effects on the prevalence of livestock predation. Note: variables lacking bars were not selected in the best model based on AICc (i.e., they were not significant).

Fig. 3. *Promedio de los efectos calculado con el método de mínimos cuadrados para los niveles de variables categóricas (HFP, huella humana; NPA, áreas naturales protegidas) y coeficientes de regresión para los indicadores cuantitativos (por ejemplo, la densidad de carreteras, la densidad de ganado, la altura de la cubierta forestal, la densidad de población humana [HPD]). El promedio de los efectos y los coeficientes de regresión se indican en unidades originales tras la transformación logarítmica inversa. Las líneas discontinuas representan una probabilidad de 0,5. Las variables cuantitativas con coeficientes de regresión inferiores a 0,5 tienen efectos negativos en la frecuencia de la predación del ganado. Nota: las variables que no se indican en las barras no fueron seleccionadas en el mejor modelos sobre la base del AICc (esto es, no fueron significativas).*

as movement corridors facilitating predator transit between ranches and protected areas (Rosas-Rosas et al 2008). Conversely, for black bears, the spatial occurrence of predation records on livestock increased as the land surface became increasingly dominated by human activities. In Mexico, bears readily habituate to the presence of humans, adapting to urbanization, agricultural land use changes, and other modifications (Juárez-Casillas and Varas 2013, Nuñez-Torres et al 2020). Their less cryptic nature and diurnal behavior relative to large felids makes them more conspicuous near human settlements (Ditmer et al 2018). These conditions are characteristic of much of northeastern Mexico, which represents the black bear's distribution constraints between Mexico and the US, marking the southern edge of the species' range.

In conclusion, our study, in alignment with others (Montalvo et al 2016, Treves et al 2011, Torres-Romero et al 2023, Torres-Romero and Bender 2024), underscores that incidents of livestock predation follow discernible patterns, arising from a complex interplay of landscape, anthropogenic, topographic, and environmental factors. While some factors may be beyond our control, we emphasize the significance of addressing anthropogenic changes through strategic interventions such as urban planning, selective logging, and infrastructural development that consider wildlife needs (Kuiper et al 2022, Torres-Romero et al 2023, Torres-Romero and Bender 2024). Additionally, promoting more intensive agriculture over expansive practices, while leaving adequate wildlife habitat, can establish crucial movement corridors in human-modified landscapes. Effective management of high-level human development and targeted efforts in regions economically vulnerable to predator-induced losses are pivotal in conflict prevention and tolerance enhancement, respectively (Krofel et al 2021, Torres-Romero et al 2023, Torres-Romero and Bender 2024). Classification of of key variables shows that evaluating the magnitude of, and identifying risk factors associated with carnivore predation on livestock emerges as a valuable tool for conflict management, conservation planning, and the formulation of wildlife management programs (Bagchi and Mishra 2006, Torres-Romero and Bender 2024). For instance, these models can effectively classify and predict predation events, thereby facilitating the development of tailored policies that subsidize effective conflict mitigation and prevention tools and resources for financially vulnerable communities. Moreover, these models exhibit adaptability to evolving data, accommodating new variables identified by subsequent studies and offering flexibility to be assessed at different regional scales, thus catering to the diverse needs of states or local municipalities.

References

Amador-Alcalá S, Naranjo EJ, Jiménez-Ferrer G, 2013. Wildlife predation on livestock and poultry: implications for predator conservation in the rainforest of south-east Mexico. *Oryx* 47(2), 243-250. DOI: 10.1017/S0030605311001359

Angelieri CC, Adams-Hosking C, Ferraz KM, de Souza MP, McAlpine CA 2016. Using Species Distribution Models to Predict Potential Landscape Restoration Effects on Puma Conservation. *Plos One* 11(1), e0145232. DOI: 10.1371/journal.pone.0145232

Azevedo FC de, Murray DL, 2007. Evaluation of potential factors predisposing livestock to predation by jaguars. *The Journal of Wildlife Management* 71(7), 2379-2386. DOI: 10.2193/2006-520

