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Investigating Cause-Specific Mortality of Sheep to Determine the Impacts of Carnivores on Domestic Livestock

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INVESTIGATING CAUSE-SPECIFIC MORTALITY OF SHEEP TO DETERMINE

THE IMPACTS OF CARNIVORES ON DOMESTIC LIVESTOCK

by

Nathan Jacob Floyd

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ABSTRACT

Investigating Cause-Specific Mortality of Sheep to Determine the Impacts of Carnivores on Domestic Livestock

by

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Utah State University, 2022

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Populations of mammalian carnivores are growing in the western United States. Carnivores frequently prey on species that are highly valued by humans, including livestock and wild game, which causes conflicts with livestock producers and hunters. Accurate and updated information on the impact of predators on prey is essential when making management decisions and mitigating domestic livestock losses, yet it is difficult to detect mortalities and determine whether depredation has occurred when livestock graze on public allotments. We sought to accurately quantify the effects of predation on domestic lambs when grazing on public allotments in Utah. We placed 934 VHF-collars on lambs in seven herds that graze on public allotments at two study sites – one in Northern and one in Central Utah. We then monitored collared lambs daily throughout the summer grazing season (April-September 2021). Of the 934 collared lambs, there were 51 (5%) lamb mortalities, for which 28 were determined to be from predation, 12 from non-predatory causes, and 11 were from unknown causes, as they were too decomposed to accurately determine a cause of death. Predators responsible included coyote (*Canis latrans*), cougar (*Puma concolor*), and bobcat (*Lynx rufus*). We found noticeable differences in the causes and number of mortalities among herds but no differences between study sites or in predation rates within herds over time. Our results suggest lamb survival may primarily be a function of animal husbandry practices or specialization by individual predators within a grazing allotment. This study provides insight into what factors influence lamb mortality, and highlights areas ranchers and managers might focus on when seeking to increase lamb survival and reduce depredation.

(42 pages)

PUBLIC ABSTRACT

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Nathan J. Floyd

Livestock and carnivores interact in ways that are considered conflict throughout the world. In the western United States, livestock are often grazed on public lands in close proximity to predators in their natural habitat, and can be killed as prey. Livestock losses to predators can threaten rancher's livelihoods. Sheep and lambs are especially vulnerable to predators due to their small size and lack of defensive abilities. To reduce the impacts that predators have on livestock, it is important for ranchers and wildlife biologists to have an accurate understanding of how many livestock die and are killed by predators when grazing on public lands. To better understand how sheep and lambs are affected when grazing on public lands, we used 934 VHF-radio collars placed on lambs in seven different sheep herds and monitored them from April-September 2021 to determine causes of death. In our study, 51 collared lambs died. Of these, 28 were found to have been killed by predators and 12 died of other causes, but we could not determine a cause for 11 because the carcasses were too decomposed. Predators that were found to have killed lambs include coyotes *(Canis latrans),* cougars (*Puma concolor*), and bobcats (*Lynx rufus*). We found that the biggest factor in determining how many lambs died were differences in animal husbandry (i.e., how the ranch operates when taking care of the lambs) or from specialization by individual predators within an allotment. We did not find any relationship among the time of year, whether a lamb was male or female, or the location of the lambs with how many died by predators. These results can help ranchers better care for their sheep and biologists better manage the predators in the areas where sheep are grazing.

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Nathan J. Floyd

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INTRODUCTION

Large carnivores and humans have a long history of conflict (Feldman 2007, Marshall et al. 2016). In the United States, large carnivores have experienced considerable reductions in populations and extermination from substantial portions of their historical native range due to human effects (Slagle et al. 2017; Young and Goldman 1944; Mattson and Merrill 2002; McCollough 2011). These extermination and control efforts continued until the latter part of the 20th century when changes in public perception led to legislation restricting the methods and practices used for carnivore control (Feldman 2007).

Changes in perception and concerted recovery efforts of carnivores in their native range have led to the recovery of and an increase in carnivore populations, particularly in the western United States (Bangs et al. 1998; Treves and Karanth 2003). Coyotes (*Canis latrans*) have increased in numbers and expanded their range despite efforts to reduce and eliminate populations (Prugh et al. 2009; Hody and Kays 2018). The trend is similar but slower for large carnivores, including wolves (*Canis lupus*), cougars (*Puma concolor*), and bears (*Ursus spp*.) (LaRue et al. 2019; Miller 1990; Slagle et al. 2017; Vonholdt et al. 2008). As carnivore populations continue to recover and grow alongside our growing human population, conflicts between carnivores and livestock will likely also increase.

