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2 authors:

Daniel Kinka
Utah State University

Julie Young
USDA National Wildlife Research Center & Utah State University

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Evaluating Domestic Sheep Survival with Different Breeds of Livestock Guardian Dogs☆

Daniel Kinka [a], Julie K. Young [a,b,*]

[a] Utah State University, Department of Wildland Resources, Logan, UT 84322-5230, USA
[b] USDA-WS-NWRC-Predator Research Facility, Millville, UT 84321, USA

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ABSTRACT

Livestock guard dogs (LGDs; *Canis familiaris*) have been widely adopted by domestic sheep *(Ovis aries)* producers because they reduce predation by wild carnivores. LGDs were originally used in the United States to reduce coyote *(Canis latrans)* depredations, but their efficacy against a suite of large carnivores, including wolves *(Canis lupus)*, brown bears *(Ursus arctos)*, black bears *(Ursus americanus)*, and cougars *(Puma concolor)*, and whether specific breeds perform better than others remains unclear. To assess breed-specific effectiveness at reducing depredations from a suite of livestock predators, we compared survival rates of sheep protected by different breeds of LGDs, including three breeds from Europe (Turkish kangal, Bulgarian karakachan, and Portuguese cão de gado transmontano) and mixed-breed LGDs, "whitedog," common in the United States. With the help of participating sheep producers, we collected cause-specific mortality data from domestic sheep in Idaho, Montana, Oregon, and Wyoming between 2013 and 2016. All three of the novel breeds of LGD tested were associated with overall reductions in sheep depredation relative to whitedogs, ranging from 61% to 95% ($P < 0.05$). In terms of predator-specific effectiveness, the Turkish kangal was associated with decreases in depredation from cougars ($e^{\beta} = 0.31$, 95% CI = 0.10–0.94, $P = 0.04$), black bears ($e^{\beta} = 0.33$, 95% CI = 0.28–0.37, $P < 0.01$), and coyotes ($e^{\beta} = 0.56$, 95% CI = 0.35–0.90, $P = 0.02$). The Bulgarian karakachan was associated with a decrease in coyote depredations ($e^{\beta} = 0.07$, 95% CI = 0.01–0.49, $P < 0.01$). The Portuguese transmontano was not associated with significant reductions in depredation hazard for any specific predator. Although variations in breed-specific effectiveness were subtle and nuanced, these findings will help livestock producers and wildlife managers make tailored decisions about how best to incorporate different breeds of LGD into sheep grazing regimes.

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Introduction

Livestock guardian dogs (LGDs) are domestic dogs *(Canis familiaris)* of a few dozen breeds that have been bred and trained to protect livestock from depredation, injury, and theft. LGDs are effective at reducing depredations by a number of carnivores, including coyotes (*Canis latrans;* Andelt and Hopper, 2000); dingoes (*Canis lupus dingo;* van Bommel and Johnson, 2012); black bears (*Ursus americanus;* Smith et al., 2000); and cheetahs (*Acinonyx jubatus;* Marker et al., 2005). LGDs' effectiveness at reducing depredations from other carnivores, such as wolves, brown bears, and cougars, has been suggested but not empirically tested (although see Espuno et al., 2004). LGDs enjoy a rich tradition in European history that dates back at least 5 000 yr (Smith et al., 2000; Rigg, 2001; Coppinger and Coppinger, 2002; Gehring et al., 2010a) but were first imported to the United States in the 1970s as an alternative to poisoning for lethal predator control (Feldman, 2007). Scientific research on LGDs began at about the same time and indicates that LGDs are one of the few nonlethal management techniques that both reduce domestic sheep *(Ovis aries)* depredations (Black and Green, 1984; Green et al., 1984; Andelt, 1992; Andelt and Hopper, 2000; Smith et al., 2000; Hansen et al., 2002; Rigg, 2002; van Bommel and Johnson, 2012) and provide long-term results (Shivik, 2006; Gehring et al., 2010a, 2010b). As such, it is generally concluded that LGDs are an effective tool for mitigation of livestock depredations, with reported declines in depredation between 11% and 100% (Smith et al., 2000). Consequently, the use of LGDs for reducing livestock depredations has been widely adopted by sheep producers in the United States.

LGD breeds initially selected for use in the United States were chosen at a time when wolves *(Canis lupus)* were almost entirely absent from the landscape (Bangs et al., 2005) and sheep depredations by brown bears *(Ursus arctos)* and cougars *(Puma concolor)* were rare or poorly documented (Smith et al., 2000; Gehring et al., 2010a, 2010b; Urbigkit

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* Correspondence: Julie K. Young, USDA-WS-NWRC-Predator Research Facility, 4200 S 600 E Cache County Rd, Millville, UT 84321, USA.
E-mail address: julie.k.young@usda.gov (J.K. Young).

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and Urbigkit, 2010). As is still the case (National Agricultural Statistics Service, 2011, 2013), coyotes were the primary depredator of domestic sheep. Further, most of the literature on LGD use in the United States predates the reintroduction of wolves and expansion of brown bear and cougar populations in the Northern Rocky Mountains. Since then, depredations by these large carnivores have allegedly caused some sheep ranchers to sell their remaining herds (National Agricultural Statistics Service, 2011, 2013), limiting the viability of rural communities that depend on agricultural competitiveness. In turn, declines in the number of livestock producers may impede conservation of large carnivores that rely on relatively undeveloped private rangelands, as the desertion of agriculture leads to increasing landscape fragmentation via subdivision or other land use conversions (Hobbs et al., 2008). Although pastoralists have used LGDs to guard against large carnivores for centuries, LGDs' effectiveness deterring large carnivores like wolves, brown bears, and cougars has seldom been scientifically evaluated outside of some work using LGDs to promote cheetah conservation (Marker et al., 2005). LGDs are sometimes killed by wolves (Bangs et al., 2005), and LGDs sometimes kill wolves (Tepeli and Taylor, 2008). There is also some limited or anecdotal evidence of LGD-wolf interactions (Coppinger et al., 1988; Gehring et al., 2006, 2010a, 2010b), as well as one study that modeled the predictive benefit of using LGDs to defend against wolves (Espuno et al., 2004), but beyond this, little is known about how effective LGDs are at deterring wolves or other large carnivores, or whether efficacy varies among different breeds of LGDs.

Scientists have given little attention to potential LGD breed differences in predator-specific deterrence. Some researchers have sought to identify differences among LGD breeds—most commonly measured in terms of behavior (i.e., trustworthiness, attentiveness, and protectiveness) or rancher-reported depredation loss, and although significant differences in depredation were not detected, behavioral differences were identified (Black and Green, 1984; Coppinger et al., 1988; Green and Woodruff, 1983, 1988; Kinka and Young, 2017). These behavioral differences may extend into efficacy against large carnivores, but anecdotal evidence suggests LGD breeds and crosses currently used in the United States may not be well-suited to dealing with wolves, brown bears, and cougars (Coppinger et al., 1988; Urbigkit and Urbigkit, 2010). Meanwhile, some LGD breeds in Europe and Asia are currently underused in the United States, and many of them have long histories of deterring large carnivores in their native countries (Rigg, 2001; Urbigkit and Urbigkit, 2010).