Arriaga L, Espinoz, JM, Aguilar C, Martínez E, Gómez L, Loa E, (Coord), 2000 Regiones terrestres prioritarias de México. Comisión Nacional para el Conocimiento y Uso de la Biodiversidad. CONABIO, Mexico. http://www.conabio.gob.mx/conocimiento/regionalizacion/doctos/terrestres.html

Bagchi S, Mishra C, 2006. Living with large carnivores: predation on livestock by the snow leopard (*Uncia uncia*). *Journal of Zoology* 268(3), 217-224. DOI: 10.1111/j.1469-7998.2005.00030.x

Bradley EH, Pletscher DH, 2005. Assessing factors related to wolf depredation of cattle in fenced pastures in Montana and Idaho. *Wildlife Society Bulletin* 33(4), 1256-1261. DOI: 10.2193/0091-7648(2005)33[1256:AFRTWD]2.0.CO;2

Calatayud J, Rodríguez MÁ, Molina-Venegas R, Leo M, Horreo, JL, Hortal J, 2019. Pleistocene climate change and the formation of regional species pools. *Proceedings of the Royal Society B* 286(1905), 20190291. DOI: 10.1098/rspb.2019.0291

Cavanaugh JE, Neath AA, 2019. The Akaike information criterion: Background, derivation, properties, application, interpretation, and refinements. *WIREs, Wiley Interdisciplinary Reviews: Computational Statistics* 11(3), e1460. DOI: 10.1002/wics.1460

Ceballos G, Zarza H, González-Maya JF, de la Torre JA, Arias-Alzate A, Alcerreca C, Barcenas HV, Carreón-Arroyo G, Chávez C, Cruz C, Medellín D, 2021. Beyond words: from jaguar population trends to conservation and public policy in Mexico. *Plos One* 19(6), e0305642. DOI: 10.1371/journal.pone.0305642

CEDRSSA (Center for Studies on Sustainable Rural Development and Food Sovereignty), 2019. Resultados de la Encuesta Nacional Agropecuaria. Available online at: http://www.cedrssa.gob.mx/ [Accessed January 2023].

Chávez-Tovar JC, 2005. Puma (*Puma concolor*). In: *Los Mamíferos Silvestres de México*: 364-367 (G. Ceballos, G. Oliva, Eds). CONABIO-UNAM-Fondo de Cultura Económica, México DF, México.

Chávez-Tovar C, Ceballos G, 2014. Puma. In: *Mammals of Mexico*: 505-507 (G Ceballos, Ed). Johns Hopkins University Press, Baltimore, USA.

Chávez C, Zarza H, 2009. Distribución potencial del hábitat del jaguar y áreas de conflicto humano-jaguar en la península de Yucatán. *Revista Mexicana de Mastozoologia* 13(1), 46-62. DOI: 10.22201/ie.20074484e.2009.13.1.35

Chinchilla S, Van den Berghe E, Polisar J, Arévalo C, Bonacic C, 2022. Livestock-Carnivore coexistence: Moving beyond preventive killing. *Animals (Basel)* 12(4), 479. DOI: 10.3390/ani12040479

CIESIN, CIAT, 2015. *Gridded Population of the World, version 4 (GPWv4): Population density grid*. NASA Socioeconomic Data and Applications Center (SEDAC), Palisades, NY, USA.

Ciucci P, Mancinelli S, Boitani L, Gallo O, Grottoli L, 2020. Anthropogenic food subsidies hinder the ecological role of wolves: insights for conservation of apex predators in human-modified landscapes. *Global Ecology and Conservation* 21, e00841. DOI: 10.1016/j.gecco.2019.e00841

CNOG, 2014. *Insurance of Death for the Attack of Predators*. LXXVIII Ordinary General Assembly, Zacatecas, México DF.