Carnivores prey on livestock, and the direct loss of livestock to carnivores can have significant economic impacts on livestock producers. Indirect losses further impact profits through expenditures on carnivore management, loss of investment in the livestock, and elimination of future potential profits, such as from future breed stock (Connolly 1991). Additionally, carnivores can impact the welfare of livestock, increasing stress, reducing feeding efficiency, and requiring husbandry practices to change in response to the presence of carnivores (Connolly 1991). Thus, reducing the effects of livestock-carnivore conflict is important in the conservation and management of carnivore populations (Linnell 2012; Treves, 2009; Breck et al. 2011), and in protecting the welfare of ranchers and the livestock industry (Bangs and Shivik 2001; Naughton-Treves et al. 2002; Jones 2004).

Accurate and updated information on the impact of carnivores on livestock is vital to ensure that mitigation and management efforts are as effective and efficient as possible (Breck et al. 2011), yet some livestock lost to carnivores goes undetected. Undetected losses are an important but often unquantified source of mortality (Bowns et al. 1973). Documented confirmation of depredation is often required to legally remove depredating carnivores and to receive compensation for qualifying livestock losses (Wagner et al., 1997). Compensation programs reimburse producers for livestock killed by certain carnivores, such as cougars, black bears, and wolves (Wagner et al. 1997), but not for others, such as coyotes. This makes accurate classification of which carnivores caused each depredation highly valuable to producers. However, classification can be problematic or impossible due to the difficulty in finding dead livestock. Even when depredations are identified, the cause of death may not be possible to determine due to effects of decomposition, scavenging by other animals, or in areas of dense vegetation or rough terrain. Additionally, some carnivores, such as cougars, may drag carcasses away from the site of the kill and conceal them, or consume the carcass entirely (Palmer et al. 2010). The difficulty in detection and classification of depredation may result in carnivores causing greater losses than what a producer is compensated for (Wagner et al. 1997).

Since its peak in the 1940s, the sheep and wool industry has declined by nearly 90% (Jones 2004; Palmer et al. 2010). Many factors have contributed to this decline, such as a decrease in the demand for wool after the development of cheaper synthetic fibers, and decreasing consumption of lamb and mutton, particularly in the United States (Jones 2004; Ribera et al. 2004). Losses from predation, however, are consistently cited as the primary or contributing factor when sheep operations shut down (Parker and Pope 1983; Jones 2004). In 2014, over 500,000 lambs were lost to depredation nationally at a loss of 102 million USD (USDA 2015). Estimates of lambs lost to predators range from 1-8% annually (Klebnow and MacAdoo 1976). In a 1979 study in central Utah (Taylor et al. 1979), losses of 4–8% of lambs to carnivores were reported, and a more recent study in the same area found ~5% of lambs were killed by carnivores (Palmer et al. 2010). Coyotes were responsible for over two-thirds of the depredations, cougars accounted for 31%, and black bears for the remaining 2% of the depredations (Palmer et al. 2010). In September 2021, the same time this study concluded, the market price of lamb averaged $2.47/pound (USDA 2021) and the lambs on our study ranged from 90-100lbs on average at the time of shipping (Personal communication), meaning a 5% lamb loss of a herd with 1000 lambs would equal a nearly $10,000 loss due to predators from one herd alone.

Techniques used to determine the cause and number of sheep mortalities have a high degree of uncertainty. Current metrics used to inform policy-making and to direct carnivore management often rely on self-reported data. A better understanding of the causes of mortalities would allow wildlife managers and producers to more effectively focus their efforts when protecting livestock and managing predators. Thus, there is a need to improve the quality of data used to inform carnivore and livestock management.

This study sought to determine the cause-specific mortality of domestic lambs, animals less than one-year-old, grazing on summer range. We focused on lambs because they account for approximately 99% of sheep depredations in Utah and represent the greatest economic impact to producers (Palmer 2009, Taylor et al. 1979). The study was conducted in partnership with several sheep operations in northern and central Utah. Our objectives were to (1) determine total lamb mortality due to predation versus other causes of death (e.g. disease, exposure) and (2) to investigate and classify carnivore-caused mortalities to determine which carnivore species was responsible. Results will inform ranchers and wildlife managers of the mortality rate and cause for these locations and give a better understanding of where to focus conflict mitigation efforts.