Despite this paucity of research regarding efficacy against large carnivores, LGDs continue to be accepted as a useful nonlethal management technique for bridging the gap between carnivore conservation and livestock damage control (Shivik, 2006; Gehring et al., 2010a, 2010b). In fact, they may have a mediating effect on tolerance for predators (Rust et al., 2013) and reduce the retaliatory killing of certain endangered carnivores (Marker et al., 2005; González et al., 2012). To the extent that LGDs deter depredation of livestock and potentially reduce the need for lethal removal of carnivores, they are an asset to conservation efforts, increasing the sustainability of ranching and promoting good stewardship of natural resources. However, if LGDs currently used in the United States are ineffective at deterring depredations from large carnivores like wolves, brown bears, and cougars, then they are of limited use to ranchers and conservationists. The long tradition of LGD use in European countries with wolves, brown bears, and large felids suggests that LGDs have the potential to be an effective deterrent to larger carnivores, but the supposition has gone largely untested.

To date, research suggesting LGDs reduce sheep depredations from a host of carnivores are almost exclusively based on the results of survey and self-reported data (Black and Green, 1984; Green et al., 1984; Andelt, 1992; Andelt and Hopper, 2000; Hansen et al., 2002; Rigg, 2002; van Bommel and Johnson, 2012; Scasta et al., 2017). Both techniques suffer from recall bias and false reporting (Bradburn et al., 1987), as the discerning cause of death from livestock carcasses can be difficult and subject to prejudices related to tolerance for large carnivores (Hazzah et al., 2009). When assessing the effectiveness of LGDs in the presence of a diverse guild of livestock predators (e.g., brown bears, wolves, cougars, black bears, coyotes), it is necessary to empirically determine the cause of death.

Recent widespread use of LGDs in the United States, their proven effectiveness against a host of smaller livestock predators, and their potential role in carnivore conservation illustrate the need for a large-scale investigation of LGD effectiveness, especially in places where conflict between livestock and large carnivores is growing. Here, we examined the relative effectiveness of three novel breeds compared with whitedogs in the United States. We use the term "whitedog" to refer to a heterogenous group of LGDs including crosses of multiple LGD breeds and LGDs of unknown genetic origin. We defined effectiveness as a statistically significant reduction in sheep depredation from a diverse guild of carnivores associated with a particular LGD breed. Previous research has already established that LGD use provides significant reductions in livestock loss compared with operations that do not employ LGDs (Smith et al., 2000). Currently in the United States, as in other countries, the use of LGDs with free-ranging sheep is nearly ubiquitous. As such, there is little practical utility in comparing sheep survival between flocks with LGDs and those without. Instead, we placed three novel breeds of LGDs with long histories of use in areas of Europe with large carnivores (i.e., Turkish kangal, Bulgarian karakachan, and Portuguese cão de gado transmontano) directly with sheep producers throughout the northwestern United States and compared these LGDs with whitedogs already in use. Brief histories and descriptions of each novel breed can be found in Rigg (2001), Urbigkit and Urbigkit (2010), and Kinka and Young (2017). Because of their longevity of use in countries with histories of coexistence among domestic sheep, LGDs, and large carnivores, we hypothesize that the novel breeds tested here will be more effective than common U.S. whitedogs at preventing depredations from large carnivores. We collected data in the field, usually <48 hr after depredations occurred, to address issues of recall bias and false reporting. Of particular interest is what effect LGD breed has on the survival of domestic sheep in the presence of competing risks. Results will help managers and ranchers make informed decisions about which breeds of LGD to use in areas with different assortments of carnivore species.

Methods

Livestock Guardian Dogs

Starting in 2012, we imported three breeds of LGDs to the United States and placed them on working ranches. These novel, imported breeds included the Turkish kangal ($n = 20$), Bulgarian karakachan ($n = 6$), and Portuguese cão de gado transmontano (henceforth "transmontano," $n = 6$), which were selected for their boldness toward large carnivores, history of use in areas with wolves or brown bears, lack of aggression towards humans, and reported larger average size (Rigg, 2001; Urbigkit and Urbigkit, 2010). We imported most novel-breed LGDs from their countries of origin, but some kangals were sourced in the United States from reputable breeders who were able to trace their kangals' purebred status to their Turkish origins.

Once we placed LGDs with collaborating domestic sheep producers, they were cared for by the producers and their staff and bonded to their sheep using traditional practices (cf., Sims and Dawydiak, 2004). Collaborating sheep producers were selected on the basis of their willingness to participate in a study of novel LGDs and a history or potential for conflict with wolves, brown bears, or cougars. Conflict with coyotes was ubiquitous across the study area. We randomly distributed kangals, karakachans, or transmontanos among available collaborators at their time of arrival in the United States. Age of individual LGDs at the time of delivery varied but was usually younger than 12 months. Although most US sheep producers are familiar with LGD use, project staff provided continuous support by offering information concerning the

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proper handling and implementation of LGDs so as to maximize their effectiveness. All novel-breed LGDs were spayed or neutered at about 1 yr of age to minimize problems of unintentional breeding and wandering.

In addition to the kangals, karakachans, and transmontanos, we also monitored extant mixed-breed LGDs (hereafter "whitedogs") belonging to collaborating sheep producers. After discussions with collaborating producers we are confident that, at most, 1 − 2 whitedogs were purebred LGDs. For the purpose of comparison, we treated all whitedogs already in use in the United States as a single control breed. On the basis of our collaboration and conversations with many ranchers and wildlife managers, we believe this generic whitedog, of multiple genetic origins, is indicative of the average LGD in use throughout the northwestern United States. As whitedogs and imported LGDs were primarily cared for and used by a number of different livestock producers, LGD husbandry practices varied between ranches. However, study staff regularly checked in on all LGDs in the study, both in the field and in winter pastures and ranches, to ensure that they were well cared for, provided enough food, received appropriate veterinary care when necessary, and were managed in accordance with standard best management practices regarding LGDs (cf., Sims and Dawydiak, 2004). Most whitedogs were spayed or neutered, but this was at the discretion of the livestock producer and owner.

LGDs worked in teams of 2 − 8 dogs, mostly in teams of 3 (39% of sheep guarded) or 4 (36% of sheep guarded). We evaluated different combinations of novel-breed LGDs with existing whitedogs to assess whether the substitution of kangals, karakachans, or transmontanos for whitedogs is associated with loss prevention. On 19 occasions an LGD needed to be relocated or removed from the study at the request of a producer if they were unsatisfied with the dog. Although our intention was to test only one LGD breed per sheep band, the requirements of our collaborating producers necessitated that we combine LGDs of multiple breeds with some sheep bands. Due to the constraints of collaborating with working livestock ranches, we accounted for deviations from this study design at the time of analysis by including the specific combination of LGDs in our models.

