Human–Wildlife Interactions 13(1):29–41, Spring 2019 • digitalcommons.usu.edu/hwi

Spatial relationships between livestock guardian dogs and mesocarnivores in central Texas

Nicholas A. Bromen, Department of Wildlife and Fisheries Sciences, Texas A&M University, 534 John Kimbrough Blvd., 2258 TAMU, College Station, TX 77843, USA

Justin T. French, Department of Wildlife and Fisheries Sciences, Texas A&M University, 534 John Kimbrough Blvd., 2258 TAMU, College Station, TX 77843, USA

John W. Walker, Department of Ecosystem Sciences and Management, Texas A&M University, 2138 TAMU, San Angelo, TX 78701, USA

Nova J. Silvy, Department of Wildlife and Fisheries Sciences, Texas A&M University, 534 John Kimbrough Blvd., 2258 TAMU, College Station, TX 77843, USA

John M. Tomeček, Department of Wildlife and Fisheries Sciences, Texas A&M University, 534 John Kimbrough Blvd., 2258 TAMU, College Station, TX 77843, USA *tomecek@tamu.edu*

Abstract: The use of livestock guardian dogs (*Canis lupus familiaris*; LGDs) to deter predators from preying on domestic sheep (*Ovis aries*) and goat (*Capra* spp.) herds continues to increase across the United States. Most research regarding the efficacy of LGDs has been based on queries of rancher satisfaction with LGD performance, yet little is known regarding LGD influence on mesocarnivores, including those species against which they protect livestock. Here, we provide some preliminary observations regarding the effect of LGDs deployed with sheep and goat herds from May 2016 to April 2017 on the detected activity of mesocarnivores within occupied pastures on a 2,027-ha ranch in Menard County, central Texas, USA. Specifically, we were interested in learning if the presence of LGDs might affect the activity of nontarget mesocarnivores (i.e., mammalian predators that do not pose a predation threat to sheep or goats) apart from carnivores that do. To conduct this research, we deployed global positioning system radio-collars on 4 LGDs to record their positions and evaluate their spatial distribution across the ranch over the course of the study. To detect and quantify the presence of these carnivores across the ranch, we established a grid of remote cameras that continuously surveyed for their presence over the course of a year. We detected 8 mesocarnivore species and documented variable effects on activity by each species in relation to the locations of the radio-marked LGDs. Environmental factors rather than LGD presence accounted for most of the variation we observed in mesocarnivore activity. Mesocarnivore activity was also highest in areas without livestock. For those concerned with livestock–wildlife coexistence, our results suggest that LGD presence does not alter the activity of mesocarnivores not typically identified as a threat to sheep and goats. For those managing for livestock predation, our results suggest that LGD presence may negatively influence the activity of bobcats (*Lynx rufus*), though this effect was not independent from the influence of elevation.

Key words: *Canis lupus familiaris*, environmental factors, livestock guardian dogs, mesocarnivores, nontarget species, predator control, radio-telemtry, Texas

The decline of large carnivores across North America over the last 2 centuries (Laliberte and Ripple 2004) caused shifts among extant carnivore guilds, which in turn may directly or indirectly alter community structures (Ripple and Beschta 2004, Donadio and Buskirk 2006, Roemer et al. 2009, Ripple et al. 2013), releasing prior competition pressure placed on smaller mesocarnivores (Soulé et al. 1988, Crooks and Soulé 1999, Berger and Conner 2008, Ritchie and Johnson 2009). Researchers are just beginning to explore the direct and indirect ecological effects of the mesocarnivore guild, often with regard to intraguild competition, prey communities, and trophic interactions (Paine 1969, Estes et al. 1998, Arias-Del Razo et al. 2012, Miller et al. 2012).

Mesocarnivores may fill multiple ecological roles in an ecosystem, from apex predators to primary consumers (Feldhamer et al. 2003, Prugh et al. 2009, Ritchie and Johnson 2009). Many species within the guild are omnivorous, aiding in both seed dispersal and the regulation of granivorous rodent populations, theoretically contributing to the reproductive success of seed-bearing primary producers within a community (Jordano et al. 2007, Rosalino et al. 2010, Jensen et al. 2012, Miller et al. 2012). Nevertheless, most mesocarnivores are considered pests to agricultural communities in North America and have been subject to eradication and control efforts at the private, state, and federal levels (Wade and Bowns 1982, Neale et al. 1998, Roemer et al. 2009, National Agricultural Statistics Service [NASS] 2010). While interest in the community ecology of mesocarnivores has emerged in recent years, science must address practical carnivore conservation in the context of balancing human–wildlife conflict, especially with regard to ranching operations (Prugh et al. 2009, Ritchie and Johnson 2009, Newsome et al. 2015, Treves et al. 2016).

These conflicts typically come in the form of livestock losses to predation from carnivores (Pearson and Caroline 1981, Sacks and Neale 2007). At the turn of the twenty-first century, NASS within the U.S. Department of Agriculture (USDA) reported an estimated annual loss of $16.5 million in sheep (*Ovis aries*) and a loss of $3.4 million in goats (*Capra* spp.) to predators, the majority of which (60.7% and 35.6%, respectively) have been attributed to coyotes (*Canis latrans*; NASS 2000, Animal and Plant Health Inspection Service [APHIS] 2015*a*). As recently as 2014, 1.8% of adult sheep and 3.9% of lamb losses in the United States were attributed to predators, and although loss to predation accounts for a low percentage of overall livestock mortality, these damages were valued at >$18 million (APHIS 2015*b*). Nationwide stocking of sheep fell to 89% of its historical high from the 1950s in 2008 (Palmer et al. 2010), with recent numbers in 2015 standing at approximately 5.28 million head overall (APHIS 2015*b*). Despite substantial declines in the market over the last several decades and the low net effect of predators on livestock mortality, ranchers have largely cited loss to predation as being the main reason they have given up sheep production (Landivar 2003, Jones 2004, Palmer et al. 2010). As such, improved techniques for mitigating wildlife damage from carnivores have been sought in recent decades, as active and often lethal forms of predator control may no longer be effective in every setting or situation.

Strategies to mitigate livestock depredations range from lethal removal to the integration of domestic animals with strong defensive behaviors such as llamas (*Lama glama*), donkeys (*Equus assinus*), and domestic dogs (*C. lupus familiaris*) into their stock (Linhart et al. 1979, Green and Woodruff 1983, Meadows and Knowlton 2000, Dohner 2007). Livestock raisers in Europe and Asia have employed livestock guardian dogs (LGDs) since antiquity to help protect their livestock groups (Dawydiak and Sims 2004), yet their behavior and effectiveness at deterring predator species from livestock has scarcely been quantified (van Eeden et al. 2018). The inferences of most LGD studies have been based primarily on queries of rancher satisfaction rather than empirical trials and field-based study design (Andelt 1992, Coppinger et al. 1983, Green and Woodruff 1983, Green et al. 1984). Since their introduction to ranches in the United States in the 1970s, the use of LGDs in North America has grown, facilitating some study and experimentation regarding shepherding practices, including evaluations of different LGD breeds (Andelt 1999) and mixed breeds (Black and Green 1981). Nevertheless, limited data exists regarding the behavior of LGDs relative to the execution of their guardian duties, though the beginnings of a rigorous understanding of LGD behavior as a nonlethal wildlife damage management tool has arisen in the last decade (Gehring et al. 2010, Treves et al. 2016).