METHODS

Study Area

We intensively monitored seven sheep herds (n=1000-2020 lambs per herd; Table 1) in two areas representative of Utah's sheep industry and carnivore community (Fig. 1). The Manti study site consisted of parts of Utah and Sanpete counties west and southeast of Provo, Utah. We monitored two herds owned by two producers in this site. The Cache study site was located in Cache County, south and east of Logan, Utah. We monitored five herds owned by four different producers in this site. These sites were chosen based on conversations with sheep ranchers and wildlife managers, and they are representative of sheep ranching methods and depredation rates of sheep in Utah, and other areas in the Intermountain West.

Vegetation and topography varied between herds, and during the time of year. In the spring, lambs were generally grazed on private lands. Dominant vegetation types included grass pastureland, sagebrush (*Artemesia spp.)*, pinyon/juniper woodlands, oak brush (*Quercus gambelii* Nutt.), and some western maple (*Acer macrophyllum* Pursh.) and quaking aspen (*Populus tremuloides Michx.)* forests. The terrain was generally not rugged, but there were some small mountains and rolling hills. Elevation ranged from 1800-2200m. As the lambs were transported to their summer grazing areas in higher elevations, the majority of land consisted of public grazing allotments on US National Forest lands. Dominant vegetation in these allotments consisted of dense aspen and conifer foests, sagebrush, chokecherry (*Prunus virginiana* L.), and exposed upland slopes. These grazing areas were located in more rugged terrain at higher elevations.

Elevation ranged from 1800-3300m. Annual precipitation rate averaged 25-46 cm for the Manti study site and approximately 41cm for the Cache study site.

Species located in these areas that have been documented killing lambs include coyote, cougar, black bear, bobcat (*Lynx rufus*), golden eagle (*Aquila chrysaetos*), bald eagle (*Haliaeetus leucocephalus*), common raven (*Corvus covax*), red fox (*Vulpes vulpes*), and domestic dog (*Canis familiaris)*.

Because the sheep were privately owned, husbandry methods differed greatly between the sheep herds and throughout the year. For example, some ranchers shed lamb while others lamb on open range. Other methods in which ranchers participating in our study differed in their operations included the timing and method of docking (i.e. castration and removal of the tail), preventative treatment (e.g. pine tar for flies after docking), presence and number of guardian animals (dogs, alpacas), number of grazing locations, and intensity of the herding and bedding practices. All sheep herds were accompanied by a herder and herding dogs when on public grazing allotments. USDA Wildlife Services, and private trappers, conducted their normal predator control efforts throughout the study.

Once the sheep herds were moved to the summer grazing areas, we monitored them daily. Monitoring consisted of locating the sheep herd and confirming the presence of each collared lamb using a VHF receiver. Occasionally, lambs could not be detected. This was usually because terrain features blocked the signal or sheep and lambs wandered too far from the herd. Extra efforts were made to locate the missing individual as time allowed. If the frequency was not detected, the frequency was marked and searched for again the following day. This was repeated each day throughout the summer grazing season. Extra efforts were also made to locate any missing frequencies after the sheep were removed from the grazing allotment and the majority of the collars removed.

Table 1. Total lambs, collared lambs, collared lamb loss, time on range, cause of death, and predator depredation numbers, for the seven herds monitored during the spring and summer grazing season 2021, Utah, USA.

	Site	Total Lambs	Collared Lambs	Collared Lamb Losses	Start date	Time on Range (Days)	Predation Loss	Non-Predation Loss	Unknown Cause	Cougar	Coyote	Bobcat	Unknown Predator
7	Cache	1030	134	9	24-Apr	79	7	1	1	5	2	0	0
6	Cache	1192	132	2	26-Apr	36	2	0	0	1	1	0	0
5	Manti	1289	135	17	25-May	150	13	2	2	1	6	4	2
4	Manti	1269	132	8	18-Jun	141	3	3	2	0	3	0	0
3	Cache	1307	131	2	8-Jun	89	1	0	1	1	0	0	0
2	Cache	2020	137	10	15-Jul	60	2	6	2	1	1	0	0
1	Cache	1093	133	3	19-Jul	57	0	0	3	0	0	0	0
Total		9200	934	51	24-Apr	612	28	12	11	9	13	4	2

