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Predicting spatial factors associated with cattle depredations by the Mexican wolf (*Canis lupus baileyi*) with recommendations for depredation risk modeling

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ABSTRACT

Aim: Predation on livestock is one of the primary concerns for Mexican wolf (*Canis lupus baileyi*) recovery because it causes economic losses and negative attitudes toward wolves. Our objectives were to develop a spatial risk model of cattle depredation by Mexican wolves in the USA portion of their recovery area to help reduce the potential for future depredations.
Location: Arizona and New Mexico, USA.
Methods: We used a presence-only maximum entropy modeling approach (Maxent) to develop a risk model based on confirmed depredation incidents on public lands. In addition to landscape and human variables, we developed a model for annual livestock density using linear regression analysis of Animal Unit Month (AUM), and models for abundance of elk (*Cervus canadensis*), mule deer (*Odocoileus hemionus*) and white-tailed deer (*Odocoileus virginiana*) using Maxent, to include them as biotic variables in the risk model. We followed current recommendations for controlling model complexity and other sources of bias.
Results: The primary factors associated with increased risk of depredation by Mexican wolf were higher canopy cover variation and higher relative abundance of elk. Additional factors with increased risk but smaller effect were gentle and open terrain, and greater distances from roads and developed areas.
Main conclusions: The risk map revealed areas with relatively high potential for cattle depredations that can inform future expansion of Mexican wolf distribution (e.g., by avoiding hotspots) and prioritize areas for depredation risk mitigation including the implementation of active non-lethal methods in depredation hotspots. We suggest that livestock be better protected in or moved from potential hotspots, especially during periods when they are vulnerable to depredation (e.g. calving season). Our approach to create natural prey and livestock abundance variables can facilitate the process of spatial risk modeling when limitations in availability of abundance data are a challenge, especially in large-scale studies.

1. Introduction

Large carnivores can cause conflicts with humans by preying on livestock, which causes economic losses and, in some cases, negative attitudes toward carnivores (Treves and Bruskotter, 2014; Dickman et al., 2013). A variety of non-lethal approaches to reduce human-carnivore conflicts are available. Some studies show that non-lethal methods were often more effective than lethal methods (Treves et al., 2016; Santiago-Avila et al., 2018), however, other studies report that there is high variation, indeterminacy and lack of scientific evidences in non-lethal methods effectiveness (Miller et al., 2016; Eklund et al., 2017; Eeden et al., 2018). Moreover, depredation on livestock by wolves may be a learned behavior and therefore may be difficult to stop if all individuals in a pack are involved (Harper et al., 2005). An

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alternative approach is to prevent conflicts from occurring, which may be more efficient and less costly than trying to reduce conflict after it has occurred. Prevention of conflicts depends on recognizing the conditions that promote these conflicts (Linnell et al., 1999). Therefore, predicting future depredations from their past patterns can lead to optimum interventions for reducing carnivore-livestock conflicts (Treves and Rabenhorst, 2017). Predictive spatial models find relationships between ecological variables and spatial processes and are commonly used tools to plan strategies for wildlife management (Guisan and Zimmermann, 2000). Risk maps, created by spatial models, predict spatial distributions of potential conflicts between humans and carnivores, and provide an opportunity for early warning (Edge et al., 2011; Treves et al., 2004; Treves et al., 2011; Miller, 2015). Moreover, identifying the role of landscape, natural prey, and livestock characteristics in depredation can help inform management of livestock and wildlife to reduce depredations (Miller et al., 2015; Treves and Rabenhorst, 2017).

The Mexican wolf (*Canis lupus baileyi*) is an example of a carnivore that is being restored to part of its native range, but which can cause conflicts with humans. Historically, the Mexican wolf occurred in portions of the American Southwest and south through central Mexico, although there is disagreement about precise historical range limits (Heffelfinger et al., 2017; Hendricks et al., 2016; Parsons, 1998). Historical efforts to eradicate Mexican wolves due to conflicts with livestock resulted in their extirpation from the United States by 1970 (Bednarz, 1988; Brown and Shaw, 2002). The Mexican wolf was listed as endangered under the US Endangered Species Act in 1976 upon which the last individuals were captured from the wild in Mexico to initiate a captive breeding program (McBride, 1980). The first releases of captive-bred Mexican wolves occurred in 1998 within a primary recovery zone in the Apache National Forest in east-central Arizona. Wolves were allowed to disperse throughout the Blue Range Wolf Recovery Area (BRWRA), which included additional areas of the Apache and Gila National Forests in Arizona and west-central New Mexico (see Fig. S1. 1 of Appendix S1 in Supporting information). The small founding population and low gene diversity have been a concern in Mexican wolf recovery efforts (Harding et al., 2016). In 2015, revisions to the regulations for the nonessential experimental population of the Mexican wolf resulted in a dramatic increase in the area where Mexican wolves would be allowed to occupy, from the former BRWRA to the Mexican Wolf Experimental Population Area (MWEPA), which includes areas of Arizona and New Mexico south of Interstate Highway 40 (Appendix S1; U.S. Fish and Wildlife Services [USFWS], 2015). This expansion will increase Mexican wolf-livestock conflicts (USFWS, 2015). From 1998 to 2017 the Mexican wolf population in the US has generally increased from an initial 11 wolves in 3 packs to a maximum of 114 wolves within 22 packs during 2017 (USFWS, 2017). Residents of Arizona and New Mexico that oppose Mexican wolf restoration, do so primarily because of concerns about livestock and human safety (Schoenecker and Shaw, 1997). Depredation by Mexican wolves on livestock occurs throughout the year on private and public lands. Prior to 2007 management removal of wolves from the population was negatively impacting population growth. Protocols were altered to emphasize non-lethal and proactive strategies and minimize removals (USFWS, 2017).