Study Area

Study sites included parts of 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 Helena to Dillon; and parts of Bighorn National Forest in Wyoming (see Fig. 1). Because of the large geographic distribution of study sites, habitat characteristics varied. Sites included remote areas of public lands where livestock are grazed by permit through the Forest Service or Bureau of Land Management, as well as fenced and unfenced private lands. In many of these locations there is a history of conflict between sheep producers and large carnivores, while others were deemed to have the potential for conflict due to proximity to extant populations of wolves, brown bears, or cougars. We based such designations on input from state and federal wildlife officials and area livestock producers. Relative abundances of each carnivore in each specific study area are not known, but a large geographic distribution of study areas was necessary to include enough sheep bands to support a complex statistical design. Instead, we controlled for this through the use of nested random effects in our statistical models.

Data Collection

We collected cause-specific sheep mortality data from domestic sheep that died during the summer grazing season (May–October, 2013–2016), usually <48 hr after the animal died. We determined cause of death by investigating carcasses for a kill pattern that matched a known carnivore (generally from carcass location, amount of hemorrhaging, and teeth spacing), as well as investigating the area for tracks, scat, and evidence of scavenging, whenever possible. However,

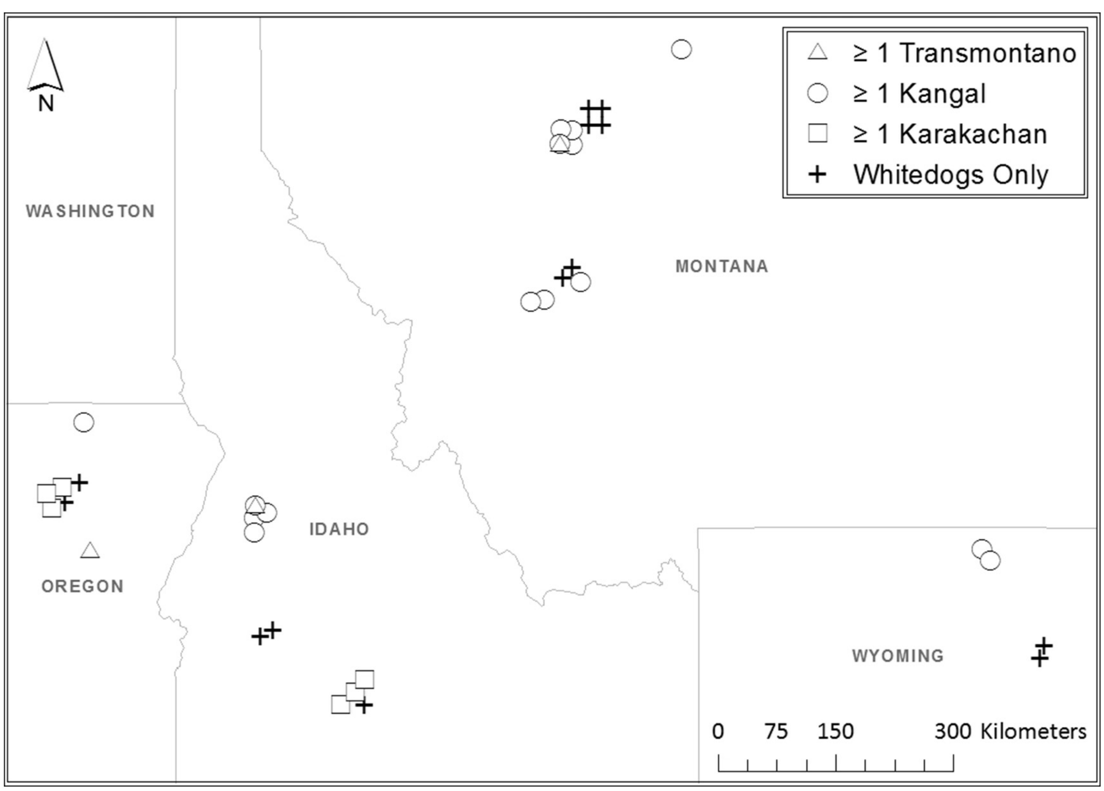

Figure 1. Extent of study site, with each symbol indicating the location of a monitored sheep band ($N = 35$ total sheep bands) in a single yr of the study (2013–2016). Circles, squares, and triangles indicate the location of a monitored sheep band grazed with whitedogs and at least one kangal, karakachan, or transmontano, respectively. The two triangles inscribed inside circles indicate bands grazed with at least 1 kangal and 1 transmontano, in addition to whitedogs. Crosses indicate sheep bands with only whitedogs.

we also relied on evaluations conducted by USDA–Wildlife Services Specialists and would defer to their expertise in determining thecause of predation. For each sheep mortality discovered, we also received detailed oral and written reports from the shepherds who attended the sheep band. The shepherds were usually the first, and sometimes the only, individuals to see a carcass. Shepherds were also our primary source for identifying nonpredator mortality (e.g., sickness, drowning). Due to the inherent subjectivity of field necropsy techniques to determine cause of death, we were conservative about ascribing cause of death and recorded some mortalities as "unknown predator" or "unknown" if nonpredator mortality could not be ruled out. Specific predators were not ascribed as the cause of death unless it could be verified by project staff or a Wildlife Services Specialist, or the shepherd could provide specific evidence to suggest the predator (e.g., pictures or descriptions of wound characteristics and/or kill pattern).

To develop a survival database for sheep, we created a spreadsheet with an entry for every sheep from every sheep band monitored from 2013 to 2016. Because the exact number of sheep in a commercial sheep band is usually counted at the beginning and end of each grazing season, we were able to create a complete dataset for each band in most cases (rather than having to monitor a sample of the population). The total number of sheep counted at the end of the season was known to have survived and marked as censored on the last day of the grazing season. Known mortalities were marked as dead on the date that corresponded to the day the carcass was found minus the approximate age of the carcass in days. Unaccounted-for sheep were assumed to have died from an unknown cause and treated as special cases. We calculated time of death for unaccounted-for sheep as the midpoint between the last day the sheep was counted as alive and the first day it was identified as missing. As such, we censored many unaccounted-for sheep exactly halfway between the start and end of the ≈5-mo grazing season for a particular band.