Livestock guardian dogs rarely physically confront predators; instead, they respond to livestock threats by presenting themselves as territorial deterrents (i.e., visual, auditory, and perhaps olfactory) to other carnivores (Findo 2005, Allen et al. 2017, van Bommel and Johnson 2017). The appeal of LGDs as a tool to manage wildlife damages rose from reports of fewer livestock losses from ranchers who used them (Andelt and Hopper 2000) and from empirical evidence that LGD presence may offset livestock predation loss in experimental trials (Linhart et al. 1979, McGrew and Blakesley 1982). Considerations for the time and expense of lethal control practices for the ranchers or regional government may also factor in to the choices available to livestock producers with regard to predator control (Green et al. 1984, Palmer et al. 2010). Among those that favor LGDs due to their less-than-lethal approach to wildlife damage management, the question remains: although LGDs appear to reduce damages to livestock, what unintended consequences do they have for the ecosystems and wildlife? Effects of LGDs on nontarget wildlife must also be considered as with any wildlife damage management tool.

Given the lack of data on effects on nontarget wildlife, we sought to examine the influence of LGDs on nontarget mesocarnivores (i.e., predators typically not considered a predation threat to livestock) among all mammalian carnivores inhabiting rangelands of the Edwards Plateau region of central Texas, USA. The Edwards Plateau is in the largest sheep and goat producing region of the state, leading the United States in sheep numbers, mohair produced, and losses of these livestock to predation (Gober 1979, APHIS 2015*b*). We evaluated the influence of LGDs on mesocarnivores in the context of intense sheep and goat production to determine the relative influence of LGDs on the activity of target and nontarget members of the mesocarnivore community compared to habitat factors and to examine whether nontarget mesocarnivore activity is negatively correlated with LGD space use.

Study area

We conducted our study on the Martin Ranch, a 2,027-ha ranch in Menard County, Texas, owned and operated by Texas A&M AgriLife Research in the Edwards Plateau Ecological Region (Gould 1966). Elevation at the Martin Ranch ranges from 613–678 m, averaging 648 m above sea level amid subtle rolling hills scattered throughout the countryside. Climate is characterized by semi-arid conditions, a mean annual temperature of 18°C, and a mean precipitation of 58 cm over a 30-year average. January is the coldest month (0–16°C) of the year and July is the hottest (21–35°C; National Oceanic and Atmospheric Administration 2016). Dominant overstory vegetation cover for carnivores found across the site consists mostly of plateau live oak (*Quercus fusiformis*), with intermittent juniper (*Juniperus ashei)* and mesquite (*Prosopis glandulosa*) woodlands atop understories comprised of native grasses, cacti, brush species, and forbs (Wrede 2010, National Resources Conservation Service [NRCS] 2015). The 4 prevailing ecological sites found on the ranch are (low stoney hill, clay loam, shallow, and draw (NRCS 2015). Low stoney hill and shallow sites occur at higher elevations, which feature thinner soils and support shrub-dominated plant communities, while clay loam sites support open mesquite-Texas wintergrass savannahs typically found above and alongside the draws (NRCS 2015). Vegetation occurs on relatively shallow clay loam soils (<5 cm) atop limestone bedrock, often exposed in the arid draws carved out through periodic flooding.

Animal management

Net-wire livestock fences divided the ranch into 9 pastures, averaging 224 ha per pasture. The ranch contained 58 km of unpaved roads, which received varying degrees of use. A consistent water supply was provided to the pastures of the ranch by 22 troughs drawn from water wells. The ranch supported approximately 200 sheep, 200 goats, 100 cattle (*Bos taurus*), and 4 LGDs over the course of the study period according to a decision-deferred rotational grazing regime. University staff whelped, weaned, and raised LGDs with a number of the sheep in bonding pens prior to deployment on the ranch. Upon deployment, 3 LGDs integrated among groups of sheep while the fourth integrated with the goat herd. No LGDs at the site were observed to be integrated among cattle. The LGDs roamed freely on the ranch, with occasional handling by humans for health exams and vaccinations. Self-feeders supply an *ad libidum* diet of kibble placed at 7 feeders located at water troughs throughout the ranch. Lethal predator control is a common practice throughout the surrounding area, though it has not been practiced on the ranch for at least 5 years prior to the onset of this study.

Methods

Mesocarnivore activity

We collected field data from May 2016 through April 2017. To assess the presence and activity of target and nontarget mesocarnivore species across the study area over time, we deployed trail cameras across the ranch and checked them monthly throughout the year (Zielinski and Kucera 1995, Schauster et al. 2002, Kelly 2008). Known livestock depredators in the region we regard as target species included bobcats (*Lynx*

