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Original Research

Livestock Depredation by Coyotes and Domestic Dogs in Mexico

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ABSTRACT

The impact of domestic dog and coyote depredation on livestock has received little attention in Mexico. We used livestock depredation insurance claims from 2017 to 2020 and landscape attributes to identify the magnitude of depredation and model the risk of depredation by domestic dogs and coyotes throughout Mexico using maximum entropy modeling. Combined livestock depredations by coyotes and domestic dogs comprised 50.3% of all livestock depredation claims in Mexico. Depredation by domestic dogs was associated with landscape attributes indicative of rural villages and subsistence livestock husbandry. More intensive or larger-scale agricultural land uses (e.g., farming, large ranching enterprises) were associated with coyote depredation, in particular increasing presence of small- to medium-sized livestock (i.e., sheep, etc.). Both domestic dogs and coyotes posed a risk of depredation across much of Mexico (i.e., 23% and 40% of Mexico with > 0.50 likelihood of depredation, respectively), with risk likelihood maps for each canid being similar (i.e., similarity indices = 0.75–0.84) for most risk levels but showing little similarity with respect to regions of high (> 0.70) and very high (> 0.90) likelihood of depredation (similarity = 0.38 and 0.19, respectively). By identifying areas of high depredation risk, our models provide a planning tool to facilitate allocation of resources such as insurance programs, identify areas that would benefit from additional mitigation programs, and provide guidance for managing landscape attributes to decrease risk and limit vulnerability of livestock to predation.

Introduction

Livestock ranching has deep cultural roots in Mexico, and Mexico ranks seventh internationally in production of cattle with ~34 million head (≈17/km^2; SIAP-SAGARPA 2016). Raising livestock is also an important subsistence activity in low- and middle-income countries including Mexico (Romañach et al. 2007; Amador-Alcalá et al. 2013). In many economically depressed areas of rural Mexico, individuals keep a limited number of livestock as their primary assets, which constitute economic reserves for emergencies such as unemployment and local community celebrations (Amador-Alcalá et al. 2013). Consequently, depredation of livestock can be economically devastating to small rural producers and rural communities and can potentially have a significant economic impact on extensive ranching enterprises (O'Gara et al. 1983).

In Mexico, the general public and many other user groups popularly associate livestock depredation with large carnivores, particularly black bear *(Ursus americanus)*, puma *(Puma concolor)*, and jaguar *(Panthera onca)* (Amador-Alcalá et al. 2013; CNOG 2014; Peña-Mondragón et al. 2016). However, smaller, more common species such as coyotes *(Canis latrans)* and domestic dogs *(Canis familiaris)* also prey on small- and medium-sized livestock (CNOG 2014). Domestic dogs and coyotes, for instance, are the most abundant, opportunistic, and adaptable carnivores in North America (Hidalgo-Mihart et al. 2004; Vanak and Gompper 2009; Monroy-Vilchis et al. 2020). Both species readily habituate to the presence of humans, and human alterations of natural communities (i.e., habitats minimally impacted by intensive anthropogenic changes, such as urbanization, clearing, habitat type conversions to intensive agriculture and other uses, etc.) are associated with their expansion into new regions (Butler et al. 2004; Hidalgo-Mihart et al. 2004; Monroy-Vilchis et al. 2020). Widespread range and population expansions in Mexico demonstrate the quick adaptation of these canids to humans and land-use change (Hidalgo-Mihart et al. 2004; Espinoza-Medinilla et al. 2018; Monroy-Vilchis et al. 2020).

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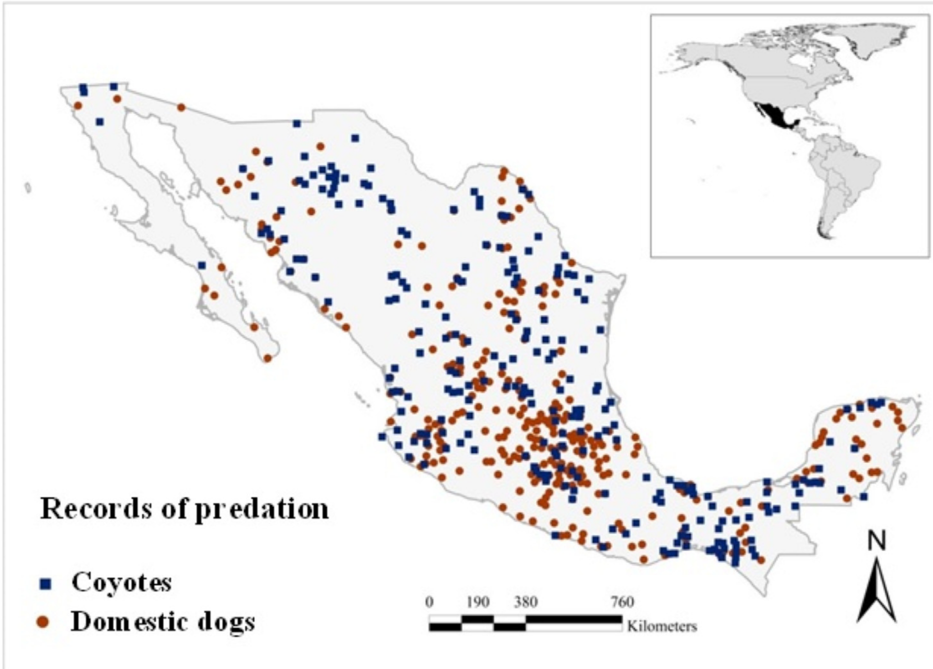

Figure 1. Location of sites of livestock predation (2017−2020) by coyotes and domestic dogs in Mexico.