Each sheep record in the survival dataset also included the total number of LGDs (any breed) with the band, the number of sheep in the band, estimated average age of all LGDs in the band, as well as the number of kangals, karakachans, and transmontanos with the band. When, in some cases, LGDs were removed or added to a band, each sheep was censored at the time of the change and reentered in the dataset with new covariate values corresponding to the number and breed of LGDs with the band. Ages for all kangals, karakachans, and transmontanos were known at the time of analysis; however, specific ages could not be determined for 22 of 53 whitedogs. Rather than removing all records for sheep with a whitedog of unknown age, we set any unknown whitedog ages at the mean age for all whitedogs across the 4 yr of the study. Substituting average whitedog age in the case of unknown ages, we subsequently averaged the age of all LGDs in a sheep band together, such that every sheep survival record included an estimated average age for all LGDs in the band. Mortality records from bands where the total number of sheep were unknown were removed. Further, mortality records from sheep bands where only the end-of-season headcount for sheep was known (i.e., the starting headcount of sheep was missing or unknown) were removed from the dataset before analysis unless their covariate structure matched another sheep band with complete records. For instance, documented depredations from a sheep band with 2 whitedogs and 1 kangal but an unknown total number of sheep would still be retained for analysis so long as there was another sheep band already present in the data with 2 whitedogs, 1 kangal, and a known total number of sheep. In this way, neither mortality nor survival was overrepresented for sheep with a unique covariate structures. We removed records of sheep grazed with rare LGD breed combinations (i.e., fewer than 10 records) as well so as not to bias survival estimates for underrepresented LGD pack structures.

Table 1
Cox proportional hazard model selection based on delta Akaike's information criterion (ΔAIC). Only the top three models are shown (cumulative AIC weight = 0.842). Note that the third model is the global model. Number of parameters (np), AIC weights (w_i), and cumulative AIC weights (Cum. w_i) are also shown. In the model structure "LGD" is the number of LGDs (of any breed) in a band, "Sp" is the number of sheep in a band, "LGD:Sp" is the interaction term of number of LGDs and number of sheep in a band, "Kn" is the number of kangals in a band, "Kr" is the number of karakachans in a band, "Tr" is the number of transmontanos in a band, "eA" is the estimated average age of all LGDs in a band, "F" is whether or not the band was in a fenced pasture (1 = fenced, 0 = open range), and "Y" is the categorical effect of yr (2013−2016). The number of whitedogs (if any) with a band were included in the "LGD" term but were not assessed as a unique breed. All models share a common nested random error structure of sheep band within producer within state.

Model	*np*	ΔAIC	w_i	cum. w_i
LGD + Sp + Kn + Kr + Tr + eA	6	0.00	0.449	0.449
LGD + Sp + LGD:Sp + Kn + Kr + Tr + eA + F	8	0.48	0.353	0.802
LGD + Sp + LGD:Sp + Kn + Kr + Tr + eA + F + Y	9	4.84	0.040	0.842

Statistical Analyses

We first tested the effect of LGD breed against any type of predation. As the fate of any individual sheep in a monitored band was known to a high degree of certainty, we chose to analyze data within the context of time-to-event survival models (cf., Kleinbaum and Klein, 2005). Specifically, we used semiparametric Cox Proportional Hazard (CPH; Cox, 1972) models because they allow for the inclusion of covariates and do not require assumptions about the shape of the underlying mortality hazard (Wolfe et al., 2015). Instead, CPH models allow mortality hazards to vary by time, with covariates acting multiplicatively (i.e., proportionally) on the hazard at any point in time (Bradburn et al., 2003). We modeled the hazard of predation (all causes) as the outcome of interest, collapsing all other sources of mortality into the censored category. The unit of interest was each individual sheep in a sheep band, as the hazard of depredation acts more on the individual sheep than the sheep band. Primary covariates of interest were the number of kangals, karakachans, and transmontanos with a band. We also included fixed effects for total number of LGDs (any breed) with the band, number of sheep in the band, the interaction of number of sheep and number of LGDs in a band, estimated average age of all LGDs in a band, whether the band was on open range or in a fenced pasture, and year (treated categorically). We included the number of whitedogs with a band in the total number of LGDs term, but we did not assess whitedogs as a unique breed in our models. Including the number of whitedogs in the model would have resulted in the sum of the kangal, karakachan, transmontano, and whitedog terms perfectly summing to the number of LGDs' term. Instead, we treated whitedogs as a baseline or generic breed in the models against which we tested the three other breeds. For instance, examining the global CPH equation (Table 1), we see that any examination of the "nLGD" term requires holding all other fixed effects constant at their mean values, such that any change in "nLGD" must be specifically attributed to the addition or subtraction of a whitedog from a hypothetical sheep band. We also employed a random-effect structure of sheep band nested within producer nested within state to account for unmeasured differences in husbandry practices and potential differences in predator densities between bands. We consider all combinations of fixed effects to be biologically relevant and therefore include all combinations of main effects as candidate models. Analysis was performed using the "coxme" function (Therneau, 2015) available in R version 3.3.2 (R Core Team, 2016). Model selection for fixed effects was conducted using Akaike's Information Criterion (AIC).

To investigate potential differences in cause-specific hazard as a function of LGD breed, we analyzed the data using a competing risk (CR) framework, which allows for the consideration of multiple causes of death (Heisey and Patterson, 2006; Murray et al., 2010). In the CR framework each separate cause of death is mutually exclusive to the others, summing to the total probability of mortality. The CR framework is also more robust to bias estimates of cause-specific

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risk resulting from individuals being censored from observation before having a chance to succumb to a particular hazard (Kleinbaum and Klein, 2005). To assess the breeds one at a time, we derived three new datasets from the original survival data. We created the kangal dataset by removing any data from bands with karakachans or transmontanos, the karakachan dataset by removing any data from bands with kangals or transmontanos, and the transmontano dataset by removing any data from bands with karakachans or kangals. As such, each dataset contained data from whitedog-only bands, as well as data from bands to which one or more of the experimental breed of interest was added. First, we modeled survival using three types of risk—predation, sickness, and missing—but focused only on the probability of depredation. Next, we modeled survival for each potential cause of depredation, allowing for seven different types of risk—nonpredation, wolf, brown bear, cougar, black bear, coyote, and unknown predator. As fixed effects in each of the competing risk regression models, we included number of LGDs, number of sheep, and number of novel-breed LGDs with the band (depending on which data set was being used). CR models do not accommodate random effects, so we were unable to include a nested random term to account for differences in predator abundance or husbandry practices in these models. We performed CR analyses using the "cmprsk" and "riskRegression" functions (Gray, 2015; Gerds et al., 2017) available in R version 3.3.2 (R Core Team, 2016).

Results

In total, we worked with 12 producers and 35 sheep bands over the 4 yr of the study to monitor 20 individual kangals, six karakachans, six transmontanos, 53 whitedogs (Fig. 1, Table 2), and > 88 000 sheep. After removing incomplete records from the dataset, we retained 88 073 records for analysis. Records show 181 sheep were depredated, 114 died from sickness or drowning, 13 died from unknown causes, 8 were killed by an LGD, and 252 were missing and assumed dead from unknown causes. All sheep identified as missing were grazed on open range. The sample size of sheep kept with karakachans and transmontanos was smaller than for kangals and whitedogs (Table 3). Of the 31 documented wolf depredations, 19 occurred in a single band that included two kangals. We analyzed competing risk data for kangals with and without this outlier event.