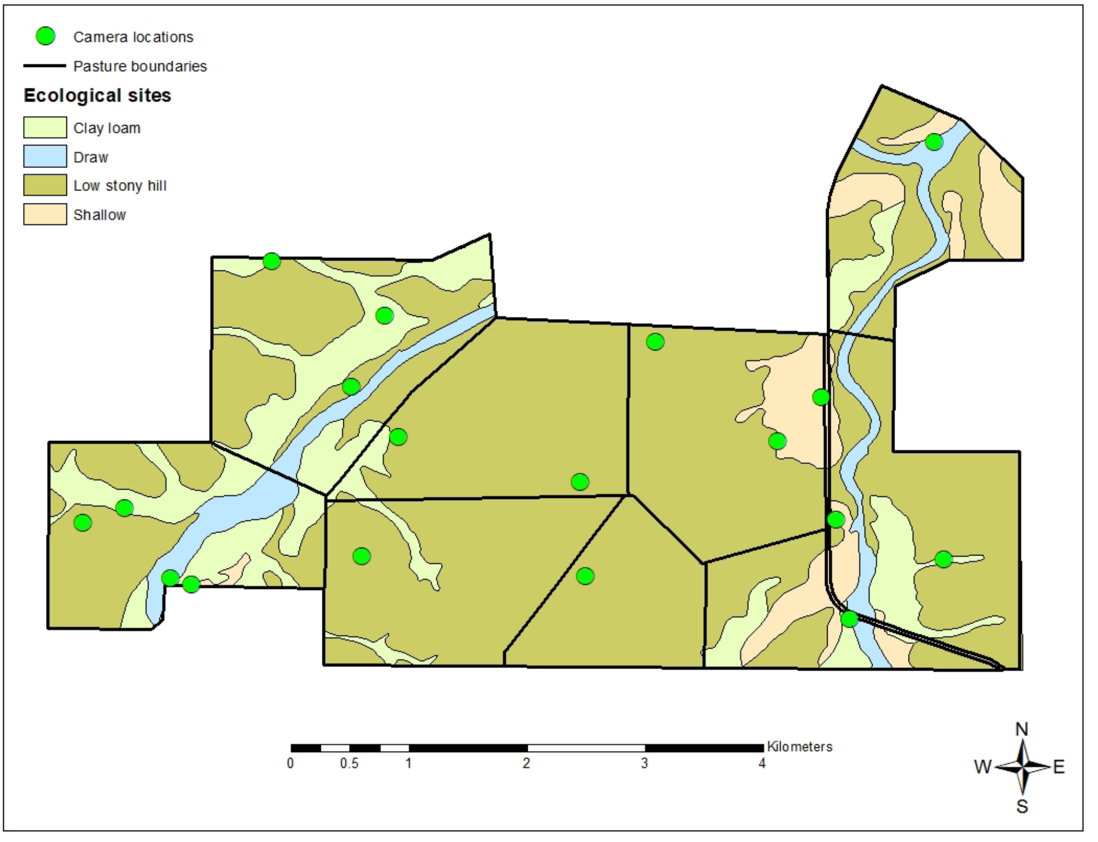

Figure 1. The Martin Ranch, central Texas, USA study site delineated by 9 fenced pastures, displaying the distribution of each ecological site across the ranch and the stratified random locations of each remote camera (*n* = 18) deployed.

rufus) and coyotes. Other mesocarnivores in the region we regarded as nontargets included American badgers (*Taxidea taxus*), gray foxes (*Urocyon cinereoargenteus*), raccoons (*Procyon lotor)*, ringtails (*Bassariscus astutus*), as well as striped skunks (*Mephitis mephitis*), hog-nosed skunks (*Conepatus mesoleucus*), and potentially Western spotted skunks (*Spilogale gracilis*; Feldhamer et al. 2003).

We set up a remote camera array according to a stratified random design, distributing the 18 cameras across the 4 ecological sites found throughout the ranch in proportion to the total area available for each site (Burton et al. 2015). We generated camera locations (Figure 1) accordingly in ArcMap (v.10.4.1 ESRI software, ESRI, Redlands, California, USA). We attached all cameras to t-posts at a height of 45 cm from ground level as to set the detection field for each camera on an analogous plane to the target species. Photographic detections represented a measure of activity in an area. To avoid biased representations of animal activity, no cameras were baited (Kelly 2008). Each pasture contained at least 1 camera for pasture-level representation across the study site. We checked all cameras monthly to collect photographic detection data stored on memory cards along with depleted batteries, replacing them at each interval through the study term.

Three camera models were available for use at the onset of the study. The camera grid comprised of 4 Reconyx HC600 Hyperfire (Reconyx, Holmen, Wisconsin, USA), 8 Bushnell Trophy Cam (Bushnell Corporation, Overland Park, Kansas, USA), and 8 Moultrie M-80 (Pradco Outdoor Brands, Birmingham, Alabama, USA) digital remote cameras. We set all cameras to take photos at 3-megapixel resolution in a 3-photo series (1-second interval between photos in a series) at medium sensitivity. All photographic detections of mesocarnivore species derived throughout the year were entered into a relational database (FileMaker Pro v.14, Apple Inc., Cupertino, California, USA; relational database) for each detection, noting: (1) the species detected, (2) the date and time of occurrence, and (3) the location of the camera where each detection took place.

LGD spatial data

To moniter LGD spatial movements, we deployed a global positioning system (GPS) on 4 LGDs (Global Positioning System, Vertex series model, Vectronic Aerospace, Germany). The GPS units logged locations at a 3-hour interval (8 times daily), then transmitted data via satellite.

The IRIDIUM satellite network communication system transmitted positions to laboratory servers daily. All locations were exported from proprietary software (GPSx, Vectronic Aerospace Gmbh, Berlin, Germany) to our relational database at the conclusion of the study and were accessed from this database directly from R for analysis using the *RODBC* package (Ripley and Lapsley 2017). We applied a fixed kernel density estimator (KDE; Worton 1989) using the reference smoothing parameter algorithm across all locations of all dogs to estimate the relative intensity of LGD space use across the study site. The LGD space use can be viewed as the probability of an LGD occurring at any location in space throughout the study site at any given time over the course of the study as well as the proportion of time an LGD spent at any given location. We considered LGD space use intensity (SUI) as an explanatory variable for determining whether their distribution across the study site influenced the detections of mesocarnivores in areas the LGDs were present.

We also considered elevation, slope, and canopy cover as explanatory variables for associating mesocarnivore detections with environmental variables under the presumption that mesocarnivore activity in the study area may be additionally influenced by such factors that determine habitat characteristics. Even throughout a range of 65 m, both elevation and slope largely drive vegetation associations in the region as a consequence of periodic hydrological events that drive soil local conditions and plant communities. As plateau live oak accounts for the majority of tree canopy on the ranch, the cover it provides may also drive the distribution of mesocarnivores, particularly the semi-arboreal species such as gray foxes and ringtails (Trapp 1978, Haroldson and Fritzell 1984).

Percent slope and elevation were derived in ArcMap from 10-m resolution digital elevation maps available from the Texas Natural Resource Information System (TNRIS; http://www.tnris.org). Oak canopy cover was derived from the 2016 National Agriculture Imagery Program 1-m resolution color-infrared images, accessed through TNRIS. Oak canopy cover was identified using an interactive supervised classification (Campbell and Wynne 2011), derived using spectral analysis tools within ArcMap, and was readily distinguishable as a separate spectral class apart from juniper and mesquite. Percent canopy cover was then calculated from this classified output at a 10-m resolution as the average of the 1-m pixels (n = 100) within each 10-m pixel. Values of LGD space use intensity, slope, elevation, and canopy cover were extracted from the location of each camera and used as predictors to explain variation in mesocarnivore activity.

The LGDs were placed on the ranch prior to our opportunity to conduct research there, and thus we could not sample an analogous period of time before their arrival to measure the effects LGDs may have on the spatial distribution of target and nontarget mesocarnivores post-introduction. Similarly, no analogous sites void of LGDs were available to survey in the adjacent rangelands at that time to provide an adequate control site. Thus, we proceed in the acknowledgment that this is a descriptive case study and the results obtained are limited in their power of statistical inference.