Risk of depredation is frequently associated with specific landscape attributes (Rosas-Rosas et al. 2010, 2020; Carvalho et al. 2015), which can be influenced by land-use change, human population density, and intensity of livestock production (Zarco-González et al. 2013; Reyna-Sáenz et al. 2019). Conflicts associated with livestock depredation in Mexico are particularly severe in regions with higher human impacts, such as conversion of natural habitats to agricultural uses, overexploitation of the natural prey base, and where livestock occur in close proximity to high-quality large carnivore habitat, particularly near protected areas (Carvalho et al. 2015; Rosas-Rosas et al. 2020). Because carnivore species respond differently to natural landscapes and anthropogenic impacts, understanding the circumstances associated with depredation by particular species or guilds is necessary to identify risk factors, ameliorate conflicts, and maintain functional communities including viable carnivore populations (Rosas-Rosas et al. 2020).

Consequently, we evaluated the magnitude of, and identified risk factors associated with, coyote and domestic dog depredation on livestock in Mexico. We used locations of canid depredations on livestock in combination with spatial information on landscape attributes to assess the risk likelihood of human-canid conflicts due to livestock depredation throughout Mexico. We did this to identify regions and landscape attributes most associated with risk of canid depredation of livestock, which can provide information to identify potential problem areas before they emerge, aid in development of strategies that decrease risk and limit vulnerability of livestock to predation, and guide allocation of resources such as new mitigation programs.

Methods

Study area

Mexico is an ecologically diverse country located in the tropics and subtropics of North America covering almost 2 million km^2 (Fig. 1) (INEGI 2017). Topography of Mexico is varied with $>$ 65% of the nation $\geq$ 1 000 m in elevation. Climates include tropical, humid, dry, temperate, cold, and other types (García 2004). Vegetation is consequently variable and includes tropical and temperate forests, arid, and alpine vegetation (Rzedowski 2006). Approximately 63.5% of Mexico is in agricultural production, including approximately 13.5% in intensive agriculture (i.e., row cropping, cultivated pastures, livestock feedlots, etc.) and 43–50% in extensive native grazed rangeland (Peel et al. 2010; Ibarrola-Rivas and Nonhebel 2019). Ejidos (i.e., communal lands managed by the local community and primarily used for agriculture; 43.4% of Mexico) and small rural agrarian communities (9.1% of Mexico) contribute significantly to agricultural land uses (CEDRSSA 2019), with the latter likely not adequately included in estimates of livestock ownership (see later).

Size and intensity of agricultural operations are extremely varied, with small operations common. For example, $>$ 30% of corn production involves operations of $<$ 5 ha across Mexico and 42% of cattle production involved $<$ 100 head (16% of producers having $<$ 20 head) in Chihuahua (Carmona Martínez et al. 2007; INEGI 2019). These values underestimate the actual proportion of small holdings, which have not been rigorously quantified (Carmona Martínez et al. 2007). Livestock production totaled approximately 600 million head in 2016, of which cattle (34 million), hogs (16 million), sheep and goats (9 million) were the predominant mammals, and chickens (534 million) and turkeys (4 million) the predominant poultry (SIAP-SAGARPA 2016). Agriculture contributes approximately 3.5% of Mexico's GDP (World Bank 2015) and livestock culturally has enormous importance as economic assets, income, and social status for the rural population (Leos-Rodriguez et al. 2008).

Carnivores are the fourth richest mammalian order in Mexico and include 29 terrestrial carnivore species (Ceballos and Arroyo-Cabrales 2012). Moreover, coyotes and domestic dogs are the most abundant medium-sized carnivores, and both species occupy a variety of habitats throughout Mexico including agricultural, grassland, woodland, dry forest, rainforests, and arid vegetation, including in and adjacent to human settlements.

Predation records

We compiled a database of coyote and domestic dog livestock depredation records from 2017 to 2020, obtained from the National Confederation of Livestock Organizations (CNOG 2020). The dataset suggests that dog depredations are related to killing sheep, while coyotes are related to killing sheep, goats, or cattle (not necessarily adult livestock). The Confederation of Livestock Organizations (CNOG) is a nongovernmental organization dedicated to protecting livestock against death, forced slaughter, or injuries caused by predator depredations, including reimbursing livestock owners for losses from predators through livestock insurance (CNOG 2014). Livestock insurance investigators from CNOG are highly experienced in determining carnivore species responsible for depredation events. Techniques used to differentiate coyote and domestic dog depredations included direct witnessing of depredations; method of killing (coyotes and domestic dogs have distinctly different methods of killing; coyotes typically attack and kill with compression bites to the neck, leading to suffocation or death by internal bleeding. In contrast, dogs usually inflict open wounds indiscriminately across the body, especially along the flanks; neck wounds caused by dogs are either superficial or severe lacerations that are easily differentiated from the distinct puncture wounds of coyotes); maiming of multiple individuals, characteristic of dogs; presence of tooth punctures, hemorrhage, severed blood vessels, and damage to muscle tissue and trachea subcutaneously on the neck; identification of tracks, scats, and hair at the site; whether depredation was fed upon and feeding pattern (coyotes tend to feed on internal organs first, whereas dogs, if they feed, tend to feed on external tissue first); and species identification using environmental DNA from wounds or area of depredation (Schaefer et al. 1981; Hygnstrom et al. 1994). In general, coyote and domestic dog depredation is easily differentiated; for example, agricultural producers were able to correctly differentiate coyote from domestic dog depredation in $>$ 94% of cases (Hygnstrom et al. 1994).