Cox Proportional Hazards Models

The best CPH model for sheep survival (by AIC rank) retained the fixed effects of number of sheep, number of LGDs, estimated average age of LGDs, number of kangals, number of karakachans, and number of transmontanos. There were only two models with a delta AIC ≤ 2.00, reaching a cumulative model weight of 0.80. Between the two top models every candidate fixed effect is represented except year (see Table 1). We tested the utility of including a nested random effect (i.e., band within producer within state; a post-hoc control of relative predator abundance and varying husbandry methods) in our global model against an identical CPH model without the random effect using a likelihood ratio test and found the variance associated with the random effect was not likely to be due to chance ($\chi^2 = 218.71$, $P < 0.001$). We also tested for a possible correlation between number of LGDs and number of sheep and found them only weakly correlated (0.13). Currently, there is no supported method for calculating residuals from mixed-effect CPH models.

Table 2
Number of individual livestock guardian dogs (LGDs) by breed retained in dataset for analysis. Certain individuals were present in multiple years of the study, and the number of individual LGDs by year is shown. "#" denotes "number of." Mean age and standard deviation of age are shown as well. Note that ages were only known for 31 of the 53 whitedogs in the study, and mean age and standard deviation of age for whitedogs were calculated using that sample of the total population of whitedogs.

	# Individuals	# Individuals × Yr	Mean age (mo)	Standard deviation of age (mo)
Kangal	20	37	22	16
Karakachan	6	8	14	9
Transmontano	6	7	11	4
Whitedogs	53	71	39	29
All breeds	85	123	29	25

Table 3
Model results for all mixed-effects Cox proportional hazards models with delta Akaike's information criterion (ΔAIC) < 2.00. Results are shown as coefficient beta values for fixed effects (log hazard ratios) with standard error shown in parentheses below. All models share a common nested random error structure of sheep band within producer within state.

	Top Cox proportional hazards models	
	1	2
Number of livestock guardian dogs	1.421[1]	2.014[1]
	(0.308)	(0.744)
Number of sheep	0.002[1]	0.004[2]
	(0.001)	(0.001)
Interaction of		−0.0003
number of sheep & number of LGDs		(0.0004)
Number of kangals	−0.931[2]	−0.877[2]
	(0.385)	(0.430)
Number of karakachans	−1.590[2]	−1.423[3]
	(0.731)	(0.738)
Number of transmontanos	−2.847[1]	−2.966[1]
	(0.730)	(0.698)
Estimated average age	−0.058[3]	-0.055[3]
	(0.033)	(0.031)
Fenced pasture vs. open range		4.276[2]
		(1.867)
Fitted log likelihood	−1852.0	−1852.0
ΔAIC	0.00	0.48
Model weight	0.449	0.353

[1] $P < 0.01$.
[2] $P < 0.05$.
[3] $P < 0.1$.

Examining only the top model, increasing the number of LGDs with a band increased the risk of predation for any given sheep in the band by ≈4× ($e^{\beta} = 4.14$, $P < 0.001$). However, the way the model is parameterized, this term represents increasing the total number of LGDs by adding a whitedog (and not any other breed) to the band. For each additional sheep added to a band, the risk of depredation also increased marginally ($e^{\beta} = 1.002$, $P < 0.001$). Increasing the average age of LGDs in the band by 1 mo also marginally reduced the risk of sheep depredation, although the term is only weakly significant ($e^{\beta} = 0.94$, $P = 0.08$). Holding all other variables constant, the substitution of one kangal for one whitedog decreased the risk of sheep predation by nearly 60% ($e^{\beta} = 0.39$, $P = 0.02$). Likewise, the substitution of one karakachan for one whitedog decreased the risk of sheep predation by ≈80% ($e^{\beta} = 0.20$, $P = 0.03$), and the substitution of one transmontano for one whitedog decreased the risk of sheep predation by ≈95% ($e^{\beta} = 0.06$, $P < 0.01$). Both of the top models retained the number of LGDs, the number of sheep, estimated average LGD age, and all three novel breeds as predictor variables at similar magnitudes (see Tables 1 & 3). The second most likely model of sheep depredation (AIC weight = 0.35) also included the nonsignificant interaction term ($P > 0.1$) and the effect of fenced pastures (n = 8 037) versus open range (n = 80 036; see Table 3). This model predicts a nearly 720% increase in the risk of sheep predation on fenced pastures compared with sheep on open range ($e^{\beta} = 71.94$, $P = 0.02$).

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Table 4
Number of sheep depredations by predator in sheep bands including at least one of each of the novel-breed LGDs. "Mean Sheep" indicates the average flock size in each category. "All Predation" includes depredated sheep where the predator could not be determined and therefore may be greater than the sum of depredations identified as wolf, brown bear, cougar, black bear, and coyote. Note that some bands included LGDs from two of the novel breeds. Thus, rows 1–3 in the table are not mutually exclusive and the last row of the table does not indicate totals from the first four rows. A single sheep band with two kangals experienced unusually high wolf depredation in 2014, accounting for 19 of the 28 total wolf depredations in that category.

	Mean sheep	*n*	All predation	Wolf	Brown bear	Cougar	Black bear	Coyote
At least 1 kangal	2 310	45 581	90	28	14	4	13	12
At least 1 karakachan	1 672	9 848	11	1	0	5	1	1
At least 1 transmontano	1 879	6 924	15	4	1	0	3	6
Only whitedogs	2 157	30 304	76	7	1	6	3	51
All combinations		88 073	181	36	15	15	17	68

Table 5
Model results for competing risk regression models for kangals. Includes data from whitedog-only bands and bands with at least one kangal dog present. Results are shown as coefficient beta values for fixed effects (log hazard ratios) with standard error shown in parentheses below. "#" denotes "number of."

	All predation ($n = 155$)	Competing risk regression models for kangals				
		Wolf ($n = 31$)	Brown bear ($n = 14$)	Cougar ($n = 10$)	Black bear ($n = 13$)	Coyote ($n = 61$)
# Livestock guardian dogs	0.120[1]	−0.023	3.800[2]	0.993[2]	1.030[2]	0.231
	(0.069)	(0.101)	(1.260)	(0.377)	(0.121)	(0.160)
# Sheep	−0.0001	0.0010[2]	−0.0182[2]	−0.0001	0.0017[2]	0.0003
	(0.0001)	(0.0001)	(0.0060)	(0.0005)	(0.0002)	(0.0002)
# Kangals	−0.091	0.269[2]	0.220	−1.169[3]	−1.121[2]	−0.577[3]
	(0.091)	(0.058)	(0.234)	(0.564)	(0.070)	(0.239)

[1] $P < 0.10$
[2] $P < 0.05$.
[3] $P < 0.01$.