CNOG, 2020. *Datos sobre el Seguro Ganadero en México*. Reportes internos de la Confederación Nacional de Organizaciones Ganaderas, México DF

CONANP (Comisión Nacional de Áreas Naturales Protegidas), 2022. *Áreas Naturales Protegidas de México*. Semarnat-Conanp. http://sig.conanp.gob.mx/website/pagsig/info_shape.htm

Davis H, Weir RD, Hamilton AN, Deal JA, 2006. Influence of phenology on site selection by female American black bears in coastal British Columbia. *Ursus* 17(1), 41-51. DOI: 10.2192/1537-6176(2006)17[41:IOPOSS]2.0.CO;2

Delfín-Alfonso CA, López-González CA, Equihua M, 2012. Potential distribution of American black bears in northwest Mexico and implications for their conservation. *Ursus* 23(1), 65-77. DOI: 10.2192/URSUS-D-11-00007.1

Dickman AJ, Hazzah L, Carbone C, Durant SM, 2014. Carnivores, culture and 'contagious conflict': multiple factors influence perceived problems with carnivores in Tanzania's Ruaha landscape. *Biological Conservation* 178, 19-27. DOI: 10.1016/j.biocon.2014.07.011

Ditmer MA, Rettler SJ, Fieberg JR, Iaizzo PA, Laske TG, Noyce KV, Garshelis DL, 2018. American black bears perceive the risks of crossing roads. *Behavioral Ecology* 29(3), 667-675. DOI: 10.1093/beheco/ary020

Flores-Armillas VH, Valenzuela-Galván D, Peña-Mondragón JL, López-Medellín X, 2019. Human-wildlife conflicts in Mexico: Review of status and perspectives. *Ecosistemas y Recursos Agropecuarios* 7(1), e2274. DOI: 10.19136/era.a7n1.2274

García E, 2004. *Modificaciones al sistema de clasificación climática de Koppen: 90*. 5th edition. Instituto de Geografía-UNAM, México.

Gervasi V, Linnell JDC, Berce T, Boitani L, Cerne R, Ciucci P, Cretois B, Derron-Hilfiker D, Duchamp C, Gastineau A, Grente O, Huber D, Iliopoulos Y, Karamanlidis AA, Kojola I, Marucco F, Mertzanis Y, Männil P, Norberg H, Pagon N, Pedrotti L, Quenette P-Y, Reljic S, Salvatori V, Talvi T, von Arx M, Gimenez O, 2021. Ecological correlates of large carnivore depredation on sheep in Europe. *Global Ecology and Conservation* 30, e01798. DOI: 10.1016/j.gecco.2021.e01798

Gervasi V, Nilsen EB, Odden J, Bouyer Y, Linnell JDC, 2014. The spatio-temporal distribution of wild and domestic ungulates modulates lynx kill rates in a multi-use landscape. *Journal of Zoology* 292(3), 175-183. DOI: 10.1111/jzo.12088

Ghoddousi A, Soofi M, Hamidi AK, Lumetsberger T, Egli L, Khrozyan I, Kiabi BH, Waltert M, 2016. Assessing the role of livestock in big cat prey choice using spatiotemporal availability patterns. *Plos One* 11(4), 0153439. DOI: 10.1371/journal.pone.0153439

Gilbert M, Nicolas G, Cinardi G, Van Boeckel TP, Vanwambeke SO, Wint GRW, Robinson TP, 2018. Global distribution data for cattle, buffaloes, horses, sheep, goats, pigs, chickens and ducks in 2010. *Scientific Data* 5, 180227. DOI: 10.1038/sdata.2018.227

González-Abraham C, Ezcurra E, Garcillán PP, Ortega-Rubio A, Kolb M, Bezaury Creel JE, 2015. The Human Footprint in Mexico: Physical Geography and Historical Legacies. *Plos One* 10(5), e0121203. DOI: 10.1371/journal.pone.0121203

Hair JF, Black WC, Babin BJ, Anderson RE, 2014. *Multivariate Data Analysis*, 7th edition. Pearson Education Limited, Upper Saddle River.

Hoogesteijn A, López C, Núñez R, Rosas-Rosas O, Flebes J, 2016. El jaguar y las comunidades rurales: uso de densidad humana y bovina para identificar zonas de conflicto a nivel nacional en México. In: *Conflictos entre felinos y humanos en Latinoamérica, Bogotá, Colombia*: 49-60 (C Castaño-Uribe, R Lasso, A Hoogesteijn, A Díaz-Pulido, E Payan, Eds). Serie Editorial Fauna Silvestre Neotropical, Bogotá DC, Colombia.