We undertook several data cleaning steps to reduce the potential bias in the occurrence records (Cobos et al. 2019), including 1) we only considered unique records with geographic coordinates for continental Mexico; 2) we removed occurrences lacking geographic references; and 3) we filtered occurrences for each canid at 20 km before model development to reduce spatial autocorrelation among occurrence points and thus avoid model overfitting (Boria et al. 2014; Brown 2014). The specified distance was based on empirical evidence from similar modeling exercises and spatial resolution of environmental predictors; this graduated filtering method is useful to eliminate spatial clusters of occurrences to a single point within the user-specified distance (see Brown 2014). In practice, this filtering process allows selection of one of the occurrence points at random and eliminates the points that fall at a distance $\leq$ 20 km radius; filtered points were later split into training (70%) and testing data (30%) to be used in model calibration (see later).

Risk modeling

We included five classes of variables for modeling risk of depredation (Table 1). We obtained 1-km^2 resolution Normalized Difference Vegetation Index (NDVI) raster datasets from MODIS imagery (https://lpdaac.usgs.gov/) and used NDVI, an index of photosynthetic activity related to vegetation cover, precipitation, and temperature, as a surrogate for primary productivity (the annual integral values of NDVI are strongly correlated with net primary productivity; Schloss et al. 1999). We synthesized monthly NDVI rasters for the period 2002–2014 into a composite raster using principal components analysis in ArcMap 10.1 (Lira-Noriega et al. 2018). We included the first two principal components as variables in our risk modeling. The first principal component accounted for 80.4% of the variance in the data and described landscape greenness. The second principal component accounted for 7.8% of the variance in the data and described seasons, with lower values corresponding to the winter/dry season (Jan–Mar) and higher values to the summer/wet season (Jul–Aug).

Table 1
Classes of variables, actual variable, and sources of variables used to model risk of depredation by domestic dogs and coyotes in Mexico.

Class	Variables	Source
Topographic	Elevation	CONABIO 2016
Habitat/primary productivity	NDVI PC1 (primary productivity) NDVI PC2 (seasonality)	https://lpdaac.usgs.gov/
Human impact	Population density	CIESIN 2010
	Road density	Meijer et al. 2018
	Human footprint	Venter et al. 2016
Livestock density	Cattle Horses Goats Sheep Hogs Chickens	Gilbert et al. 2018
Bioclimatic	Bio 1: Annual mean temperature Bio 2: Mean diurnal temperature range Bio 5:Maximum temperature of warmest month Bio 6: Minimum temperature of coldest month Bio 12: Mean annual precipitation Bio 13: Mean precipitation of wettest month Bio 14: Mean precipitation of driest month	Vega et al. 2017

We used human population density for 2010 (CIESIN 2010), human footprint (Venter et al. 2016), and road density (Meijer et al. 2018) to asses human impacts on the landscape at a spatial resolution of 1 km^2. We included density (i.e., total numbers of adult individuals per km^2) of multiple species of livestock because livestock abundance is considered a primary driver of conflicts between humans and carnivores, at a spatial resolution of 0.083333 decimal degrees (Gilbert et al. 2018). We selected livestock species (i.e., cattle, pigs, sheep, goats, horses, and chickens) because of their abundance in Mexico (see earlier), as well as their importance to producers and rural communities (i.e., horses). Livestock numbers were determined from regional agricultural statistics (Gilbert et al. 2018; http://www.fao.org/home/en/). Lastly, we included 7 bioclimatic variables (see Table 1) from those in the MERRAclim database (see Vega et al. 2017) at a spatial resolution of 2.5 minutes to assess climatic associations. We resampled variables with spatial resolutions that differed from 1 km^2 using bilinear interpolation in ArcMap 10.1 to develop rasters with a common resolution of 1 km^2 for use in risk modeling and tested all variables for multicollinearity using Spearman correlations among variables at occurrence records for each species and flagged those with correlations of $P \geq 0.7$. Although maximum entropy modeling (see later) is known to manage multicollinearity-related issues well (Feng et al. 2019), this environmental filter had the objective of providing an additional check on this issue.