Competing Risk Models

Kangals

Collapsing across all causes of predation, CR models for kangals indicate that each kangal substituted for a whitedog in a band does not significantly decrease the risk of sheep predation ($P > 0.1$). Holding the number of kangals constant while increasing the total number of LGDs (i.e., adding whitedogs) with a band may increase the risk of sheep predation, but the effect is only marginally significant ($e^{\beta} = 1.13, P = 0.08$). Increasing the number of sheep in a band also had a nonsignificant effect in the CR model ($P > 0.1$; Table 4). All three trends obfuscate those found in the top mixed effects CPH models. Regarding specific predators, increasing the number of kangals in a band is associated with a 69% decrease in sheep predation risk from cougars ($e^{\beta} = 0.31$, $P = 0.04$), a 67% decrease in risk from black bears ($e^{\beta} = 0.33$, $P < 0.001$), and a 44% decrease in risk from coyotes ($e^{\beta} = 0.56, P = 0.02$). However, replacing a whitedog with a kangal is associated with a 31% increase in risk of wolf depredation ($e^{\beta} = 1.31, P < 0.01$). The effect of kangals on brown bears was nonsignificant ($P > 0.1$).

Because 19 of the 31 documented wolf depredations of domestic sheep occurred in a single sheep band with two kangals present, we also ran our kangal CR models without this data as it may represent an outlier. Using this abridged dataset and collapsing across all causes of predation, CR models for kangals indicate that each kangal substituted for a whitedog in a band does slightly decrease the risk of sheep predation, albeit only marginally significantly ($e^{\beta} = 0.84$, $P = 0.1$). Holding the number of kangals constant while increasing the total number of LGDs (i.e., adding whitedogs) with a band may still increase the risk of sheep predation, but the effect is still weakly significant ($e^{\beta} = 1.16, P = 0.07$). Increasing the number of sheep in a band still had a nonsignificant effect in the CR model ($P > 0.1$; Table 5). These findings are more in line with the results from the CPH models. Regarding wolves, the abridged dataset for kangals shows a nonsignificant effect of kangals on wolf predation of sheep ($P > 0.1$; see Table 5).

Karakachans

Collapsing across all causes of depredation, CR models for karakachans indicate that substituting a karakachan for a whitedog decreased the risk of predation by 49% ($e^{\beta} = 0.51, P = 0.02$). Increasing the total number of LGDs (i.e., adding whitedogs) within a band increased the risk of predation ($e^{\beta} = 1.69, P < 0.001$), as did increasing the number of sheep in a band ($e^{\beta} = 1.001, P < 0.01$). All three trends corroborate those found in the top mixed-effects CPH models. Regarding specific predators, increasing the number of karakachans in a band was associated with a 93% decrease in risk of coyote depredation ($e^{\beta} = 0.07, P < 0.01$). Karakachans did not significantly affect the risk of wolf or cougar predation ($P > 0.1$; Table 6). The brown bear and black bear models failed to converge, as no brown bear killed a sheep in a band with at least one karakachan and only one sheep was killed by a black bear in a band with at least one karakachan (see Table 3).

Table 6
Model results for competing risk regression models for kangals with outlier data removed. Includes data from whitedog-only bands and bands with at least one kangal dog present except for a single band of sheep that experienced unusually high wolf depredation in 2014. Results are shown as coefficient beta values for fixed effects (log hazard ratios) with standard error shown in parentheses below. "#" denotes "number of."

	All predation ($n = 130$)	Competing risk regression models for kangals (outlier band removed) Wolf ($n = 12$)
# Livestock guardian dogs	0.146[1]	−0.109
	(0.081)	(0.420)
# Sheep	−0.0001	0.0011[2]
	(0.0001)	(0.0002)
# Kangals	−0.179[1]	−0.103
	(0.107)	(0.124)

[1] $P < 0.05$.
[2] $P < 0.01$.

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Table 7
Model results for competing risk regression models for karakachans. Includes data from whitedog-only bands and bands with at least one karakachan dog present. Results are shown as coefficient beta values for fixed effects (log hazard ratios) with standard error shown in parentheses below. "#" denotes "number of." The brown bear and black bear models failed to converge, as no sheep was killed by a brown bear in a band with at least one karakachan and only one sheep was killed by a black bear in a band with at least one karakachan.

	All predation ($n = 87$)	Competing risk regression models for karakachans		
		Wolf ($n = 8$)	Cougar ($n = 11$)	Coyote ($n = 52$)
# Livestock guardian dogs	0.524[1] (0.114)	−0.312 (0.838)	1.0367[2] (0.527)	0.342[1] (0.051)
# Sheep	0.0007[1] (0.0001)	0.0011[3] (0.0006)	0.0001 (0.0003)	0.0009[1] (0.0001)
# Karakachans	−0.673[2] (0.294)	0.066 (0.845)	0.384 (0.481)	−2.659[1] (0.990)

[1] $P < 0.01$.
[2] $P < 0.05$.
[3] $P < 0.01$.

Transmontanos

Collapsing across all causes of depredation, CR models for transmontanos indicate that substituting a transmontano for a whitedog decreased the risk of predation by 66% ($e^{\beta} = 0.34$, $P = 0.04$). Increasing the total number of LGDs (i.e., whitedogs) within a band increased the risk of predation ($e^{\beta} = 1.46$, $P < 0.01$), as did increasing the number of sheep in a band ($e^{\beta} = 1.001$, $P < 0.01$). All three trends corroborate those found in the top mixed-effects CPH models. Regarding specific predators, substituting a transmontano for a whitedog was associated with a nonsignificant decrease in risk from coyotes ($P > 0.1$; Table 7). The wolf, brown bear, cougar, and black bear models failed to converge as no sheep was verified as killed by any of those predators in a band including at least one transmontano (see Table 3).

Discussion

To better understand the contribution of different LGD breeds to sheep-loss prevention in the northwestern United States, we assessed overall and cause-specific predation in sheep as a function of the breed composition of LGDs used to guard domestic sheep. Ranked mixed-effects CPH models indicate that all three novel-breed LGDs tested here—kangals, karakachans, and transmontanos—are associated with decreases in overall depredation hazard relative to the whitedogs traditionally used in the United States. Because our CPH models included a term for total number of LGDs with a band, these results can be best understood as the effect of swapping one of these novel-breed LGDs for a whitedog, all other fixed effects being held constant. CR models of overall depredation risk show similar decreases in depredation risk associated with each of the novel breeds, although the effect of kangals only becomes significant after an outlier incident is removed. Regarding predator-specific effectiveness of the novel breeds, replacing a whitedog with a kangal (i.e., increasing the number of kangals with a band while holding total number of LGDs constant) significantly reduced the risk of cougar, black bear, and coyote depredation. Similarly, replacing a whitedog with a karakachan significantly reduced the risk of coyote depredation. Interestingly, replacing a whitedog with a kangal is associated with a significantly elevated risk of wolf depredation, but only using the full dataset. When the outlier event for kangals is removed, their effect on wolf depredation becomes nonsignificant. For all other predator-breed combinations, there is no significant effect or too little data available to effectively model an effect on depredation hazard. Disregarding an outlier in the data for kangals, none of the novel breeds were significantly better or worse at preventing depredations by wolves or brown bears relative to whitedogs.