Ibarrola-Rivas MJ, Nonhebel S, 2019. Does Mexico have enough land to fulfill future needs for the consumption of animal products?. *Agriculture* 9(10), 211. DOI: 10.3390/agriculture9100211

INEGI, 2017. *Anuario estadístico y geográfico de los Estados Unidos Mexicanos*. http://www.inegi.gob.mx. http://internet.contenidos.inegi.org.mx/contenidos/Productos/prod_serv/contenidos/espanol/bvinegi/productos/nueva_estruc/AEGEUM_2017/702825097912.pdf

Inskip A, Zimmermann C, 2009. Human-Felid conflict: a review of patterns and priorities worldwide. *Oryx* 43(1), 18-34. DOI: 10.1017/S003060530899030X

Jones MD, Tri AN, Edwards JW, Spiker H, 2015. Home-range dynamics of female Ursus americanus (Pallas)(American black bear) in a recovering population in western Maryland. *Northeastern naturalist 22*(4), 830-841. https://www.jstor.org/stable/26453738

Juárez-Casillas LA, Varas C, 2013. Evaluation of black bear (*Ursus americanus*) diet and consequences in its conservation in Sierra de Picachos, Nuevo León, Mexico. *Revista Mexicana de Biodiversidad* 84(3), 970-976. DOI: 10.7550/rmb.33376

Kaartinen M, Luoto M, Kojola I, 2009. Carnivore-livestock conflicts: Determinants of wolf (*Canis lupus*) depredation on sheep farms in Finland. *Biodiversity and Conservation* 18(13), 3503-3517. DOI: 10.1007/s10531-009-9657-8

Kansky R, Kidd M, Knight AT, 2014. Meta-analysis of attitudes toward damage-causing mammalian wildlife. *Conservation Biology 28*(4), 924-938. DOI: 10.1111/cobi.12275

Khanal G, Mishra C, Suryawanshi KR, 2020. Relative influence of wild prey and livestock abundance on carnivore-caused livestock predation. *Ecology and Evolution* 10(20), 11787-11797. DOI: 10.1002/ece3.6815

Krofel M, Elfström M, Ambarlı H, Bombieri G, González-Bernardo E, Jerina K, Laguna A, Penteriani V, Phillips JP, Selva N, Wilson SM, Zarzo-Arias A, Groff C, Huber D, Karamanlidis AA, Mertzanis Y, Revilla E, Bautista C, 2021. Human–Bear Conflicts at the Beginning of the Twenty-First Century: Patterns, Determinants, and Mitigation Measures. In: *Bears of the World. Ecology, Conservation and Management*: 213-226 (V Penteriani, M Melletti, Eds). Cambridge