Capture, handling, and release of the LGDs adhered to the guidelines established by the Animal Care and Use Committee of the American Society of Mammologists; no handling was conducted outside the scope of protocol #AUP #2012-207A and SOP#2015-008A permitted by the Texas A&M University Agricultural Animal Care and Use Committee.

Data analysis

We first summed total counts and proportional frequencies of mesocarnivore detections per species from all cameras across the grid over the entire study period. To account for variations in down time between cameras due to battery

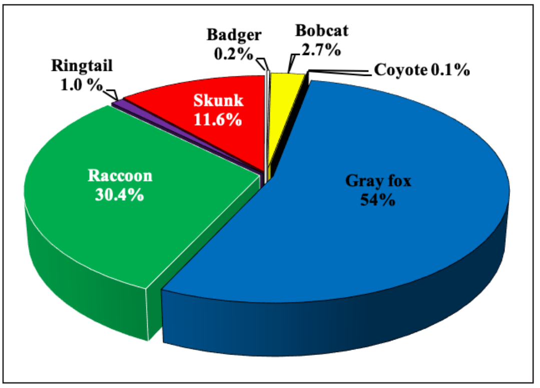

Figure 2. Proportions of all mesocarnivore detections by species observed across the camera grid, May 2016 to April 2017, Martin Ranch, Menard County, Texas, USA.

depletion or camera failure, detections were converted to a daily rate (detections per day) by dividing the total number of detections of each species for each camera by the total number of days each camera was active. Species detected <5 times over the course of the study were excluded from subsequent analysis due to lack of inferential power in such small sample sizes.

We used redundancy analysis (RDA; Legendre and Legendre 2012) to evaluate relationships between mesocarnivore activity, LGD space use, and the environmental variables of slope, elevation, and canopy cover. The RDA can be viewed as a multivariate multiple regression that is capable of accommodating collinear explanatory variables. This allows for the simultaneous analysis of the relationships between each species, the relationship of each species with the chosen explanatory variables, as well as the relationships between all explanatory variables given. The RDA utilizes permutation testing, permitting analysis without distributional assumptions (Legendre and Legendre 2012) and produces a triplot of the relationships between the predictors (as applied here) of LGD activity, elevation, slope, and oak canopy cover to the responses of mesocarnivore detection rates. The triplot is a superimposition of 2 biplots (1 principal component analysis [PCA] of the response variables, constrained by a PCA of the explanatory variables). The bottom and left axes are the scales of the centered response. The top and right axes are the scales of the standardized explanatory variables. Type II scaling (which preserves the relationships between variables) was used to produce the graphical representation of these results. In this output of the analysis, variables pointing the same direction are positively correlated while those pointing opposite directions are negatively correlated, and variables that are plotted at 90° to each other are uncorrelated.

We performed all analyses using R statistical software (R Development Core Team 2013) using the RStudiov.0.99.903 graphic user interface (RStudio, Inc. Boston, Massachusetts, USA). To perform the RDA analysis in R, we used the *rdaTest* statistical package (Legendre and Durand 2014).

Results

Mesocarnivore detections

Of the 6,570 potential trap days from the 18 remote cameras, we censored 604 (9.2%) due to camera failure, depleted batteries, or full memory cards (mostly due to wind-triggers from affected vegetation). The remaining 5,966 trap days yielded 1,269 detections of mesocarnivores throughout the yearlong sampling period. We observed 8 mesocarnivore species at the ranch, detected in varying proportions. These include the American badger (n = 3), bobcat (n = 34), coyote (n = 1), gray fox (n = 685), raccoon (n = 386), ringtail (n = 13), and skunk (n = 147; Figure 2), of which 115 detections were of striped skunks, 22 detections were of hog-nosed skunks, and 10 detections were of skunks unidentifiable at the species level. No Western spotted skunks were detected. We aggregated all skunk detections into a single species category (i.e., skunk) due to our inability to discern between these species in those 10 photographic detections. No large carnivores were detected across the study site, despite recent sightings in the county of mountain lions (*Puma concolor;* Texas Parks and Wildlife Department [TPWD] 2008) and black bears (*Ursus americanus*). Coyote (n = 1) and badger (n = 3) detections were excluded from analysis due to low detection yields for these species.

Influence of LGDs on mesocarnivore detections

We captured 85.7% of the overall variation in mesocarnivore activity in the first 2 canonical axes of our RDA (Figure 3). The 4 explanatory variables used in the analysis (elevation, slope, canopy cover, and SUI) combined explained

