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Spatial associations of livestock guardian dogs and domestic sheep

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Abstract: Livestock guardian dogs (*Canis lupus familiaris*; LGDs) have been used for centuries to protect livestock, primarily domestic sheep (*Ovis aries*), from depredation by large carnivores. While previous studies have shown their efficacy, the mechanisms in which LGDs protect livestock have largely remained unstudied. Livestock guardian dogs are often considered to be effective only if they remain in spatial proximity to the livestock they are protecting. We determined space use of LGDs relative to domestic sheep on open-range grazing allotments used by working ranches in the Rocky Mountains area of the northwest United States between August 2012 and October 2016. We determined dynamic space use, measured as proximity of LGDs to domestic sheep, and evaluated if this metric differed by breed, sex, or age. The LGDs and sheep were fitted with global positioning system transmitters to obtain location data that were subsequently compared by the above traits using multiple mixed-effect linear models. We found no differences in proximity to sheep on open range among LGDs for any of the 3 traits. Overall, we did find a temporal effect in that all of the LGDs studied were closer to sheep in early morning hours when sheep moved the shortest distances and predators are most likely to be active. These results suggest any of the breeds tested, along with sex or age of these LGD breeds, will remain in proximity to sheep when properly bonded.

Key words: activity patterns, *Canis lupus familiaris*, carnivore, human–wildlife conflict, livestock protection dog, northern Rocky Mountains, predation

Measuring shared space use can be useful to understanding a variety of behavioral processes. Shared space use among animals can be measured as static (i.e., home-range overlap) or dynamic (i.e., space-time proximity; Macdonald et al. 1980). Dynamic space use often focuses on spatial proximity. This metric has been used in numerous ways in wildlife studies, ranging from assessing risks of pathogen transmission to predator–prey dynamics. For example, Woodroffe and Donnelly (2011) used movement data of African wild dogs (*Lycaon pictus*) and domestic dogs (*Canis lupus familiaris*) to determine risk of disease transmission. Benson and Patterson (2014) reported that pack cohesion for gray wolves (*C. lupus*) radio-marked with global positioning system (GPS) differed between seasons. Spatial proximity data obtained through the use of GPS collars illustrated sociality among individuals of 2 carnivore species often considered to be solitary: fossa (*Cryptoprocta ferox*) and cougar (*Puma concolor*; Lührs and Kappeler 2013, Elbroch and Quigley 2016). These studies illustrate the broad applications for GPS-location data from animals sharing space and how such data can improve our ecological understanding of the species being monitored.

Space use can be a metric of livestock guardian dog (LGD) effectiveness. Livestock guardian dogs are a specialized type of domestic dog bred and trained to bond with and protect livestock from wild predators. Dogs have been used in this role for at least 5,000 years (Gehring et al. 2010), yet the mechanisms that enhance their efficacy have largely remained unstudied.

It is generally accepted that LGDs must

bond with the livestock they are employed to protect. Livestock producers note that LGDs that are bonded with livestock are less likely to roam and more likely to stay among the livestock, suggesting the importance of evaluating metrics of bonding. Determining shared space use among livestock and LGDs, specifically by measuring proximity, could serve as such a metric. Even so, only a few studies have evaluated space use of LGDs (Gipson et al. 2012; van Bommel and Johnson 2014a, b; Webber et al. 2015). van Bommel and Johnson (2014*a*, *b*) showed that Maremma sheepdogs spent the majority of their time with livestock but made movements away from stock, especially at night. While informative, this study was limited to a single breed of LGD in a scenario where livestock were maintained in fixed pastures. There are at least 33 breeds of LGDs used throughout the world (Rigg 2001), used in a variety of grazing systems.

In many parts of the world, transhumance grazing is common. In transhumance systems, LGDs and livestock move across landscapes instead of remaining in fixed pastures, typically to take advantage of forage resources found at higher altitudes each summer. One of the more common scenarios in the western United States is domestic sheep (*Ovis aries*), shepherds, horses (*Equus caballus*), herding dogs, and LGDs traveling through and between undeveloped stretches of public lands each summer. In this system, LGDs are typically used to protect domestic sheep from large carnivores, including 2 wild canids, the gray wolf and coyote (*C. latrans*).