University Press, Cambridge.
Kuijper DPJ, Sahlén E, Elmhagen B, Chamaillé-Jammes S, Sand H, Lone K. Cromsigt JP GM, 2016. Paws without claws? Ecological effects of large carnivores in anthropogenic landscapes. *Proceedings of the Royal Society B* 283, 20161625. DOI: 10.1098/rspb.2016.1625
Kuiper T, Loveridge AJ, Macdonald DW, 2022. Robust mapping of human-wildlife conflict: controlling for livestock distribution in carnivore depredation models. *Animal Conservation* 25(2), 195-207. DOI: 10.1111/acv.12730
LaRue M, Nielsen C, 2011. Modelling potential habitat for cougars in Midwest North America. *Ecological Modelling* 222(3), 897-900. DOI: 10.1016/j.ecolmodel.2010.11.017
Lenth R, 2021. *emmeans: Estimated Marginal Means, aka Least-Squares Means. R package version 1.7.1*. https://rvlenth.github.io/emmeans/
Laundré JW, Hernandez L, 2010. What we know about Pumas in Latin America. In: *Cougar: Ecology and Conservation*: 76 (M Hornocker, S Negri, Eds). University of Chicago Press. Chicago, IL.
Laliberté AS, Ripple WJ, 2004. Range contractions of North American carnivores and ungulates. *BioScience* 54(2), 123-138. DOI: 10.1641/0006-3568(2004)054[0123:RCONAC]2.0.CO;2
Linnell JDC, Odden J, Mertens A, 2012. Mitigation methods for conflicts associated with carnivore depredation on livestock. In: *Carnivore Ecology and Conservation: A Handbook of Techniques*: 314-332 (L Boitani, RA Powell, Eds). Oxford University Press, Oxford.
López González CA, González Romero A, 1998. A synthesis of current literature and knowledge about the ecology of the puma (*Puma concolor* Linneaus). *Acta Zoológica Mexicana* 75, 171-190. DOI: 10.21829/azm.1998.75751713
Mazerolle MJ, 2020. *AICcmodavg: Model selection and multimodel inference based on (Q)AIC(c)*. R package version 2.3-1. https://cran.rproject.org/package=AICcmodavg
Marchini S, Macdonald DW, 2012. Predicting ranchers' intention to kill jaguars: case studies in Amazonia and Pantanal. *Biological Conservation* 147(1), 213-221. DOI: 10.1016/j.biocon.2012.01.002
Meijer JR, Huijbegts MAJ, Schotten CGJ, Schipper AM, 2018. Global patterns of current and future road infrastructure. *Environmental Research Letters* 13(6), p.064006. DOI: 10.1088/1748-9326/aabd42
Miller JRB, 2015. Mapping attack hotspots to mitigate human–carnivore conflict: approaches and applications of spatial predation risk modelling. *Biodiversity and Conservation* 24, 2887-2911. DOI: 10.1007/s10531-015-0993-6
Monter YM, Chávez-Tovar JC, Gutiérrez FR, 2021. Territorial aptitude for ecological cattle production systems and the conservation of jaguar (*Panthera onca*) and puma (*Puma concolor*) in Guerrero, Mexico. *Applied Animal Science* 37(2), 225-237. DOI: 10.15232/aas.2020-02078
Montalvo V, Alfaro L, Saenz C, Cruz J, Fuller TK, Carrillo E, 2016. Factors affecting jaguar and puma predation on livestock in Costa Rica. *Wildlife Biology in Practice* 12(1), 32-42.
Naha D, Dash SK, Kupferman C, Beasley JC, Sathyakumar S 2021. Movement behavior of a solitary large carnivore within a hotspot of human-wildlife conflicts in India. *Scientific Reports* 11, 3862. DOI: 10.1038/s41598-021-83262-5
Nuñez-Torres M, Zarco-González MM, Monroy-Vilchis O, Carrera-Treviño R, 2020. Human–black bear interactions in Northern Mexico. *Human Dimensions of Wildlife* 25(3), 1-14. DOI: 10.1080/10871209.2020.1752419
Oropeza-Hernández P, Núñez-Pérez R, Delgadillo-Villalobos JA, García-Martínez M, Servín-Martínez J, Manríquez-Martínez RE, 2014. *Guía de convivencia para la prevención de ataques de animales domésticos por carnívoros silvestres y perros ferales*. SEMARNAT-CONANP, Mexico.
Packer C, Loveridge A, Canney S, Caro T, Garnett ST, Pfeifer M, Zander KK, Swanson A, MacNulty D, Balme G, Bauer H, 2013. Conserving large carnivores: dollars and fence. *Ecology Letters* 16(5), 635-641. DOI: 10.1111/ele.12091
Peel DS, Johnson RJ, Mathews KH, 2010. Cow-calf beef production in Mexico. USDA Livestock, Dairy, and Poultry Outlook No. LDP-M-196-01.