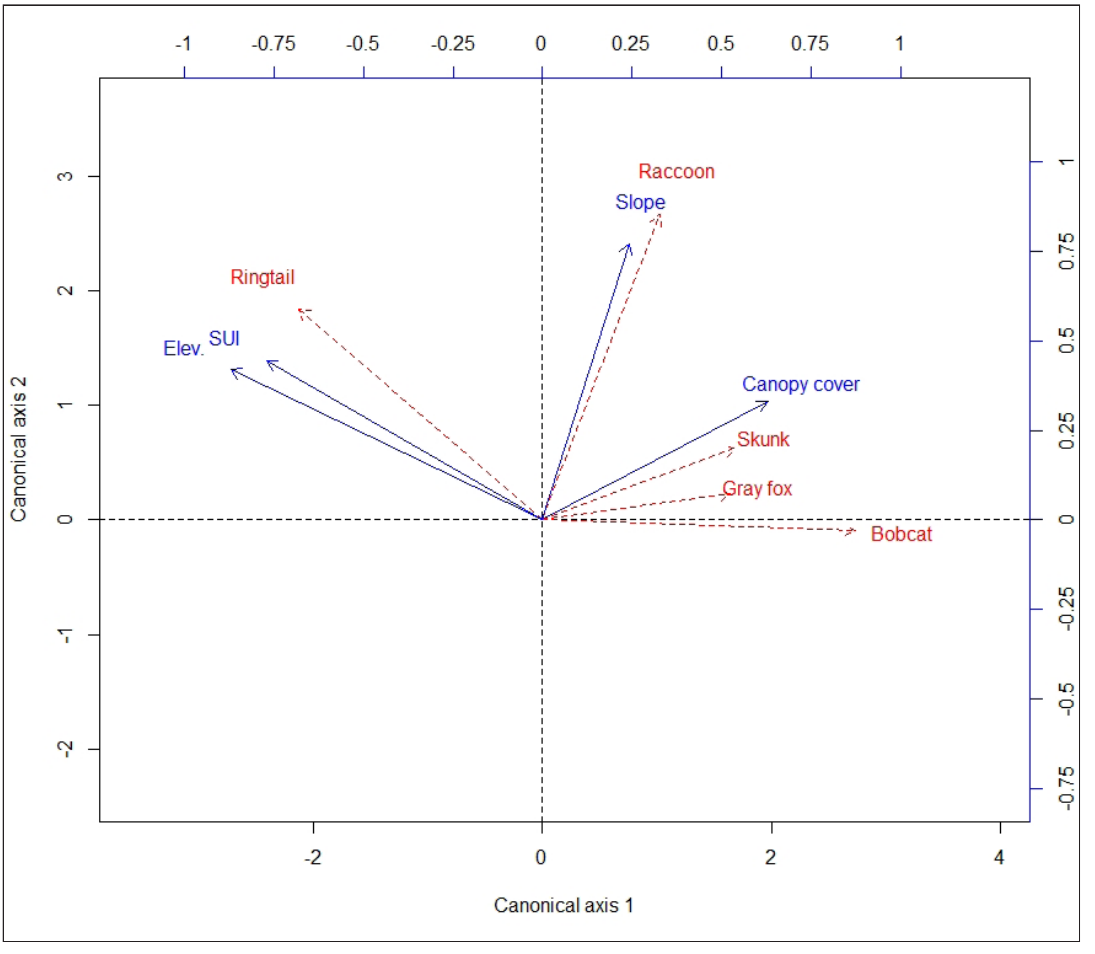

Figure 3. Triplot of relationships between mesocarnivore detection rates (responses; dashed grey vectors), livestock guardian dogs (*Canis lupus familiaris*; LGDs) space use intensity, elevation, slope, and canopy cover (predictors; solid black vectors). Canonical axis 1 captured 54.7% of the variation in mesocarnivore activity while canonical axis 2 captured 32.0%. Thus, 86.7% of the variation in mesocarnivore activity is captured in the graph. Bottom and left axes are the scales of the centered response variables and are also the scales in which the cameras (by number) are plotted. The top and right axes are the scales of the standardized explanatory variables. This plot is type II scaled to preserve relationships between variables. Correlation coefficients between variables are equal to the cosine of the angle between them, thus variables pointing the same direction are positively correlated, those pointing opposite directions are negatively correlated, and variables at 90° are uncorrelated, May 2016 to April 2017, Martin Ranch, Menard County, Texas, USA.

29.5% of the overall variation in mesocarnivore activity observed. The combined effect of these 4 variables was not a significant predictor of mesocarnivore activity ($P = 0.22$), which is likely due to the small number of sampling units (i.e., cameras) across the available space of the ranch (n = 18). However, the relationships between the explanatory and response variables are still interpretable.

Both SUI and elevation were highly correlated explanatory variables (r = 0.85; Table 1). We observed that LGD SUI was strongly and negatively correlated with bobcat activity (r = -0.70) and highly correlated with both raccoon (r = 0.70) and ringtail activity (r = 0.94). To a lesser degree, LGD space use was negatively and moderately correlated with gray fox activity (r = -0.41), though weakly so with skunk activity (r = -0.27).

Though not statistically significant, the correlations we observed between response and explanatory variables do make ecological sense and bear interpretation as plausible hypotheses for more thorough investigation. With this caveat in mind, each mesocarnivore species exhibited varied responses to the 3

Table 1. Correlation coefficients between the predictor variable of livestock guardian dog (*Canis lupus familiaris*) activity measured in terms of space use intensity, elevation, slope, and canopy cover and the response variables of mesocarnivore activity (per species sufficiently detected) across a stratified random camera grid, May 2016 to April 2017, Martin Ranch, Menard County, Texas, USA.

	Bobcat	Gray fox	Raccoon	Ringtail	Skunk
LGD activity (SUI)	-0.70	-0.41	0.70	0.94	-0.27
Elevation	-0.89	-0.71	0.23	0.96	-0.74
Slope	-0.32	0.66	0.78	0.34	0.44
Canopy cover	0.67	0.09	0.38	-0.27	0.54

environmental variables assessed. Bobcat activity was found to be positively correlated with canopy cover ($r = 0.67$) with a high negative correlation pertaining to elevation (r = -0.89). Gray fox activity was negatively correlated with elevation (r = -0.71), yet positively correlated with slope (r = 0.66). Raccoon activity was positively correlated with slope (r = 0.78) and to a lesser degree with canopy cover (r = 0.38). Ringtail activity was positively correlated with elevation (r = 0.96), which was the only environmental association of note for this species. Skunk activity was modestly correlated with both oak canopy cover (r = 0.54) and slope (r = 0.44) while negatively correlated with elevation (-0.74). Given the high degree of redundancy between LGD SUI and elevation (Figure 3), the effects between these 2 variables on mesocarnivore activity could not be adequately partitioned.

Discussion

We detected stronger relationships between nontarget mesocarnivore activity and our set of environmental variables than from LGD presence. For the target species assessed, bobcat activity was negatively influenced by LGD presence, though elevation had a stronger effect on their activity than LGDs. Slope, elevation, and canopy cover represent key aspects of habitat for the guild, and our data suggest that these factors influenced mesocarnivore activity patterns. For example, bobcat and gray fox activity increased at lower elevation sites with extensive canopy cover and higher available slopes, respectively, though they are not known to maintain core areas that overlap (Chamberlain and Leopold 2005, Donadio and Buskirk 2006). Raccoons and skunks were more active in steep, wooded sites, and ringtail activity was higher in areas where elevation increased.

The remote cameras randomly placed across the study site did not detect coyotes in sufficient numbers during our study; thus, we were unable to draw inferences upon patterns of activity for this species. Likewise, we were unable to infer any relationship between LGD SUI and coyote activity, though this information is of particular concern to ranchers and wildlife managers seeking to mitigate depredation risk. Additionally, we did not detect a strong influence of LGD SUI alone on the activities of mesocarnivores observed throughout the study period that did not coincide with similar influences from environmental variables. Although it is tempting to assert that LGDs are the source of variability in mesocarnivore patterns of space use, temporal factors and other ecological variables likely account for much of the variability that we were unable to capture with our set of explanatory variables here.

Nevertheless, we observed that bobcats and gray foxes were more active in areas where LGDs did not occur, and this partitioning of space may merit further examination. It is also feasible that livestock (and closely associated LGDs) may be selecting sites with higher elevation across the ranch in areas that do not comprise high quality habitat for bobcats and gray foxes. We observed extremely high fidelity of the 4 LGDs to livestock animals (Appendix 1), and though rotated throughout the ranch, the livestock tended to be more often stocked in pastures containing areas of higher elevation (in the low stoney hill ecological sites). These sites typically comprise a greater diversity of browse species, considered more appropriate for sheep and goats compared to lower elevation areas (Holecek et al. 2011) such as clay loam sites, which exhibit greater grass production and were at times stocked with non-LGD-bonded cattle. This would explain the high degree of correlation between SUI and elevation. For those seeking to use LGDs in varied landscapes, these results empirically demonstrate that LGDs remain close to bonded livestock and suggest that strategic placement of livestock may also assist in minimizing contact between LGDs and mesocarnivores of depredation concern.