It is likely that the increased hazard of wolf depredation associated with kangals in the full dataset was driven by a single sheep band grazed in central Idaho in 2014, which happened to be guarded by two kangals and one whitedog. The band incurred at least 19 wolf depredations throughout the season, nearly two thirds of all the wolf depredations detected throughout the study and included in our analyses. Clearly, this incidence represents a statistical outlier that can greatly skew the results of any survival model, thereby warranting its exclusion from the data. However, while wolf depredations of domestic sheep are infrequent, when they do occur, wolves tend to kill many sheep at a time (Muhly and Musiani, 2009). In this way, the incident may be simultaneously biologically relevant and statistically irrelevant. Thus, we chose to model the data both with and without this incident in CR models. Excluding the outlier from the dataset caused the effect of kangals on wolves to become nonsignificant, but rather than clarifying the role of kangals in defending domestic sheep from wolf depredation, this example probably indicates that far more data would be necessary to properly model the effect of any LGD breed on the lethality of rare but costly wolf attacks. Interestingly, both shepherds in charge of this outlier band believed one of the kangals to be exceptionally good at deterring wolves, despite the unusually high numbers of wolf depredations that year. Both believed that more sheep would have been killed by wolves without this female kangal dog.

In addition to breed-specific effects, most of our CPH and CR models of sheep survival indicate that increasing the number of sheep in a band increased the risk of predation. That each additional sheep added to a band would increase the risk of depredation for any sheep in that band (albeit by a small amount) is somewhat intuitive: a bigger band may simply be a bigger target. Indeed, wolves that fed exclusively on livestock were shown to target larger flocks (Vos, 2000). In our system, large sheep bands were probably easier for a predator to track and more detectable from a distance. Although grouping behavior by wild ungulates has long been considered an antipredator strategy (e.g., Lazarus, 1979), prey also decrease group size to avoid detection by predators. For example, elk *(Cervus elaphus)*, a primary prey item of wolves, have been shown to keep group size low in high-risk habitat when wolves are present (Creel and Winnie, 2005). In addition, LGDs may become less effective as more and more sheep are added to a band, increasing the ratio of LGDs to sheep and, presumably, increasing the burden of guarding for each LGD. The magnitude of this effect is small but also significant, which is not surprising considering that the addition of a single sheep to a band of 1 000 is unlikely to significantly impact the depredation hazard across the entire band. However, adding 500 sheep to the same band would multiply the effect magnitude to a level of practical significance. The sole exception to this effect for band size is the CR model for kangals and brown bears (see Table 4), which indicates that each additional sheep added to a band with kangals reduced the risk of brown bear depredation by about 2%. It may be that a larger sheep band creates a larger disturbance as it moves through the landscape, which brown bears avoid the same way they seasonally avoid human disturbance (Ordiz et al., 2017). It may also have been an artefact of our study design, as we documented fewer brown bear encounters than we predicted when designing the study. A lack of brown bear depredations in sheep bands with karakachans or transmontanos meant that we were unable to replicate this finding in other CR models.

Perhaps less intuitive are our results showing that increasing the number of LGDs with a band could increase the risk of depredation. As described earlier, this term also serves as a proxy for a number of whitedogs. That is, holding all else constant in the model, increasing the number of LGDs in a band equates to adding a whitedog to the band. The effect of adding any other breed to the band while also increasing the total number of LGDs was not explicitly tested, in that it requires the simultaneous manipulation of two model terms. Still, it is unclear why adding an LGD of any breed would increase the risk of depredation for a sheep in that band. LGDs did occasionally kill sheep when they were young or not properly bonded, but we relegated the eight

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LGD depredations in our final dataset to the “sick or other” category of mortality or as a special case in our analyses, so it did not drive any pattern of increased risk corresponding to number of LGDs. It is also possible that having too many LGDs with a sheep band leads to “boredom” and wandering behavior among LGDs, which would reduce guarding effectiveness (Zingaro et al., 2018). However, the average ratio of sheep to LGDs in our study was > 679:1, and wandering behavior was seldom reported. This ratio of sheep to LGDs is relatively high compared with some studies (Espuno et al., 2004), so it is unlikely that this is the cause of our finding. What is more likely is that by not explicitly modeling carnivore density associated with each sheep band (although we attempted to with nested random effects), the number of LGDs in a band was somewhat collinear with the unmodeled risk of predation risk. Predation risk is impacted by large carnivore presence and spatial density (Hebblewhite and Merrill, 2007). In our study system, producers often responded to elevated risk that they perceive on the landscape by adding additional LGDs to a band. If producers are accurately gauging such risk, then increasing the number of LGDs in a band would be largely collinear with increasing depredation risk, albeit an imperfect proxy. That we were unable to control for this potential collinearity during data collection is an example of the constraints imposed on this study by collaborating with working sheep producers. Instead, we attempted to correct for this through the use of nested random effect in our modeling exercise. Nevertheless, our nested random effect structure in the CPH models may have failed to capture all of this variance, and the number of LGDs may have served as a partial proxy for predation risk. We were unable to manipulate the number of sheep or the number of LGDs with a band for the sake of this research and only included the term in our models as a control. As such, results for number of sheep and number of LGDs presented here, as well as their respective effects on sheep survival, should not be considered prescriptive of ideal band size or ideal ratio of LGDs to sheep. Future studies should investigate the optimal ratio of LGDs to sheep, as it is a salient question for producers and one that has not been adequately studied.

Because we mostly imported novel breeds from their countries of origin as puppies, the novel-breed LGDs tested here tended to be younger, on average, than their whitedog counterparts. Whitedogs included in the study ranged from very young to very old depending on which whitedogs producers were already using to guard their sheep (Table 8). LGDs younger than 2 yr of age may not be as effective as their adult counterparts (Sims and Dawydiak, 2004). Recent research also shows differences in LGD behavior before and after 2 yr (van Bommel and Johnson, 2012). It is unclear at what age LGDs tend to senesce, but conventional wisdom among sheep producers suggests that LGDs become less effective starting at around 8 yr old. We did not include individual-level covariates for LGDs, such as age, in CPH and CR models as it is unclear how they could be integrated into our model structure and how the results would be interpreted, since multiple LGDs were present with each band. Further, the exact age of 25% of the whitedogs was unknown by their owners. Instead, we included a fixed effect of estimated average age of all LGDs with a band in our CPH modeling exercise. Results indicate that each additional month of average LGD age is associated with a statistically significant 5 − 6% reduction in depredation hazard. This corroborates findings that older LGDs are more effective guardians than very young LGDs and may continue to improve over time. Nevertheless, the fact that, despite their generally younger age, kangals, karakachans, and transmontanos were associated with decreased overall depredation risk as well as decreased risk in depredation from a number of specific predators compared with the generally older whitedogs only adds strength to our findings of their greater effectiveness. In other words, the relatively inexperienced novel-breed LGDs seem to have outperformed an average whitedog.