Peña-Mondragón JL, Castillo A, 2013. Depredación de ganado por jaguar y otros carnívoros en el noreste de México. *Therya* 4(3), 431-446. DOI: 10.12933/therya-13-153
Ramesh T, Kalle R, Milda D, Gayathri V, Thanikodi M, Ashish K, Giordano AJ, 2020. Patterns of livestock predation risk by large carnivores in India's Eastern and Western Ghats. *Global Ecology and Conservation* 24, e01366. DOI: 10.1016/j.gecco.2020.e01366
Rabinowitz AR, Nottingham BGJr, 1986. Ecology and behavior of the jaguar (Panthera onca) in Belize, Central America. *Journal of Zoology* 210, 149-159. DOI: 10.1111/J.1469-7998.1986.TB03627.X
Reyna-Sáenz F, Zarco-González MM, Monroy-Vilchis O, Antonio-Némiga X, 2019 Regionalization of environmental and anthropic variables associated to livestock predation by large carnivores in Mexico. *Animal Conservation* 23(2), 192-202. DOI: 10.1111/acv.12527
Rosas-Rosas OC, Bender LC, Valdez R, 2008. Jaguar and Puma Predation on Cattle Calves in Northeastern Sonora, Mexico. *Rangeland Ecology and Management* 61(5), 554-560. DOI: 10.2111/08-038.1
Rosas-Rosas OC, Núñez R, 2014. Jaguar y puma. In: *Ecología y Manejo de Fauna Silvestre en México*: 331-352 (R Valdez, JA Ortega-S, Eds). Colegio de Postgraduados, Texcoco, México.
Rosas-Rosas OC, Silva-Caballero A, Duran-Fernandez A (Eds), 2020. *Manejo y conservación del jaguar en la Reserva de la Biosfera Sierra del Abra Tanchipa*. Colegio de Postgraduados, Estado de México, México.
Rzedowski J, 2006. *Vegetación de Mexico*, 1st edition. Comisión Nacional para el Conocimiento y Uso de la Biodiversidad, México.
R Core Team, 2021. *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/
Simard M, Pinto N, Fisher JB, Baccini A, 2011. Mapping forestcanopy height globally with spaceborne lidar. *Journal of Geophysical Research* 116(G4). DOI: 10.1029/2011JG001708
Torres-Romero EJ, Bender LC, 2024. Extent and Patterns of Livestock Depredation in Mexico. *Rangeland Ecology and Management* 96(1), 23-31. DOI: 10.1016/j.rama.2024.05.002
Torres-Romero EJ, Giordano AJ, Ceballos G, López-Bao JV, 2020. Reducing the sixth mass extinction: Understanding the value of human-altered landscapes to the conservation of the world's largest terrestrial mammals. *Biological Conservation* 249, 108706. DOI: 10.1016/j.biocon.2020.108706
Torres-Romero EJ, Lira-Noriega A, Rosas-Rosas OC, Bender LC, 2023. Livestock Depredation by Coyotes and Domestic Dogs in Mexico. *Rangeland Ecology and Management* 87, 97-104. DOI: 10.1016/j.rama.2022.12.003
Treves A, Martin KA, Wydeven AP, Wiedenhoeft JE, 2011. Forecasting environmental hazards and the application of risk maps to predator attacks on livestock. *Bioscience* 61(6), 451-458. DOI: 10.1525/bio.2011.61.6.7
Treves A, Naughton-Treves L, Harper E, Mladenoff D, Rose R, Sickley T, Wydeven A, 2004. Predicting human-carnivore conflict: a spatial model derived from 25 years of data on wolf predation on livestock. *Conservation Biology* 18(1), 114-125. DOI: 10.1111/j.1523-1739.2004.00189.x
Treves A, Krofel M, McManus J, 2016. Predator control should not be a shot in the dark. *Frontiers in Ecology and the Environment* 14(7), 380-388. DOI: 10.1002/fee.1312
Wolf C, Ripple WJ, 2017 Range contractions of the world's large carnivores. *Royal Society Open Science* 4, 170052. DOI: 10.1098/rsos.170052
World Bank, 2015. *Agricultura, valor agregado (% del PIB)*. Available online at: http:// datosbancomundial.org/indicator/NV.AGR.TOTL.ZS?end=2014&locations= MX&start=1995&view=map&year=2015 [Accessed on January 2023].
Woodroffe R, Thirgood S, Rabinowitz A, 2005. The impact of human-wildlife conflict on natural systems. In: *People and Wildlife, Conflict or Co-existence?*: 1-12 (R Woodroffe, S Thirgood, A Rabinowitz, Eds). Cambridge University Press, England.
Zarco-González M, Monroy-Vilchis O, Alaníz J, 2013. Spatial model of livestock predation by jaguar and puma in Mexico: Conservation planning. *Biological Conservation* 159, 80-87. DOI: 10.1016/j.biocon.2012.11.007