We observed a lack of direct negative spatial effects for mesocarnivore activity due solely to LGDs in our study. As such, there is reason to suspect that LGDs can operate without significantly disrupting nontarget mesocarnivore species, thereby fulfilling needs of agricultural producers and conservationists alike. The goal of any noninjurious predation management practice is to provide for coexistence with predatory wildlife. The precise influences of LGDs (or any introduced species used as a management tool) on various taxa calls for further scrutiny, regarding both carnivore guild dynamics and unintended consequences stemming from their introduction into landscapes (Roemer et al. 2001), while considering the potential magnitude of effects they may place upon an ecosystem.

Nonlethal tools for predation management may appear to fulfill needs for coexistence with native wildlife, but those managing for wildlife damage must critically evaluate the potential effects of these tools on other species. Our study addressed only the spatial activity of the mesocarnivore guild present at our study site. Some studies have noted effects of LGDs on native wildlife that may cause conservationists to critically evaluate their use (Vercauteren et al. 2008, Gingold et al. 2009). For obscure carnivores as well as for threatened or endangered species that inhabit grazing lands, potential effects from LGDs should also factor into decisions regarding their use to manage damages to livestock. In Texas, many livestock producers also incorporate incomes from wildlife, either by harvest or viewing, into their annual revenue stream. If it should be observed that LGDs strongly influence the abundance, activity patterns, or presence of economically valuable game species in the state, such as white-tailed deer (*Odocoileus virginianus*) or wild turkeys (*Meleagris gallopavo* spp.), then such effects may potentially exceed local human tolerance for LGDs.

Appreciation for the role of carnivores in ecosystems has grown in accordance with the use of nonlethal tools to mitigate wildlife conflict in recent decades, and LGDs continue to gain popularity among ranching operations both across the country and globally (Findo 2005, Treves et al. 2009, Palmer et al. 2010, van Bommel and Johnson 2012). As of 2014, 23.5% of sheep producers used LGDs to guard their livestock, a more than 2-fold increase from 10 years prior (APHIS 2015*b*). Although a wildlife damage management tool must be socially acceptable to ensure widespread adoption and support, without scientific evaluation of the total effect of the tool on ecosystems, one may inadvertently degrade the system. Our preliminary case study provides a basis to initiate further evaluations upon other influences LGDs may place upon rangeland communities.

Management implications

This study provides some first insights into the effects of LGDs on the mesocarnivore community, both for species of depredation concern and those untargeted by direct or significant management action. For the mesocarnivore species sufficiently detected, LGD space use intensity appeared to only negatively impact bobcats, thereby indicating that this management tool could provide necessary protection to livestock without unnecessarily disrupting non-target mesocarnivores in the vicinity. We recommend managers and researchers to consider potential effects of LGDs on other species and community assemblages, as grazing lands provide habitat for a great diversity of species. For many livestock raisers, income from hunting leases produces much needed revenue. Thus, it may be worthwhile to evaluate LGDs for their potential effects on game species where they occur. For those considering the use of LGDs within the range of protected species, concern over LGD impacts on sensitive species should be addressed through careful evaluation.

Acknowledgments

We extend our gratitude to cooperating ranch staff, including J. Thorne, K. Chandler, and

J. Lopez for their hospitality and assistance; without these individuals, this study would not have been possible. Special thanks also extend to T. Adams for his early contributions, F. Smeins for review of proposals and manuscripts, and most of all to M. and J. French for generously providing housing and support during field excursions. Financial support for this research was provided by the Carl and Bina Sue Martin Endowment and the Texas A&M University System. We thank A. Clark, HWI associate editor, and 3 anonymous reviewers for comments that greatly improved the manuscript.

Literature cited

Allen, L. R., N. Stewart-Moore, D. Byrne, and B. L. Allen. 2017. Guardian dogs protect sheep by guarding sheep, not by establishing territories and excluding predators. Animal Production Science 57:1118–1127.

Andelt, W. F. 1992. Effectiveness of livestock guarding dogs for reducing predation on domestic sheep. Wildlife Society Bulletin 20:55–62.

Andelt, W. F. 1999. Relative effectiveness of guarding-dog breeds to deter predation on domestic sheep in Colorado. Wildlife Society Bulletin 27:706–714.

Andelt, W. F., and S. N. Hopper. 2000. Livestock guard dogs reduce predation on domestic sheep in Colorado. Journal of Range Management 53:259–267.

Animal and Plant Health Inspection Service (APHIS). 2015*a*. Goat and kid predator and nonpredator death loss in the United States, 2015. U.S. Department of Agriculture 1-64, Fort Collins, Colorado, USA.

Animal and Plant Health Inspection Service (APHIS). 2015*b*. Sheep and lamb predator and nonpredator death loss in the United States, 2015. U.S. Department of Agriculture 1-64, Fort Collins, Colorado, USA.

Arias-Del Razo, I., L. Hernández, J. W. Laundré, and L. Velasco-Vázquez. 2012. The landscape of fear: habitat use by a predator (*Canis latrans*) and its main prey (*Lepus californicus* and *Sylvilagus audubonii*). Canadian Journal of Zoology 90:683–693.

Berger, K. M., and M. M. Conner. 2008. Recolonizing wolves and mesopredator suppression of coyotes: impacts on pronghorn population dynamics. Ecological Applications 18:599–612.

Black, H. L., and J. S. Green. 1981. Navajo use of mixed-breed dogs for management of predators. Journal of Range Management 38:11–15.

Burton, A. C., E. Neilson, D. Moreira, A. Ladle, R. Steenweg, J. T. Fisher, E. Bayne, and S. Boutin. 2015. Wildlife camera trapping: a review and recommendations for linking surveys to ecological processes. Journal of Applied Ecology 52:675–685.

Campbell, J. B., and R. H. Wynne. 2011. Introduction to remote sensing. Fifth edition. Guilford Press, New York, New York, USA.

Chamberlain, M. J., and B. D. Leopold. 2005. Overlap in space use among bobcats (Lynx rufus), coyotes (Canis latrans) and gray foxes (Urocyon cinereoargenteus). American Midland Naturalist 153:171–180.

Coppinger, R., J. Lorenz, J. Glendinning, and P. Pinardi. 1983. Attentiveness of guarding dogs for reducing predation on domestic sheep. Journal of Range Management 36:275–279.

Crooks, K. R., and M. E. Soulé. 1999. Mesopredator release and avifaunal extinctions in a fragmented system. Nature 400:563–566.

Dawydiak, O., and D. E. Sims. 2004. Livestock protection dogs: selection, care, and training, Second edition. Alpine Publications, Crawford, Colorado, USA.

Dohner, J. V. 2007. Livestock guardians: using dogs, donkeys and llamas to protect your herd (Storey's working animals). Storey Publishing, North Adams, Massachusetts, USA.