The objective of this study was to determine space use of LGDs relative to domestic sheep in mostly transhumance systems of working ranches in the northwest United States. We specifically looked at dynamic space use, measured as proximity of LGDs to domestic sheep. We hypothesized that certain characteristics of LGDs, such as breed, sex, or age, impact proximity. Results of this study will help our understanding of underlying mechanisms that affect the efficacy of LGDs.

Study area and methods

Between August 2012 and October 2016, 3 breeds of LGDs were imported from their countries of origin and placed with sheep producers practicing transhumance systems. Study sites included parts of Wenatchee National Forest and lowland sections of eastern Washington; the Blue Mountains in Oregon; the western edge of Payette National Forest and the southern edge of Sawtooth National Forest in Idaho, from McCall to Ketchum; the front range in Montana, from Shelby to Dillon; and Bighorn National Forest in Wyoming, USA. Because of the large geographic distribution of study sites, habitat characteristics varied, but study areas were generally characterized by high elevation grasslands or mixed grassland conifer forests approximately 1,000–1,500 m above sea level. Livestock producers were selected for the presence of domestic sheep on summer grazing pastures and the potential for depredation by wolves. The LGD breeds imported were Turkish Kangal, Bulgarian Karakachan, and Portuguese Cão de Gado Transmontano (henceforth called Transmontano). Most livestock producers already owned LGDs that were also used in this study, and we refer to these LGDs as whitedogs because they include crosses of multiple LGD breeds and LGDs of unknown genetic origin. Most whitedogs in our study were purebreds or crosses including Great Pyrenees, Maremma, and some Akbash. Although exact breeds could not always be determined, because of crossbreeding, none of the livestock producers had whitedogs that included crossbreeds of the 3 European breeds we tested. All Kangals, Karakachans, and Transmontanos were spayed or neutered at approximately 12 months old. Whether or not whitedogs were spayed or neutered was at the discretion of each producer.

Most LGDs worked in teams of 3 dogs of the same breed per flock. However, due to the constraints of working livestock ranches, LGDs were occasionally moved or added by the producer (i.e., not per our study design). All Kangals, Karakachans, Transmontanos, and whitedogs in the study were outfitted with GPS collars (ATS model G2110, Isanti, Minnesota, USA, or Telonics model TGW-4400-3, Mesa, Arizona, USA) for at least the transhumance grazing season of each year, typically between May and October. The LGDs were occasionally moved between bands by producers, and uncollared whitedogs were occasionally present among monitored teams of LGDs. The

Table 1. Linear mixed-model results evaluating livestock guardian dog (*Canis lupus familiaris*) distance from domestic sheep in free-ranging sheep (*Ovis aries*) bands during summer grazing seasons season (August 2012 to October 2016) on working sheep operations in Idaho, Montana, Washington, Wyoming, and Oregon, USA. Statistically significant results are highlighted with an asterisk (*) at $P < 0.05$; LCI and UCI represent the lower and upper 95% confidence interval, respectively.

Model	Variable	β	SE	*P*-value	LCI	UCI
Null	Intercept*	625.76	23.61	<0.0001	579.50	672.03
Time of day	0000–0200 (reference)*	565.44	25.13	<0.0001	516.18	614.70
	0200–0400*	-182.64	13.85	<0.0001	-209.78	-155.50
	0400–0600*	-260.04	13.83	<0.0001	-287.15	-232.93
	0600–0800*	-187.24	13.84	<0.0001	-214.36	-160.11
	0800–1000*	127.61	13.97	<0.0001	100.24	154.98
	1000–1200*	318.64	14.05	<0.0001	291.10	346.18
	1200–1400*	279.17	14.17	<0.0001	251.38	306.95
	1400–1600*	196.40	14.18	<0.0001	168.62	224.19
	1600–1800*	98.36	14.12	<0.0001	70.69	126.02
	1800–2000*	107.60	14.03	<0.0001	80.11	135.09
	2000–2200*	153.30	13.98	<0.0001	125.90	180.70
	2200–0000*	137.12	13.93	<0.0001	109.82	164.43
Sheep speed	Each 1 km/hour increase*	441.04	9.70	<0.0001	422.03	460.06
Sex	Female (reference)	596.65	39.83	<0.0001	518.57	674.72
	Male	56.72	52.08	0.281	-45.36	158.79
Age	By year increase in age	3.25	7.92	0.6818	-12.28	18.77
Breed	Whitedog (reference)*	617.4831	32.43	<0.0001	553.91	681.05
	Kangal	70.53	54.69	0.2022	-36.67	177.73
	Karakachan	-79.38	99.19	0.4267	-273.79	115.02
	Transmontano	-71.41	77.74	0.362	-223.77	80.95