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Author contributions
EJ Torres-Romero and **J Calatayud** designed the study, analyzed the data and wrote the paper with input from co-authors. All authors read and approved the final manuscript.

Conflicts of interest
No conflicts declared.

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Supplementary material

Table 1s. Explained deviance (%) for the best models and each predictor independently. Results using different buffers to omit species presences are provided: - variable not selected in the best model; RD, road density; HPD, human population density; FCH, forest canopy height; Livestock, livestock density; HFP, human footprint; and NPAs, natural protected areas.

Tabla 1s. Desviación explicada (%) de los mejores modelos y cada uno de los indicadores independientemente. Se indican los resultados obtenidos utilizando diferentes zonas de transición para omitir la presencia de las especies: - variable no seleccionada en el mejor modelo; RD, densidad de carreteras; APD, densidad de población humana; FCH, altura de la cubierta forestal; Livestock, densidad de ganado; HFP, huella humana; NPAs, áreas naturales protegidas.

Buffer (km)	Species	Full model	RD	HPD	FCH	Livestock	HFP	NPAs
0	Puma	4.48	0.32	0.72	0.92	-	3.88	-
	Jaguar	6.69	-	3.38	1.45	-	2.59	0.8
	Black bear	27.71	-	10.26	1.99	-	23.09	-
5	Puma	4.51	0.37	0.72	0.99	-	3.81	-
	Jaguar	6.88	-	3.46	1.5	-	2.78	0.78
	Black bear	27.71	-	10.26	1.99	-	23.09	-
10	Puma	4.58	0.39	0.82	1.08	-	3.71	-
	Jaguar	6.89	-	3.63	1.62	-	2.77	0.69
	Black bear	31.27	-	12.82	1.87	-	26.2	-
20	Puma	4.73	0.51	0.93	1.29	-	3.69	-
	Jaguar	7.03	-	3.98	1.7	-	2.57	0.62
	Black bear	30.82	-	11.71	1.88	-	26.34	-

Table 2s. Results of model selection based on AICc for jaguars: HPD, human population density; FCH, forest canopy height; HFP, human footprint; RD, road density; NPAs, natural protected areas; Livestock, livestock density. (In bold is the selected model).

Tabla 2s. Resultados de la selección de modelos basada en el AICc para los jaguares: HPD, densidad de población humana; FCH, altura de la cubierta forestal; HFP, huella humana; RD, densidad de carreteras; NPAs, áreas naturales protegidas; Livestock, densidad de ganado. (El modelo seleccionado se indica en negrita).

Included variables	AICc	Delta AICc
HPD+FCH+NPAs+HFP	**868.388**	**0**
Livestock+HPD+FCH+NPAs+HFP	870.094	1.706
RD+HPD+FCH+NPAs+HFP	870.207	1.819
Livestock+RD+HPD+FCH+NPAs+HFP	871.781	3.394
HPD+FCH+HFP	872.737	4.349
Livestock+HPD+FCH+HFP	874.524	6.136
Livestock+RD+HPD+FCH+HFP	875.843	7.455
HPD+NPAs+HFP	881.252	12.864
Livestock+RD+HPD+NPAs+HFP	882.285	13.898
Livestock+HPD+NPAs+HFP	883.081	14.693
HPD+FCH+NPAs	889.808	21.42
Livestock+HPD+FCH+NPAs	891.795	23.408
Livestock+RD+HPD+FCH+NPAs	892.657	24.269
Livestock+RD+FCH+NPAs+HFP	899.492	31.104
FCH+NPAs+HFP	899.796	31.408
Livestock+FCH+NPAs+HFP	901.271	32.882

Table 3s. Results of model selection based on AICc for pumas: HPD, human population density; FCH, forest canopy height; HFP, human footprint; RD, road density; NPAs, natural protected areas; Livestock, livestock density. (In bold is the selected model).