Donadio, E., and S. W. Buskirk. 2006. Diet, morphology, and interspecific killing in Carnivora. American Naturalist 167:524–536.

Estes, J. A., M. T. Tinker, T. M. Williams, and D. E. Doak. 1998. Killer whale predation on sea otters linking oceanic and nearshore systems. Science 282:473–476.

Feldhamer, G. A., B. C. Thompson, and J. A. Chapman. 2003. Wild mammals of North America: biology, management, and conservation. Second edition. Johns Hopkins University Press, Baltimore, Maryland, USA.

Findo, S. 2005. Reducing sheep losses to large predators by use of livestock guarding dogs. Beitragezur Jagd und Wildforschung 30:213–221.

Gehring, T. M., K. C. VerCauteren, and J.-M. Landry. 2010. Livestock protection dogs in the 21st century: is an ancient tool relevant to modern conservation challenges? BioScience 60:299–308.

Gingold, G., Y. Yom-Tov, N. Kronfeld-Schor, and E. Geffen. 2009. Effect of guard dogs on the behavior and reproduction of gazelles in cattle enclosures on the Golan Heights. Animal Conservation 12:155–162.

Gober, D. R. 1979. Factors affecting domestic sheep losses to predators in Trans-Pecos Texas. Dissertation, Texas A&M University, College Station, Texas, USA.

Gould, F. W. 1966. Texas plants: a checklist and ecological summary. Texas Agricultural Experimental Station, Texas A&M University System, College Station, Texas, USA.

Green, J. S., and R. A. Woodruff. 1983. Guarding dogs protect sheep from predators. U.S. Department of Agriculture, Agricultural Information Bulletin 455, Dubois, Idaho, USA.

Green, J. S., R. A. Woodruff, and T. T. Tueller. 1984. Livestock-guarding dogs for predator control: costs, benefits, and practicality. Wildlife Society Bulletin 12:44–50.

Haroldson, K., and E. Fritzell. 1984. Home ranges, activity, and habitat use by gray foxes in an Oak-Hickory Forest. Journal of Wildlife Management 48:222–227.

Holecek, J. L., R. D. Pieper, and C. H. Herbel. 2011. Range management: principles and practices. Sixth edition. Prentice Hall, Upper Saddle River, New Jersey, USA.

Jensen, P. G., C. L. Demers, S. A. McNulty, W. J. Jakubas, and M. M. Humphries. 2012. Marten and fisher responses to fluctuations in prey populations and mast crops in the northern hardwood forest. Journal of Wildlife Management 76:489–502.

Jones, K. 2004. Economic impact of sheep predation in the United States. Sheep and Goat Research Journal 19:6–12.

Jordano, P., C. Garcia, J. A. Godoy, and J. L. Garcia-Castano. 2007. Differential contribution of frugivores to complex seed dispersal patterns. Proceedings of the National Academy of Sciences 104:3278–3282.

Kelly, M. J. 2008. Design, evaluate, refine: camera trap studies for elusive species. Animal Conservation 11:182–184.

Laliberte, A. S., and W. J. Ripple. 2004. Range contractions of North American carnivores and ungulates. BioScience 54:123–138.

Landivar, R. 2003. Econometric model of the U.S. sheep and mohair industries for policy analysis. Dissertation, Texas A&M University, College Station, Texas, USA.

Legendre, P., and S. Durand. 2014. *rdatest*: Canonical redundancy analysis. R package version 1.11.

Legendre, P. and L. Legendre. 2012. Numerical ecology. Developments in environmental modeling. Volume 24. Third edition. Elsevier, Amsterdam, Netherlands.

Linhart, S. B., R. T. Sterner, T. C. Carrigan, and D. R. Henne. 1979. Komondor guard dogs reduce sheep losses to coyotes. Journal of Range Management 32:238–241.

McGrew, J. C., and C. S. Blakesley. 1982. How Komondor dogs reduce sheep losses to coyotes. Journal of Range Management 35:693–696.

Meadows, L. E., and F. F. Knowlton. 2000. Efficacy of guard llamas to reduce canine predation on domestic sheep. Wildlife Society Bulletin 28:614–622.

Miller, B. J., H. J. Harlow, T. S. Harlow, D. Biggins, and W. J. Ripple. 2012. Trophic cascades linking wolves (*Canis lupus*), coyotes (*Canis latrans*), and small mammals. Canadian Journal of Zoology 90:70–78.

National Agricultural Statistics Service (NASS). 2000. Sheep and goat predator loss. Agricultural Statistics Board, U.S. Department of Agriculture 1-11, Washington D.C., USA.

National Agricultural Statistics Service (NASS). 2010. Sheep and goat predator loss. Agricultural Statistics Board, U.S. Department of Agriculture 1-16, Washington D.C., USA.

National Oceanic and Atmospheric Administration. 2016. Annual climatological summary, Menard County, TX:1985–2015. National Oceanic and Atmospheric Administration, Washington D.C., USA.

National Resources Conservation Service (NRCS). 2015. Ecological site description, MLRA 081B-Edwards Plateau, Central Part. U.S. Department of Agriculture, San Antonio, Texas, USA.

Neale, J. C. C., B. N. Sacks, M. M. Jaeger, and D. R. McCullough. 1998. A comparison of bobcat and coyote predation on lambs in north-coastal California. Journal of Wildlife Management 62:700–706.

Newsome, T. M., J. A. Dellinger, C. R. Pavey, W. J. Ripple, C. R. Shores, A. J. Wirsing, and C. R. Dickman. 2015. The ecological effects of providing resource subsidies to predators. Global Ecology and Biogeography 24:1–11.

Paine, R. T. 1969. A note on trophic complexity and community stability. American Naturalist 103:91–93.

Palmer, B. C., M. R. Conover, and S. N. Frey.

2010. Replication of a 1970s study on domestic sheep losses to predators on Utah's summer rangelands. Rangeland Ecology and Management 63:689–695.

Pearson, E. W., and M. Caroline. 1981. Predator control in relation to livestock losses in central Texas. Journal of Range Management 34:435–441.

Prugh, L. R., C. J. Stoner, C. W. Epps, W. T. Bean, W. J. Ripple, A. S. Laliberte, and J. S. Brashares. 2009. The rise of the mesopredator. BioScience 59:779–791.

R Development Core Team. 2013. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Ripley, B., and M. Lapsley. 2017. RODBC: ODBC database access. R package version 1.3–15.

Ripple, W. J., and R. L. Beschta. 2004. Wolves and the ecology of fear: can predation risk structure ecosystems? BioScience 54:755–766.

Ripple, W. J., A. J. Wirsing, C. C. Wilmers, and M. Letnic. 2013. Widespread mesopredator effects after wolf extirpation. Biological Conservation 160:70–79.