We used maximum entropy modeling (MaxEnt v3.4.1; Phillips et al. 2006) to model factors associated with livestock depredation sites by domestic dogs and coyotes. We constructed separate models for each canid, using the landscape variables mentioned earlier to identify the attributes most associated with locations of canid depredations. We first modeled all variables individually to determine which provided useful information on distribution of depredation (i.e., variables with a lower 95% confidence interval of their area under the curve [AUC] ≥ 0.50; Swets 1988). We included only useful variables in subsequent multivariate modeling. For this, we modeled all possible candidate models using the complementary log-log (clog-log) transformation. We compared models of differing dimension by testing whether the model with the highest AUC differed from more parsimonious models. We used the critical ratio test (Pearce and Ferrier 2000 as modified by Baldwin and Bender 2008) to compare the highest AUC model with other models to determine if the increase in explanatory value was significant at $\alpha = 0.05$ following Baldwin and Bender (2008). If models did not differ, we selected the most parsimonious model. We calculated standard errors for AUC values using 30% of the locations as test data. We derived thresholds for probability of depredation presence by maximizing sensitivity and minimizing specificity (Fieldling and Bell 1997; Phillips et al. 2006). We used these thresholds to convert probabilities to binary response (presence-absence) and used the equal test sensitivity and specificity threshold values to calculate successful classification percentages. We included the latter because a model that poorly classifies the data it was built from is unlikely to have any true predictive ability (Hosmer and Lemeshow 2000). We also present the percent contributions of each variable to preferred models (i.e., the weight or relative importance of each variable in the model; Phillips et al. 2006) and determined whether the 95% CIs of variable coefficients included 0; inclusion of 0 in the CI would indicate an uninformative variable (Arnold 2010).

We also compared similarity of final risk likelihood maps (i.e., predicted likelihood of depredations by species) using Schoener's index of similarity, the *I*-statistic of similarity, and the range overlap statistic (Warren et al. 2008) in ENMTools (Warren et al. 2008, 2010). For the range overlap statistic, we further defined high likelihood of depredation as ≥ 0.70 likelihood and extremely high likelihood of depredation ≥ 0.90 and compared the overlap of these probability ranges between species.

Finally, to highlight key differences between coyote and domestic dog depredation sites (as opposed to the landscape in general), we used stepwise logistic regression (Hosmer and Lemeshow 2000) to identify variables related to the dichotomous outcome class (domestic dog depredation site vs. coyote depredation site). For this we included all predictors present in the preferred maximum entropy models for both species. We used the stepwise process to determine significant variables because it is more conservative than information-theoretic approaches (Arnold 2010).

Results

Depredations due to domestic dogs and coyotes combined totaled 1 044 of 2 075 (50.3%) depredation claims, with 755 and 289 attributed to domestic dogs and coyotes, respectively. Following data cleaning, we had 553 occurrence sites for both species (311 for domestic dog, 242 for coyote) for modeling of predation risk (Fig. 1).

Correlations among all variables used in maximum entropy modeling were ≤ 0.7 except for some of the bioclimatic variables (Bio1, Bio5, Bio6, Bio12, and Bio13; see Table 1) with each other and elevation ($P > 0.8$) and poultry with pigs ($P = 0.75$). Despite this, we included these in variable selection in MaxEnt using the jackknife procedure, as this provided an additional and potentially more robust way to identify redundant information and noninformative variables. Additionally, other studies at coarser resolutions and larger geographic extents had identified these same bioclimatic variables as the least correlated among our bioclimatic variables (e.g., Jiménez-Valverde et al. 2009). Lastly, while temperature and precipitation variables are frequently correlated with elevation,

Table 2
Area under the curve (AUC), SE, similarity of depredation likelihood map to the highest AUC model map, and probability that model differs from the highest AUC model (*P* [AUC]) for the best 1–10 variable maximum entropy models of the likelihood of depredation on livestock by domestic dogs in Mexico. Maximum entropy models including > 10 variables showed lower AUC than did the 10-variable model and were thus not included in model selection. Best fit model is in **bold.**

Variables[1]	AUC	SE	Similarity	*P* (AUC)
R,S,Tcm,HFP,Twm,Trange,Ele,Pwet,N2,HPD	0.826	0.018	–	–
R,S,Tcm,HFP,Twm,Trange,Ele,Pwet,N2,HPD	0.826	0.017	0.989	0.988
R,S,Tcm,HFP,Twm,Trange,Ele,Pwet,N2,HPD	0.826	0.017	0.988	0.726
R,S,Tcm,HFP,Twm,Trange,Ele	0.825	0.017	0.984	0.764
R,S,Tcm,HFP,Twm,Trange	0.825	0.017	0.977	0.754
R,S,Tcm,HFP,Twm	0.824	0.017	0.943	0.742
R,S,Tcm,HFP	0.821	0.017	0.933	0.441
R,S,Tcm	0.816	0.017	0.911	0.120
R,S	**0.808**	**0.019**	**0.868**	**0.060**
R	0.783	0.021	0.760	<0.001

[1] R indicates road density; S, density of sheep; Tcm, minimum temperature of coldest month; HFP, human footprint; Twm, maximum temperature of warmest month; Trange, mean diurnal temperature range; Ele, elevation; Pwet, mean precipitation of wettest month; N2, NDVI PC2; HPD, human population density.

elevation includes other relevant attributes for species habitat beyond those climatic effects.

For domestic dogs, the maximum entropy model including road density and density of sheep provided the most parsimonious fit while maintaining comparable explanatory power ($P \geq 0.060$ as compared with higher-dimensioned, greater AUC models) and fit data well (AUC = 0.808; SE = 0.019; successful classification percentage = 76%) (Table 2). Coefficients of each variable in the preferred model had 95% CIs that excluded zero. Road density accounted for the greatest contribution to model performance (51%); density of sheep contributed 49%. Likelihood of domestic dog depredation was ≥ 0.60 in regions with road densities of 0.3–2.5 km/km^2 and sheep densities ≥ $200/km^2$; ≥ 0.75 in regions with road densities of 0.4–2.0 km/km^2 and sheep densities ≥ $400/km^2$; and ≥ 0.90 in regions with road densities of 0.4–1.0 km/km^2 and sheep densities ≥ 1 $000/km^2$.