GPS radio-collars were removed over winter to save battery life when LGDs were at ranches and often kept in kennels or fenced pastures. The GPS radio-collars were programmed to collect a location every 2.5 or 5 hours, based on battery capabilities of the collar to ensure the collar would collect data for all years of the study.

During the summer grazing season (May to mid-October), we randomly selected at least 3 sheep per flock and fitted them with a GPS-location data logger (i-gotU GT-600®, Mobile Action Technology, Inc., New Taipei City 231, Taiwan) attached to a nylon dog collar. Radio-collared sheep were recaptured approximately every 6 weeks during the grazing season to exchange their collars, as this is the approximate battery life of the data loggers. If a collared sheep could not be relocated within the flock at the time of recapture, another sheep was randomly selected and equipped with the data logger. Data loggers were programmed to collect a location every hour. Most data loggers were recovered at the end of the grazing season when the sheep were corralled if they could not be recovered during the grazing season. A few data loggers broke off of their nylon dog collars during deployment, and we were unable to recover these data loggers.

Data were extracted from GPS radio-collars on LGDs. All 2D fixes and those with a positional dilution of precision of ≥5 were removed to ensure precision (D'Eon et al. 2002, D'Eon and Delparte 2005). The i-gotU data loggers did not record precision metrics. Instead, we used sheep behavior to identify and remove outlier points. We removed all fixes that exceeded 3 km/hour because the walking speed of domestic sheep is approximately 2.7 km/hour (Squires et al. 1972). While this may have removed periods of time that sheep were running, it provided a conservative estimate of accuracy in location data. Simultaneous points, defined as occurring within 1 hour of each other, were then extracted for all LGDs and sheep in the same bands using WildlifeDI in R (Long et al. 2014, R Core Team 2018), and linear distances were calculated between LGDs and sheep pairs. Multiple mixed-effect linear models (Lindstrom and Bates 1988) were then run to explore the effect of LGDs breed, sex, age, time of day, and sheep traveling speed on LGD proximity to their flock, while controlling for random differences between individual LGDs. All procedures were approved by the National Wildlife Research Center's Institute for Animal Care and Use Committee (QA-2062).

Results

We worked with 16 sheep producers, who maintained flocks during our study ranging in size from 590–2,962 sheep. During the study period, 64 LGDs were collared yielding 175,989 GPS locations, and 112 sheep were collared, yielding 245,800 GPS locations during summer grazing seasons. Of those locations, 1.7% (*n* = 3,096) fixes for LGDs were removed because they were not 3D fixes, another 1.0% (*n* = 1,633) fixes for LGDs were removed after removal of 2D fixes for lack of precision, and 1.4% (*n* = 3,412) fixes for sheep were removed for falling outside of the 3-km travel distance cutoff standard. Thus, a total of 115,261 of the LGDs and 238,441 of the sheep locations passed quality control standards and occurred during the same deployment time frame, of which there were 51,685 simultaneous locations from 266 LGD–sheep pairs within the same sheep band. This final data set included 34 whitedogs, 19 Kangals, 7 Transmontanos, and 4 Karakachans. Thus, there were more simultaneous locations from Kangals (*n* = 20,522 locations) and whitedogs (*n* = 21,934 locations) than from Karakachans (*n* = 3,043 locations) and Transmontanos (*n* = 6,186 locations). Twenty-three LGDs were female, 33 were male, and 8 were unknown sex. Age was known for 41 of the 64 LGDs. All of the unknown information was for whitedogs.