Although only included in one of the top CPH models, fenced pastures are associated with a nearly 720% higher risk of depredation for domestic sheep. Similar to the way adding sheep to a band was generally associated with an increase in risk of depredation, sheep behind fenced pastures may simply be easier for predators to find because they do not move across the landscape but are generally located in close proximity to a single ranch all year long. As pastures are typically more open and less topographically diverse than forested grazing allotments, sheep in these fenced pastures may also lack escape paths and escape terrain (cf., landscape of fear, Laundré et al., 2010). Alternatively, this higher risk could be an artefact of carcass detectability. Over the course of the study, more sheep went missing than were found and could be ascribed a cause of death. Although some proportion of missing sheep are likely to have been depredated, to be conservative, they were censored from our analyses halfway between the end of the season and the time at which they were last counted. However, all 252 sheep identified as missing were on open range. No sheep was ever classified as missing from a fenced pasture, which is to say every sheep in a fenced pasture could be accounted for. Thus, the effect of fenced versus unfenced pastures shown here likely indicates that carcasses were more reliably located and necropsied on fenced pastures, not that risk of depredation was higher there.

The sheep that went missing on open range—nearly twice as many as we could confirm having been depredated—are perhaps a limiting factor for our study. On the basis of our known ratio of depredated sheep versus those that die from other causes (≈1.25:1), the majority of the missing sheep are likely to have been depredated, but it is impossible to know the exact proportion or how those depredations would be distributed among covariate values (other than all missing sheep having been grazed on open range). Knowing the cause of death for these unaccounted-for sheep would have lent us far more statistical power, and future studies should consider methods to ensure that fewer mortalities go unaccounted.

Another limitation of our study was our inability to explicitly model variations in predation pressure between sheep bands. Keeping predation pressure constant across all carnivores and sheep bands (which is impossible) or somehow modeling predation pressure would more properly gauge the effectiveness of an LGD at reducing depredations. We attempted to model this latent variable through the inclusion of our nested random effect (band within producer within state) and a model term for study year. In this way, we hoped to capture most of the variance in predation pressure across the carnivore guild by focusing only on certain grazing pastures or allotments within a single grazing season. However, considering the surprising effect of more LGDs increasing depredation hazard (discussed earlier), it may be that the inclusion of the nested random effect of band and the fixed effect of year was insufficient to capture all of the variance in predation pressure, both within and between sheep bands. A preferred alternative would have been to try and calculate relative carnivore densities between study sites as a proxy for predation pressure, but such data were not available and it was beyond the means of our research project to collect it.

Table 8
Model results for competing risk regression models for transmontanos. Includes data from whitedog-only bands and bands with at least one transmontano dog present. Results are shown as coefficient beta values for fixed effects (log hazard ratios) with standard error shown in parentheses below. “#” denotes “number of.” The wolf, brown bear, black bear, and cougar models failed to converge, as no sheep was killed by one of these predators in a band with at least one transmontano.

	All predation ($n = 80$)	Competing risk regression models for transmontanos
		Coyote ($n = 55$)
# Livestock guardian dogs	0.379[1] (0.080)	0.337[1] (0.047)
# Sheep	0.0007[1] (0.0001)	0.0008[1] (0.00005)
# Transmontanos	−1.086[2] (0.534)	−0.620 (0.543)

[1] $P < 0.10$.
[2] $P < 0.05$.

Lastly, a small sample of sheep bands with karakachans or transmontanos resulted in a small sample of depredations on which to draw inference on predator-specific effectiveness of those breeds. As such, determining predator-specific effectiveness for those breeds was not possible for many carnivore species, but differences in overall risk of depredation were still identified. This suggests livestock producers should consider using these breeds but also sheds some light on the effort required to investigate differences in effectiveness between LGD breeds and may suggest why it has not been well studied to date.

Despite possible limitations, our findings are some of the first to show breed-specific differences in LGD effectiveness by direct comparison (but see Green and Woodruff, 1983, 1988). With > 30 unique breeds of LGDs to choose from (Rigg, 2001), sheep producers generally rely on anecdotes and shared experience when choosing a LGD breed to integrate into their operation. Here, we provide empirical evidence for three purebred LGD breeds, all of which show increased aptitude for preventing depredation of domestic sheep. Specifically, kangals outperformed whitedogs at preventing depredations from cougars, black bears, and coyotes, while karakachans outperformed whitedogs at preventing depredations from coyotes. In addition, we suggest that mature whitedogs already used by many sheep producers in the northwest United States, despite their often-uncertain genetic origin, are among the best options for protecting sheep from wolf or brown bear depredation, as there is no evidence to suggest that replacing a whitedog with a kangal, karakachan, or transmontano reduces the risk posed by these carnivores. To date, most studies of LGD effectiveness have not accounted for breed. Considering, as we have shown here, that loss prevention varies as a result of the interaction of LGD breed and predator species, the reported statistics on loss prevention for LGDs should be considered minimums only (Andelt and Hopper, 2000). This may partially explain the large variance in effectiveness reported for LGDs as well (Smith et al., 2000; Miller et al., 2016; Eklund et al., 2017). Summarily, our findings expand the literature on using LGDs as an effective nonlethal management tool for reducing depredations of domestic sheep and provide information that might help livestock producers and wildlife managers make tailored decisions about how best to incorporate different breeds of LGD into sheep grazing regimes.

Implications

Wildlife managers, LGD breeders, and researchers are frequently asked which LGD breed would work best in a given situation or with a certain predator. Here we present findings that three novel breeds of LGD—kangals, karakachans, and transmontanos—are all associated with a reduced hazard of depredation for domestic sheep, compared with mixed-breed “whitedogs.” Concerning predator-specific hazard, kangals were associated with a significant reduction in cougar, black bear, and coyote depredations, and karakachans were associated with a significant reduction in coyote depredation. We also present evidence that kangals may be less effective at reducing wolf depredations than whitedogs, although this may be an artefact of the uneven distribution of wolf depredations in our dataset. Overall, kangals appear to be a useful breed of LGD for most sheep producers, with karakachans and transmontanos also showing improvements over whitedogs. These findings will help livestock producers and wildlife managers make tailored decisions about how best to incorporate different breeds of LGD into sheep grazing regimes.

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