For coyotes, the maximum entropy model including density of sheep, density of hogs, density of goats, NDVI PC1 and PC2, elevation, minimum temperature of the coldest month, and mean precipitation of the wettest month provided the most parsimonious fit while maintaining comparable explanatory power ($P \geq 0.094$ as compared with higher-dimensioned, greater AUC models) and fit data moderately well (AUC = 0.786; SE = 0.026; successful classification percentage = 70%) (Table 3). Coefficients of each variable in the preferred model had 95% CIs that excluded zero. Collectively, density of the 3 livestock species contributed the most to model performance (67%; individually, sheep = 36%, hogs = 25%, and goats = 6%) and described a diversity of small livestock, followed by NDVI PC2 (i.e., season; 9%), mean precipitation of the wettest month (8%), elevation (6%), NDVI PC1 (i.e., greenness; 5%), and mean minimum temperature of the coldest month (5%). Likelihood of coyote depredation was > 0.60 in regions with ≥ 100 sheep, ≥ 200 hogs, and ≥ 40 goats per km^2; ≥ 161 mm of precipitation; mean minimum temperature of the coldest month = 15.0–20.5°C; at < 2 500 m in elevation; and with increasing landscape greenness until declining sharply at high values indicative of tropical vegetation. In addition, NDVI PC2 indicated a seasonal peak in winter and spring. Likelihood of coyote depredation was > 0.75 when sheep density increased to ≥ 350 per km^2; 340–580 mm of precipitation; mean minimum temperature of the coldest month = 17.9–20.0°C; at 200–1 500 m in elevation; and with increasing landscape greenness until sharply declining at high values indicative of tropical vegetation. Additionally, NDVI PC2 indicated a seasonal peak in winter.

Table 3
Area under the curve (AUC), SE, similarity of depredation likelihood map to the highest AUC model map, and probability that model differs from the highest AUC model *P* (AUC) for the best 1–14 variable maximum entropy models of the likelihood of depredation on livestock by coyotes in Mexico. Maximum entropy models including > 14 variables showed lower AUC than did the 14-variable model and were thus not included in model selection. Best fit model is in **bold.**

Variables[1]	AUC	SE	Similarity	*P*(AUC)
S,P,Tcm,Ele,Pwet,N1,N2,G,H,RD,HPD,Pann,HFP,C	0.807	0.023	–	–
S,P,Tcm,Ele,Pwet,N1,N2,G,H,RD,HPD,Pann,HFP	0.807	0.024	0.992	0.992
S,P,Tcm,Ele,Pwet,N1,N2,G,H,RD,HPD,Pann	0.806	0.024	0.962	0.880
S,P,Tcm,Ele,Pwet,N1,N2,G,H,RD,HPD	0.802	0.025	0.956	0.496
S,P,Tcm,Ele,Pwet,N1,N2,G,H,RD	0.799	0.025	0.940	0.348
S,P,Tcm,Ele,Pwet,N1,N2,G,H	0.792	0.026	0.904	0.178
S,P,Tcm,Ele,Pwet,N1,N2,G	**0.786**	**0.026**	**0.875**	**0.094**
S,P,Tcm,Ele,Pwet,N1,N2	0.777	0.027	0.856	0.032
S,P,Tcm,Ele,Pwet,N1	0.768	0.028	0.824	0.014
S,P,Tcm,Ele,Pwet	0.758	0.029	0.809	0.004
S,P,Tcm,Ele	0.749	0.028	0.781	0.001
S,P,Tcm	0.728	0.028	0.758	<0.001
S,P	0.711	0.026	0.721	<0.001
S	0.681	0.027	0.649	<0.001

[1] S indicates density of sheep; P, density of hogs; Tcm, minimum temperature of coldest month; Ele, elevation; Pwet, mean precipitation of wettest month; N1, NDVI PC1; N2, NDVI PC2; G, density of goats; H, density of horses; RD, road density; HPD, human population density; Pann, mean annual precipitation; HFP, human footprint; C, density of cattle.