Mixed effect models accounting for individual variation found that LGDs were on average 625.8 m (SE = 23.6) from the nearest GPS-marked sheep (Table 1). Tagged sheep within the same band were a mean distance of 257.4 m apart (SE = 48.9), while collared LGDs were a mean distance of 770.6 m apart (SE = 93.1). It should be noted that location data from GPS-collared LGDs was such that we calculated proximity between dogs at 2-hour intervals instead of 1-hour intervals. Modeling for the effects of sex, age, and breed on an LGD's proximal fidelity to their band resulted in no statistically or biologically significant results (Table 1). All breeds showed similar patterns of proximity to their band throughout the day (Figure 1), with time of day effect showing a high level of statistical significance and describing a difference in proximity of a functionally important magnitude (Table 1). This temporal response is a corollary to the daily movement patterns of the band. When average hourly rate of movement (m/hour) for LGDs and sheep are seen together, a clear pattern emerges (Figure 2), which is also seen in the 2 highly significant mixed-effect models being the ones evaluating the effect of time of day and sheep speed, respectively, on proximity (Table 1).

Discussion

Humans have selected for traits in LGDs across many generations that increase their success at protecting livestock from predators (Gehring et al. 2010). Thus, the different breeds of LGDs that are used in different regions of the world are relatively easy to distinguish from one another because they differ in their physical appearance (Green and Woodruff 1988, Rigg 2001). Based on selection, we expected to see differences in space use among different breeds we studied. However, our results suggested traits related to proximity during summer grazing season were similar. Along with breed, we found no differences in proximity of LGDs to domestic sheep they were grouped with during transhumance summer grazing periods by LGD sex and age. These results support our previous study where we compared the behavior among breeds (Kinka and Young 2018). Green and Woodruff (1988) also reported that ranchers did not rate any breeds higher than others, further suggesting the selected for traits related to LGD success at protecting livestock are similar across breeds.

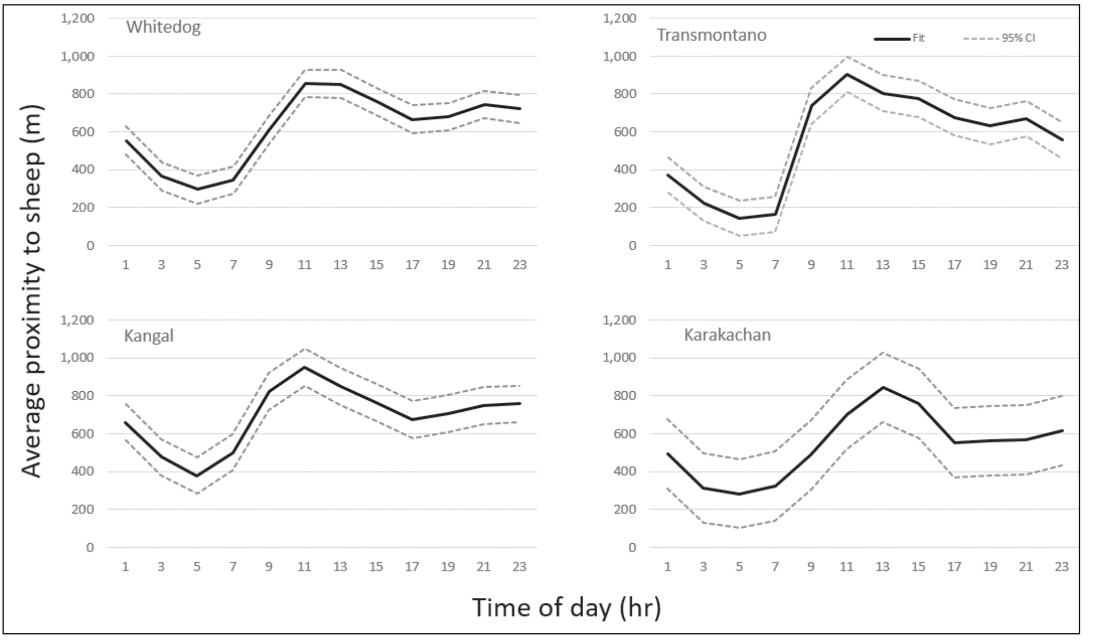

Figure 1. Average distance from domestic sheep (*Ovis aries*; m; solid line) and 95% CI (dashed line) across time for different breeds of livestock guardian dogs (*Canis lupus familiaris*) fitted with global positioning system (GPS) radio-collars during summer grazing allotment seasons (typically between May and October, August 2012 to October 2016) on working sheep operations in Idaho, Montana, Washington, Wyoming, and Oregon, USA. Randomly selected domestic sheep were fitted with GPS tags to measure distances.