Ritchie, E. G., and C. N. Johnson. 2009. Predator interactions, mesopredator release and biodiversity conservation. Ecology Letters 12:982–998.

Roemer, G. W., T. J. Coonan, D. K. Garcelon, J. Bascompte, and L. Laughrin. 2001. Feral pigs facilitate hyperpredation by golden eagles and indirectly cause the decline of the island fox. Animal Conservation 4:307–318.

Roemer, G. W., M. E. Gompper, and B. Van Valkenburgh. 2009. The ecological role of the mammalian mesocarnivore. BioScience 59:165–173.

Rosalino, L. M., S. Rosa, and M. Santos-Reis. 2010. The role of carnivores as Mediterranean seed dispersers. Annales Zoologici Fennici 47:195–205.

Sacks, B. N., and J. C. C. Neale. 2007. Coyote abundance, sheep predation, and wild prey dynamics illuminate Mediterranean trophic dynamics. Journal of Wildlife Management 71:2404–2411.

Schauster, E. R., E. M. Gese, and A. M. Kitchen. 2002. An evaluation of survey methods for monitoring swift fox abundance. Wildlife Society Bulletin 30:464–477.

Soulé, M. E., D. T. Bolger, A. C. Alberts, J. Wright, M. Sorice, and S. Hill. 1988. Reconstructed dynamics of rapid extinctions of chaparral-requiring birds in urban habitat islands. Conservation Biology 2:75–92.

Texas Parks and Wildlife Department. 2008. Mountain lions in Texas. Wildlife Division publication PWD BR W7000-232, Texas Parks and Wildlife Department, Austin, Texas, USA.

Trapp, G. R. 1978. Comparative behavioral ecology of the ringtail and gray fox in southwestern Utah. Carnivore 1:3–32.

Treves, A., M. Krofel, and J. McManus. 2016. Predator control should not be a shot in the dark. Frontiers in Ecology and the Environment 14:380–388.

Treves A., R. B. Wallace, and S. White. 2009. Participatory planning of interventions to mitigate human–wildlife conflicts. Conservation Biology 23:1577–1587.

van Bommel, L., and C. N. Johnson. 2012. Good dog! Using livestock guardian dogs to protect livestock from predators in Australia's extensive grazing systems. Wildlife Research 39:220–229.

van Bommel, L., and C. N. Johnson. 2017. Olfactory communication to protect livestock: dingo response to urine marks of livestock guardian dogs. Australian Mammalogy 39:219–226.

van Eeden, L. M., M. S. Crowther, C. R. Dickman, D. W. Macdonald, W. J. Ripple, E. G. Ritchie, and T. M. Newsome. 2018. Managing conflict between large carnivores and livestock. Conservation Biology 32:26–34.

VerCauteren, K. C., M. J. Lavelle, and G. E. Phillips. 2008. Livestock protection dogs for deterring deer from cattle and feed. Journal of Wildlife Management 72:1443–1448.

Wade, D. A., and J. E. Bowns. 1982. Procedures for evaluating predation on livestock and wildlife. Texas Agricultural Extension Service Publication B-1429, College Station, Texas, USA.

Worton, B. J. 1989. Kernel methods for estimating the utilization distribution in home-range studies. Ecology 70:164–168.

Wrede, J. 2010. Trees, shrubs, and vines of the Texas Hill Country. Second edition. Texas A&M University Press, College Station, Texas, USA.

Zielinski, W. J., and T. E. Kucera. 1995. American marten, fisher, lynx, and wolverine: survey methods for their detection. Pacific Southwest Research Station publication, U.S. Forest Service, Department of Agriculture, Albany, California, USA.

Associate Editor: Alan Clark

Appendix 1. Total counts, means, and ranges of proximity fixes, and percentage of days associated with livestock within ~300 m of named livestock guardian dogs (*Canis lupus familiaris*; LGDs) equipped with the global positioning system radio-transmitter at the Martin Ranch, central Texas, USA, July 2016 to April 2017.

LGD (by name)	Proximity fixes per day			# Days w/o fixes	# Days w/ <10 fixes	% Days near livestock
	n	Mean ± SE	Range			
Reginald[a]	28,903	93.8 ± 3.4	1–355	0	12	100.00%
Alfred	42,143	136.8 ± 5.1	0–456	2	5	99.35%
Nigel	21,497	69.8 ± 2.6	0–287	2	11	99.35%
Elizabeth	41,537	134.9 ± 4.9	0–406	2	5	99.35%

[a]Denotes the LGD bonded with the goat herd

John M. Tomeček is an assistant professor and extension wildlife specialist at Texas A&M University. As PI of the Texas Carnivore Ecology Laboratory, he leads efforts to expand knowledge of the ecology, behavior, and interactions of humans with carnivores. Much of his work centers on carnivore ecology, wildlife damage management, and zoonotic disease ecology and management. He currently serves as President-Elect of the Texas Chapter of the Wildlife Society.

Justin T. French earned his B.S. degree in wildlife and fisheries sciences at Texas A&M University in 2012. He went on to complete an M.S. degree in natural resources management from Sul Ross State University in Alpine, Texas, where he studied diets, nutrition, and habitat selection of pronghorn. He is currently a Ph.D. candidate at Texas A&M University studying coyote spatial ecology in southern Texas. His research interests include animal movement and habitat selection, rangeland ecology, and wildlife management.

John W. Walker has served as professor and director at the Texas A&M University Agricultural Research and Extension Center in San Angelo, Texas since 1997. His responsibilities include providing leadership to a multidisciplinary team of scientists that develop new technologies for increasing the efficiency and sustainability of range livestock and wildlife production. His area of expertise involves foraging ecology, modification of livestock foraging behavior, targeted livestock grazing for landscape enhancement, and near infrared spectroscopy (NIR). He received his B.S. degree in wildlife science and Ph.D. degree in rangeland ecology from Texas A&M University and his M.S. degree in range science from Colorado State University. He has authored or co-authored >60 scientific journal articles and >100 other professional publications. He serves on numerous professional and civic boards and committees and is a director for the Texas Sheep and Goat Raisers.

Nicholas A. Bromen (photo unavailable) has worked on a variety of wildlife studies and monitoring projects throughout the western United States over the last decade, more notably in the fields of carnivore and forest ecology. He earned a B.S. degree in biology from The Evergreen State College and a master's degree in wildlife and fisheries sciences from Texas A&M University.

Nova J. Silvy is a Regents Professor and Senior Faculty Fellow with the Department of Wildlife and Fisheries Sciences at Texas A&M University. He received his B.S. and M.S. degrees from Kansas State University and his Ph.D. degree from Southern Illinois University–Carbondale. He served as president of The Wildlife Society in 2000–2001 and received the Aldo Leopold Award in 2003. His research focus is upland game bird ecology.