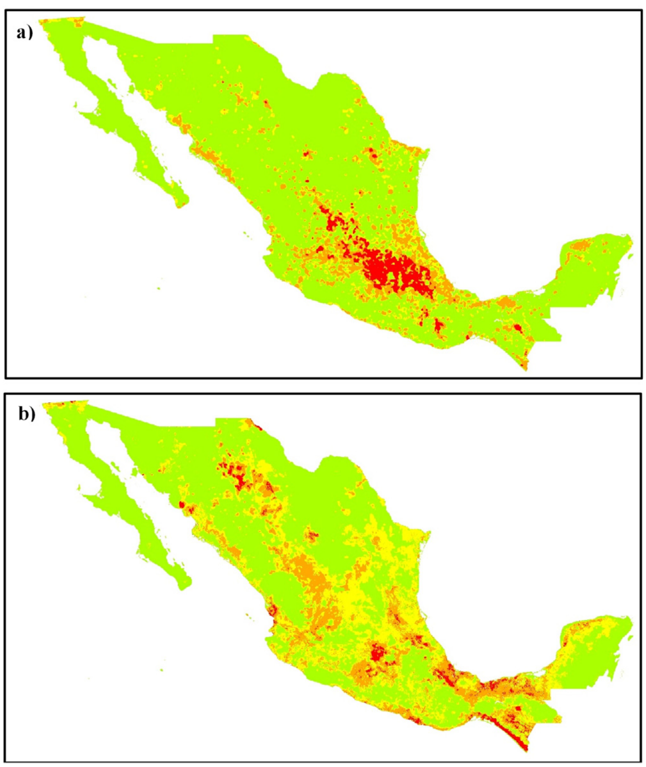

Figure 2. Likelihood maps of risk from **a,** domestic dog and **b,** coyote depredation on livestock in Mexico. Spatial model with four categories of predation risk (red ≥ 0.90; orange ≥ 0.70; yellow ≥ 0.50; green < 0.50) is shown.

Regions with ≥ 0.50, ≥ 0.70, and ≥ 0.90 likelihood of depredation by domestic dogs comprised 22.7%, 13.4%, and 3.3% of Mexico, respectively (Fig. 2). Comparable proportions for coyote depredation were 39.9%, 15.3%, and 2.2% (see Fig. 2). Overall risk likelihood maps were relatively similar for each species (see Fig. 2); Schoener's index = 0.748, *I*-statistic = 0.837, and range overlap = 0.763. However, areas with high (range overlap = 0.380) and very high (range overlap = 0.184) risk likelihood for each species showed little similarity.

Lastly, our logistical analysis (likelihood ratio $\chi^2 = 83.2$; $P < 0.001$; df = 2) identified road density ($\chi^2 = 39.6$; $P < 0.001$; df = 1) and density of sheep ($\chi^2 = 8.9$; $P = 0.003$; df = 1) as the variables most differentiating domestic dog and coyote depredation sites regardless of whether the full suite of input variables or only those appearing in preferred maximum entropy models was included. An alternative model (likelihood ratio $\chi^2 = 72.7$; $P < 0.001$; df = 2) including human-footprint instead of road density performed similarly; road density and human-footprint were substitutive in models, i.e. the addition of road density resulted in the removal of human-footprint, even though human-footprint was the first variable added in the stepwise process and road density the second. This model likewise included only human-footprint ($\chi^2 = 14.3$; $P < 0.001$; df = 1) and density of sheep ($\chi^2 = 12.1$; $P = 0.001$; df = 1). Odds of a depredation being due to a domestic dog increased 1.16X (95% CI = 1.09–1.22) per each 0.1 km/km^2 increase in road density. Odds ratios (1.000; 95% CI = 0.999–1.000) for domestic sheep included 1, indicating no real effect of sheep density. Substituting human-footprint, odds of depredation being due to domestic dogs increased 1.07X (95% CI = 1.04–1.10) for each 1 unit increase in human-footprint index; sheep relationships were the same.

Discussion

The severity of domestic dog and coyote depredation on livestock has not previously been assessed nationally in Mexico, as most prior work focused on large mammalian carnivores, particularly felids (e.g., Rosas-Rosas et al. 2010; Zarco-González et al. 2013; Reyna-Sáenz et al. 2019). We found that attacks on livestock by domestic dogs and coyotes constituted 50.3% of depredation claims in Mexico, more than attacks by any other carnivore guild. In some rural areas, one or both canids were responsible for the vast majority of attacks on livestock; consequently, economic losses incurred from domestic dogs and coyotes can be high compared with those from other carnivores (Hidalgo-Mihart et al. 2004; CNOG 2014). We also found that areas of Mexico at risk (i.e., areas with ≥ 0.50 likelihood of depredation) of coyote depredation were more common than for domestic dogs (39.9% of Mexico vs. 22.7%, respectively; for grazed lands only, these proportions increase to 79–94% and 49–53%, respectively); however, domestic dogs were actually responsible for more incidents in Mexico, possibly because they are more likely to engage in surplus killing or maiming (i.e., attacking whether needing food or not) or be present in greater numbers (Kruuk 1972; Young et al. 2011; Fulton 2014). Both species, however, pose a significant risk of depredation throughout Mexico (see Fig. 2).

We also found that different landscape attributes were most associated with depredation risk for each canid. Depredation risk from domestic dogs was most strongly related to low–moderate road density (mean = 0.85 km/km^2; > 90% of depredations < 1.9 km/km^2), levels that were indicative of rural lands and small communities (Basille et al. 2013; Ceia-Hasse et al. 2017; Kent et al. 2021). Domestic dog depredation was also associated with increasing density of sheep, which likely related to both rural subsistence livestock husbandry and small livestock being the primary prey of domestic dogs and coyotes, as either canid is capable of killing adults in addition to juveniles (Schaefer et al. 1981; Hygnstrom et al. 1994). Road density (or human-footprint; both relate to increasing anthropogenic impact on the landscape) was also the key variable differentiating actual domestic dog and coyote depredation sites, as coyote depredation was more strongly related to more rural areas with less human infrastructure impact (i.e., mean road density = 0.40 km/km^2; > 90% of depredations < 0.9 km/km^2); odds of a site being a domestic dog depredation increased 1.2X for each 0.1 km/km^2 increase in road density. However, even the likelihood of domestic dog depredation decreased as urbanization (e.g., road density > 2.5 km/km^2) increased, likely because of declining livestock availability.