The overarching goal of this study was to develop a model that explains landscape scale spatial factors associated with Mexican wolf depredation on livestock. Specific objectives included: 1) predict relative density of livestock and predict relative abundance of potential natural prey, including elk (*Cervus canadensis*), mule deer (*Odocoileus hemionus*) and white-tailed deer (*Odocoileus virginiana*), in Arizona and New Mexico with the aim of using estimates from these models as part of the initial suite of variables that were tested for inclusion within the risk model, 2) develop a risk model of Mexican wolf depredation on cattle to understand factors associated with increased risk and to illustrate spatial arrangement of depredation conflict hotspots, and 3) make recommendations for future wolf recovery and livestock management to reduce potential conflicts. Our study was important in several ways. First, the depredation risk model provides information about areas with high potential for conflict before the distribution of Mexican wolf has expanded within the revised MWEPA. This provides an opportunity to inform future management actions that can reduce potential conflicts before they occur. Second, fine scale spatial data on abundance of livestock and natural prey are rarely available for large regional study areas. We developed models for livestock density and natural prey abundance, which were tested as predictors in the risk model. Third, few studies have applied maximum entropy modeling (i.e., Maxent; Phillips et al., 2006) using current recommendations (Morales et al., 2017; Yackulic et al., 2013). We incorporated all currently recommended modeling criteria, including correcting sampling bias, defining background extent based on study goals and assumptions, testing model complexity, and avoiding overestimation in model evaluation.

2. Methods

2.1. Study area

The study area was the states of Arizona and New Mexico, USA. The risk model was developed based on depredation incidents that occurred on public lands within and near the former BRWRA and then was extrapolated as a risk map to the study area (Appendix S1).

2.2. Occurrence records

We focused our analysis on depredations on cattle by Mexican wolves because cattle represent the majority of livestock production, both in terms of numbers of animals and economic value, and because the majority of depredation incidents attributed to Mexican wolves involve cattle (USFWS, 2017). We analyzed 186 confirmed lethal depredation incidence locations (yearlings $n = 2$, heifers $n = 2$, calves $n = 108$, bulls $n = 3$ and cows $n = 71$) verified by Wildlife Services as part of the Interagency Field Team from 1998 to February 2017. To reduce the effect of sampling bias, we used spatial filtering to randomly remove all but one depredation record within each 1 km^2 pixel. After rarefaction, 162 depredation points remained in the dataset.

2.3. Independent variables

We modeled depredation risk as a function of 6 biotic (relative abundance of elk, mule deer and white-tailed deer, annual livestock density, land cover type, land cover variety, canopy cover, and cover variety), 4 human (distance to and density of roads, distance to and density of developed areas) and 6 landscape (elevation, slope, terrain ruggedness index [TRI], aspect, distance to and density of water resources) variables (see Appendix S2 in Supporting information for hypotheses, variable sources, and variable calculations).

Spatial data on the abundance of livestock was not available for the entire study area and is probably not obtainable given the large number of livestock operations and variation in how livestock are managed. Consequently, we developed a spatial layer "annual livestock density" that represents the annual capacity for livestock production as a proxy for actual livestock abundance. We applied generalized linear models and used AIC_c to model annual livestock capacity on basis of Animal Unit Month (AUM) data for 3876 allotments (covering 39% of the study area) on lands managed by the US Forest Service and Bureau of Land Management and then interpolated to the 61% remainder of our study area (see Appendix S3 in Supporting information for details of methods and results). Similarly, spatial data on the abundance or density of the primary natural prey of the Mexican wolf (elk, mule deer and white-tailed deer) were not available for the entire study area. Maxent's raw output can be directly interpreted as a model of relative abundance