The only notable difference we observed was in the distance to sheep by time of day, with LGDs being in closer proximity to sheep in early morning hours (Figure 1). Early morning is also the peak in activity by many carnivores (Theuerkauf et al. 2003, Munro et al. 2006, Eriksen et al. 2011, Kohl et al. 2018) and may therefore represent the time in which LGDs must actively protect sheep. This illustrates a possible behavioral mechanism LGDs use to protect sheep from predators—maintaining closer proximity when livestock are at greatest risk. Alternatively, this pattern may have emerged because sheep were less active during those hours, as evidenced by lower rates of distance travelled between GPS locations (Figure 2); it could simply be easier for LGDs to stay closer to sheep during periods of relative inactivity. Direct observations of LGD and sheep behavior across different times of day could be compared to proximity data to determine which mechanism is more likely to have caused this observed pattern. This could, for example, determine if LGDs are more vigilant during the morning hours when they are in closer proximity or if they are simply resting in proximity to resting sheep.

Sheep randomly assigned to wear GPS tags were on average within a few hundred meters of one another, with LGDs on average approximately double the distance from tagged sheep and >100 m closer to sheep than to another LGD (Figure 2). Sheep bands varied in size but most commonly consisted of >1,000 head. While sheep tend to flock together, the area in which an entire band can be located at a given time is relatively large and spread out. Logistically, because we were only able to deploy GPS tags on a few sheep within each band, we were unable to accurately account for band spread. Thus, it is unclear if LGDs are equidistant among the herd or use different patrolling strategies (e.g., center vs. perimeter patrollers) and whether the greater distance between LGDs alludes to their behavior or was an artefact of differences in simultaneous location intervals. However, by randomly selecting which sheep to fit with a GPS tag, we are unlikely to have significant spatial bias within sheep bands. Even so, we encourage future studies to address these additional issues.

Even though we could not measure band spread, we observed differences across time in LGD proximity to sheep showing they were

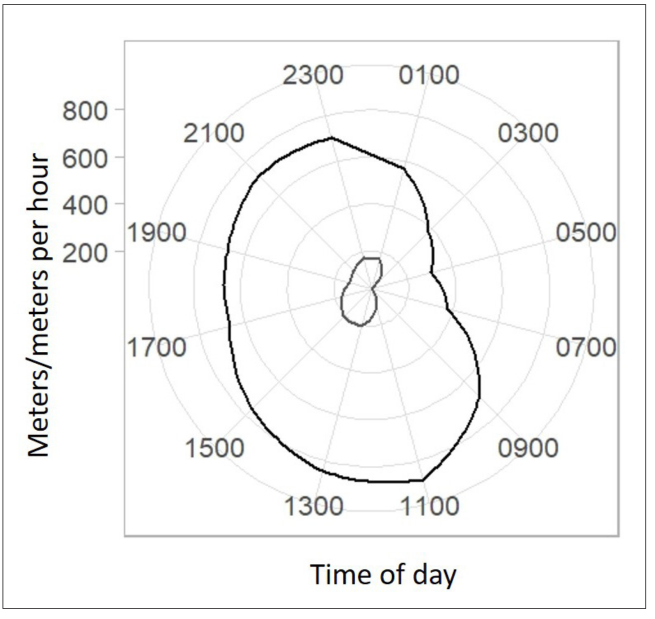

Figure 2. Average distance of livestock guardian dogs (*Canis lupus familiaris*) fitted with global positioning system (GPS) collars to sheep (*Ovis aries*; dark, outer circle) fitted with GPS tags graphed against average hourly rate of movement for sheep (m/hour; lighter inner circle). The GPS data were collected during the summer grazing season (August 2012 to October 2016) on working sheep operations in Idaho, Montana, Washington, Wyoming, and Oregon, USA.

closest to sheep at a time of day when sheep are less active but predators are most active. Webber et al. (2015) monitored female sheep with and without LGDs present and showed that when sheep were grazing with LGDs, they traveled greater daily distances than sheep without LGDs present. Combined with our results, this suggested that LGDs and sheep created a feedback loop that facilitated protection during periods of high risk. It is possible that sheep were more likely to be active with LGDs present because they detected lower risks and were less active when they detect greater risk (i.e., morning hours). At the same time, LGDs may have more difficulty staying in proximity to active sheep but may more easily stay in closer proximity when sheep were less active.