Domestic dogs rely on human-provided food and hence their presence is closely associated with anthropogenic features and human densities (Gompper 2014), although truly feral dogs can closely resemble wild canids behaviorally and subsist entirely by predation (Hygnstrom et al. 1994). Because food provided by humans is frequently inadequate, malnourished dogs often need to hunt small- to medium-sized wild and domestic animals to meet nutritional requirements in impoverished rural communities (Silva-Rodriguez and Sieving 2011), leading to livestock depredation conflicts, as well as conflicts with wildlife (Silva-Rodríguez and Sieving 2012). For example, wildlife conflicts frequently associated with domestic dogs include predation on white-tailed deer *(Odocoileus virginianus)* fawns (Rohm et al. 2007) and wild turkey *(Meleagris gallopavo)* hens on nests (Speake et al. 1985). Domestic dogs may also compete for space and prey with wild mesopredators, potentially displacing less aggressive native species (Vanak and Gompper 2009, 2010). However, because dogs, especially semiferal dogs, can be controlled by educating landowners on the problems associated with free-ranging dogs, or legal requirements such as leash laws and more effective spay and neuter programs (Young et al. 2011; Fulton 2014), depredation conflicts associated with domestic dogs are often more easily controlled than those associated with coyotes. Feral dogs can also be more easily lethally controlled than other carnivores such as coyotes (Hygnstrom et al. 1994).

Risk of coyote depredation was primarily associated with the presence of a diversity of small- to medium-sized livestock (including sheep, hogs, and goats) around depredation sites; because all individuals are vulnerable to attack, coyote depredation tends to be more strongly associated with smaller livestock (Schaefer et al. 1981; Hygnstrom et al. 1994). Presence of these species collectively accounted for 67% of the variable contributions to the best-supported risk model. Depredations were also more likely in regions with warmer, wetter climates and hence higher primary productivity at very low and mid to high elevations, climatic and topographic attributes conducive to more intensive agriculture and larger (i.e., greater numbers of livestock) ranching enterprises. Our results are consistent with previous reports indicating that livestock density was significantly related to depredation risk from other wild carnivores in Mexico (Zarco-González et al. 2013; Amador-Alcalá et al. 2013; Reyna-Sáenz et al. 2019). Moreover, risk of coyote depredation showed a seasonal effect; depredation was more strongly associated with winter and spring (which also correspond to dry seasons in much of Mexico) than summer. Increased depredation conflicts during the dry season are commonly seen with other carnivores in Mexico because of increased vulnerability when livestock and other prey are concentrated near permanent water sites, which increases encounter rates with carnivores; these areas typically also have greater stalking or ambush cover (Rosas-Rosas et al. 2008, 2010, 2020). Spring also corresponds with parturition for most livestock species, as well as coyotes; hence, coyotes take advantage of more vulnerable livestock neonates to meet the increased nutritional demands of whelping and nursing females and growing pups (O'Gara et al. 1983; Hygnstrom et al. 1994).

Presence of livestock and some degree of human impact or development was associated with depredation risk from both canids to some degree, which resulted in relatively similar patterns of landscape risk likelihood for each species across Mexico (i.e., similarity indices of 0.75–0.84 between their respective risk likelihood maps). However, areas with high (> 0.70 likelihood) and very high (> 0.90 likelihood) risk of depredation for either canid showed little similarity (0.38 and 0.19, respectively). This likely reflected that coyotes are wild carnivores while domestic dogs are at least partially domesticated and, hence, are much more closely associated with humans because of some degree of dependence on humans for food, shelter, etc. (Gompper 2014). Additionally, domestic dogs often are predators of, or act as intraguild competitors with, a wider variety of species, and often kill regardless of whether needing food or not (Young et al. 2011; Fulton 2014). This escalates depredation risk associated with domestic dogs relative to coyotes in areas more strongly influenced by humans. Despite this, however, both species were associated with and benefitted from human impacts (particularly agricultural and large ranching enterprise land-uses) to some degree in Mexico.

Data on the economic impact of livestock depredation are unavailable at the national level for Mexico, although some regional assessments have been done. For example, Peña-Mondragon and Castillo (2013) estimated the economic loss due to livestock depredation in southern Nuevo Leon as $133 000 USD for the 1992–2010 period, with most losses attributed to black bear (*Ursus americanus;* $43 000 USD), jaguar (*Panthera onca;* $39 000 USD), puma (*Puma concolor;* $17 000 USD), coyote ($28 000 USD), bobcat (*Lynx rufus;* $4 000 USD), and gray fox (*Urocyon cinereoargenteus;* $2 000 USD). They did not list domestic dogs in losses despite depredation by domestic dogs accounting for the most insurance depredation claims in Mexico, perhaps because depredation by domestic dogs is often incorrectly attributed to other species (Young et al. 2011). Elsewhere, coyotes and free-ranging dogs are considered to be among the most problematic carnivores to the livestock industry (Gee 1979; Schaefer et al. 1981; Hygnstrom et al. 1994; Bergman et al. 2009); combined losses from both species total millions in USD annually in the United States.