Tabla 3s. Resultados de la selección de modelos basada en el AICc para los pumas: HPD, densidad de población humana; FCH, altura de la cubierta forestal; HFP, huella humana; RD, densidad de carreteras; NPAs, áreas naturales protegidas; Livestock, densidad de ganado. (El modelo seleccionado se indica en negrita).

Included variables	AICc	Delta AICc
RD+HPD+FCH+HFP	**1144.977**	**0**
Livestock+RD+HPD+FCH+HFP	1145.931	0.954
RD+HPD+FCH+NPAs+HFP	1147.002	2.025
HPD+FCH+HFP	1147.616	2.638
Livestock+RD+HPD+FCH+NPAs+HFP	1147.959	2.982
Livestock+HPD+FCH+HFP	1149.103	4.126
Livestock+HPD+FCH+NPAs+HFP	1150.932	5.954
RD+FCH+HFP	1152.743	7.765
Livestock+RD+FCH+HFP	1153.588	8.61
Livestock+RD+FCH+NPAs+HFP	1155.609	10.632
RD+HPD+HFP	1155.752	10.774
Livestock+RD+HPD+HFP	1157.079	12.101
Livestock+RD+HPD+NPAs+HFP	1158.985	14.008
Livestock+RD+HPD+FCH	1184.77	39.792
RD+HPD+FCH	1184.992	40.015
Livestock+RD+HPD+FCH+NPAs	1186.748	41.77

Table 4s. Results of model selection based on AICc for black bears: HPD, human population density; FCH, forest canopy height; HFP, human footprint; RD, road density; NPAs, natural protected areas; Livestock, livestock density. (The selected model is in bold).

Tabla 4s. Resultados de la selección de modelos basada en el AICc para los osos negros: HPD, densidad de población humana; FCH, altura de la cubierta forestal; HFP, huella humana; RD, densidad de carreteras; NPAs, áreas naturales protegidas; Livestock, densidad de ganado. (El modelo seleccionado se indica en negrita).

Model formula	AICc	Delta AICc
HPD+FCH+HFP	**187.427**	**0**
RD+HPD+FCH+HFP	188.971	1.543
HPD+FCH+NPAs+HFP	189.079	1.652
HPD+HFP	190.145	2.717
RD+HPD+FCH+NPAs+HFP	190.805	3.378
Livestock+RD+HPD+FCH+HFP	190.997	3.57
Livestock+HPD+FCH+NPAs+HFP	191.128	3.701
RD+HPD+HFP	191.563	4.136
Livestock+RD+HPD+FCH+NPAs+HFP	192.855	5.428
RD+HPD+NPAs+HFP	193.632	6.204
Livestock+RD+HPD+NPAs+HFP	195.292	7.864
RD+FCH+HFP	206.381	18.953
RD+FCH+NPAs+HFP	207.599	20.172
Livestock+RD+FCH+NPAs+HFP	209.184	21.757
FCH+HFP	218.354	30.927
Livestock+RD+HPD+FCH+NPAs	237.645	50.218
RD+HPD+FCH+NPAs	247.683	60.256
HPD+FCH	250.749	63.322
RD+HPD+FCH	250.902	63.475

Table 5s. Results of sensitivity analysis on the covariation of livestock density and human impact. Least squared mean effects in original units are provided for high (High), medium (Medium), and low (Low) levels of human footprint. ΔAICc is calculated as the AICc of a model including all independent variables of livestock density and human footprint minus the AICc of a model excluding human footprint.

Tabla 5s. Resultados del análisis de sensibilidad sobre la covariación de la densidad de ganado y los efectos de la actividad humana. Se indica el promedio de los efectos calculado con el método de mínimos cuadrados en unidades originales para una huella humana elevada (High), media (Medium) y baja (Low). La ΔAICc se calcula como el AICc de un modelo que comprenda todas las variables independientes de la densidad de ganado y la huella humana menos el AICc de un modelo que excluya la huella humana.

Species	High	Medium	Low	Delta AICc
Jaguar	0.19	0.24	0.10	-11.150
Puma	0.30	0.27	0.18	-6.871
Black bear	0.83	0.81	0.20	-30.764