We found no difference by age or sex in LGD proximity to sheep, suggesting proximity may be an innate trait found across different LGD breeds, likely selected for over many LGD generations by shepherds working with the LGDs. Other studies have also shown no relationship between LGD sex and performance metrics (Leijenaar et al. 2015, Kinka and Young 2018). Most ranchers indicated LGD performance is constant or improves across time (Andelt and Hopper 2000), although some studies reported younger LGDs were more likely to die in accidents and were rated by ranchers as being less trustworthy than older LGDs (Marker et al. 2005*a*, *b*).

It typically takes 2–3 years of LGD work to pay for the costs incurred in obtaining and raising LGDs (van Bommel and Johnson 2012), returned in the form of livestock protected from predation events. This time lag is typically associated with the upfront costs of purchasing an LGD and a higher level of care and losses related to young compared to older LGDs (Marker et al. 2005*a*).

While these results offer a promising glimpse into a mechanism explaining the efficacy of LGDs, we caution against broad interpretation because we only obtained metrics from LGDs that were deemed to be working with the ranch operation. The few LGDs that were not working according to the needs of the operation for which the LGDs were placed were immediately removed from the ranch. In most cases, the LGD was simply placed on another ranch and remained in the study, but in a few cases the LGD was removed from all working ranches and therefore removed from the study. While this last category would not improve our understanding of LGD efficacy because ranchers commonly remove LGDs that do not work, it would be informative to compare proximity metrics from less successful LGDs (i.e., those placed with >1 ranch) to LGDs that were successful upon initial placement. We did not do so here because of small sample size. Further, we did *a priori* define an objective metric to categorize less successful LGDs. Because we relied on rancher participation, LGDs were quickly removed and replaced if the rancher was unsatisfied for any reason. Further, we measured proximity as a metric of efficacy but were unable to make a direct link to sheep losses with the available data. Because we worked directly with ranchers on public grazing allotments, we were unable to control the predator types and densities that may also influence LGD efficacy. These metrics would be useful in future studies to determine the importance of proximity.

Despite these noted caveats, proximity was likely an important metric of interest for a few reasons. First, ranchers were more likely to keep and work with an LGD that was in proximity to the sheep during the summer grazing season. For example, a reason some LGDs were removed from ranches or moved to a new ranch was because they roamed off property while on private lands in winter. Although we did not monitor LGDs in winter via GPS collars, livestock owners continued to work with their sheep and LGDs and informed us of LGD behavior and ranch needs. Second, LGD proximity to sheep was likely a proxy to bonding, which is believed to be a strong predictor of LGD efficacy. Finally, LGDs were more likely to detect predators near the sheep if they are in proximity to the sheep. Some ranchers relayed observations prior to our study of LGDs that leave sheep bands to pursue a predator, allowing other predators (i.e., pack mates) to attack the livestock. Having LGDs stay close to the sheep would reduce this type of risk. Our results are promising for ranchers and wildlife managers tasked with selecting LGDs to protect livestock because they suggest LGDs stayed in close proximity to the sheep they were grouped with to protect despite differences in breed, age, or sex.

Management implications

Our study found no differences in proximity to sheep on among several different breeds, sex, and age classes of LGDs during the summer grazing season on open-range allotments. In this study system, LGDs were closer to sheep in early morning hours, when sheep moved the shortest distances and predators are most likely to be active. These results suggest any breed of LGD we tested will remain in proximity to sheep if they have been properly bonded and would be suitable for use in open grazing allotment systems.

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John P. Draper is a doctoral student at Utah State University in the Department of Watershed Sciences and is a member of the Quinney College of Natural Resources Ecology Center. His research focuses on the effect of carnivores on their environment through trophic interactions at a landscape level as well as their conservation through genetic monitoring and wildlife damage management strategies that enable coexistence.

Daniel Kinka is the Wildlife Restoration Manager for American Prairie Reserve (APR). He works as a restoration ecologist and manages APR's conservation beef program, Wild Sky. This manuscript includes data collected during his graduate work in ecology at Utah State University, which focused on livestock guardian dogs as a nonlethal carnivore management tool for Northwestern sheep producers.