The true economic and cultural impact of livestock depredation, however, depends on the size and intensity of the livestock enterprise, economic status of the producer, the type of livestock predated, etc. (Hoogesteijn et al. 2016). For rural subsistence producers, a single predation event can devastate the family economy (Peña-Mondragón et al. 2016). While depredation losses may not necessarily present a significant economic impact to larger ranching enterprises, they may be socially unacceptable and consequently foster intolerance of carnivores (Rosas-Rosas et al. 2020). In Mexico, the primary program to address livestock depredation at the national level is livestock insurance (CNOG 2014). Compensation to affected livestock holders is often slow and inefficiently allocated, however. Our identification of high-risk zones for depredation can aid in directing livestock insurance (and other) financial assistance to areas most vulnerable to depredation, possibly increasing efficacy and consequently trust and participation in the program.

Aside from livestock insurance, alternative strategies to reduce human-carnivore conflicts in Mexico and elsewhere include physical barriers (Packer et al. 2013) and use of guard dogs or other guard animals (Conover 2002; Allen et al. 2019). More commonly in Mexico and other low- and middle-income countries, local villagers and ranchers resort to retaliatory killing as retribution for livestock depredations, compromising the conservation of many carnivore species (Marchini and MacDonald 2012; Reyna-Sáenz et al. 2019) without appreciably reducing the threat to livestock or the vulnerability of livestock (Rosas-Rosas et al. 2008, 2010). Hence, these actions are often ineffective in reducing depredation because they fail to address the underlying ecological reasons behind conflicts.

Risk models of livestock depredation address these underlying reasons by delineating regions of risk and identifying landscape attributes that contribute to this risk. Hence, our models identify areas of higher risk for canid depredation that merit further, more localized, evaluation. Moreover, by identifying landscape attributes that contribute to risk, actions that alter these features to decrease vulnerability of livestock can be identified, tested, and implemented if effective.

The latter application can include critical evaluation of management recommendations. For example, the distribution of domestic dogs and coyotes across Mexico is associated with human populations, livestock, and habitat alterations (see earlier; Gehrt and Riley 2010; Ordeñana et al. 2010; Gompper 2014). Thus, some interest groups advocate for regional landscape planning that incorporates preservation of natural habitats to potentially limit their distribution and consequently conflicts. This assumes that because the geographic expansion of coyotes in Mexico has resulted from alteration of natural habitats (Hidalgo-Mihart et al. 2004; Espinoza-Medinilla et al. 2018; Monroy-Vilchis et al. 2020), sites where original habitats are preserved could potentially function as geographic barriers to slow coyote colonization. However, because proximity of protected areas is strongly associated with livestock depredation conflicts with other species such as large felids (Rosas-Rosas et al. 2010, 2020; Peña-Mondragón and Castillo 2013; Montalvo et al. 2016), such a strategy may simply switch depredation conflicts from one guild to another. Nor would such a strategy address conflicts with domestic dogs. This illustrates the importance of developing integrated actions to address livestock depredation from the full continuum of potential predators (Conover 2002), guided by risk models such as ours that identify regions of higher risk and the factors that contribute to elevated risk.

Implications

Livestock conflicts associated with coyotes and domestic dogs are not exclusive to Mexico (e.g., Schaefer et al. 1981; Hygnstrom et al. 1994; Conover 2002; Bergman et al. 2009; Gehrt et al. 2010), and effective conflict mitigation for these species, given their habitat plasticity, behavioral adaptability, and varying levels of depredation conflicts across their range, is facilitated by planning tools that identify specific landscape attributes associated with conflict sites. Once identified, the level of risk for any particular area can be accurately predicted, and landscape features that increase depredation risk can be directly modified by management when possible. However, domestic dogs and coyotes are very different carnivores, and thus strategies to decrease depredation risk should be tailored to each species's attributes and behaviors. For example, alteration of human behavior, such as better care, feeding, and restraint of dogs, may have a greater impact on domestic dog conflict areas than actions aimed specifically at risk factors related to domestic dog depredation.

In addition to the earlier information, depredation mitigation actions at the ranch or rural community level in Mexico may include development of additional free water sites to minimize livestock and wild prey concentrations during dry seasons when vulnerability to coyote depredation increases; increased resources devoted to lethal control of coyotes and feral dogs in very high risk sites (both species) or during dry seasons (coyotes); alternative livestock husbandry practices such as confinement during parturition to limit vulnerability and availability of neonates (Hygnstrom et al. 1994); and favoring larger livestock species where possible. At regional or planning levels, mitigation actions may include more efficient targeting of livestock insurance programs as described earlier. Additionally, because funding to compensate for livestock depredation is often limited, our risk mapping can also identify areas where governmental, NGO, and private entities may choose to implement additional mitigation programs; prioritize lethal control of canid predators; reward producers who graze in lower-risk areas with additional compensation programs; or discourage new operations in higher-risk areas by limiting access to restitution programs, all prioritized on the basis of the degree of risk. Mitigation efforts should also include education programs or regulations aimed at controlling free-ranging dogs. Such approaches are equally applicable to other regions experiencing depredation by domestic dogs and coyotes, or other carnivores.

Declaration of Competing Interest

None.

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