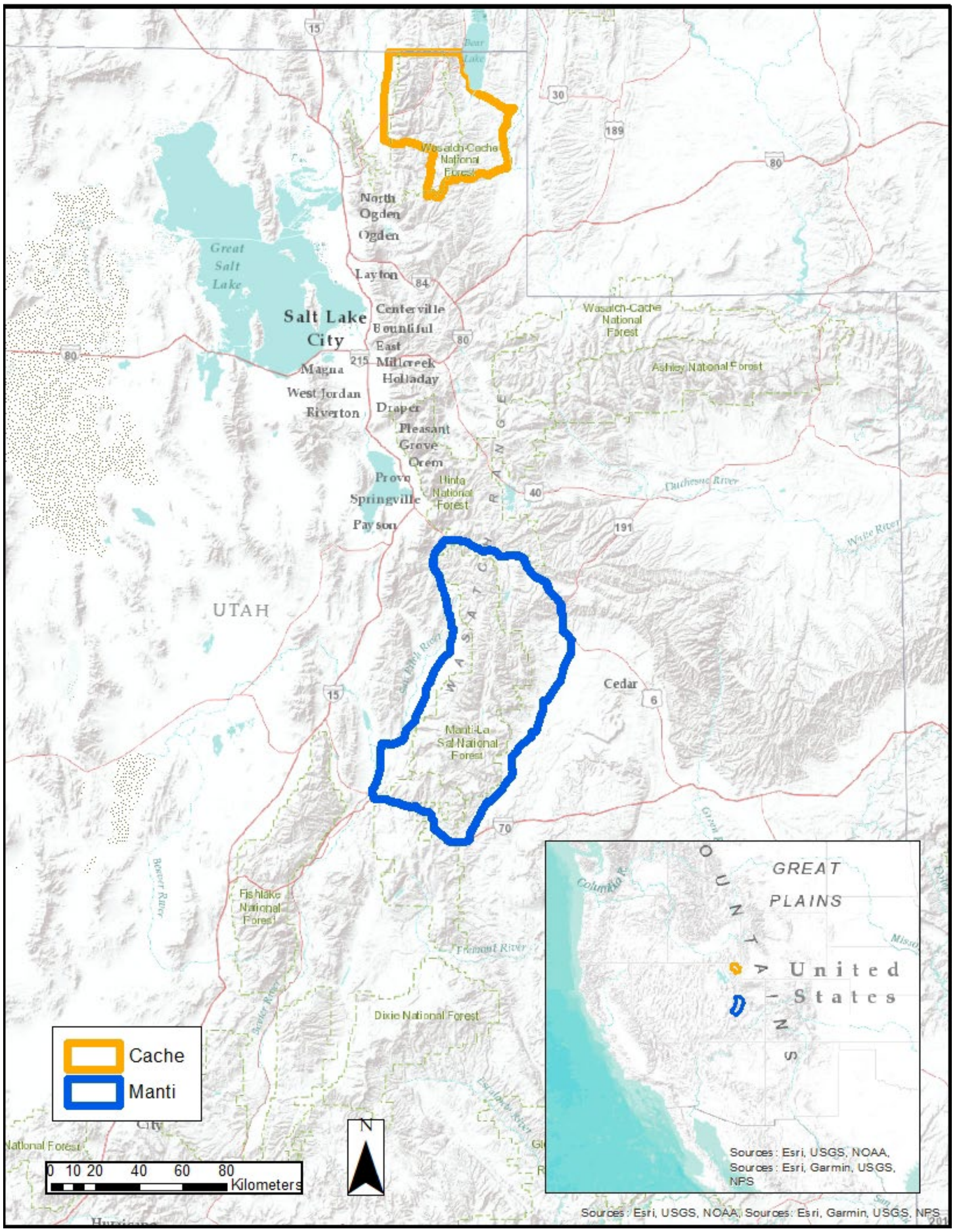

Figure 1. Two study sites for evaluating domestic lamb mortality in Utah, USA 2021. The Cache study site is marked in orange and the Manti study site is marked in blue. We monitored domestic lambs in five herds in the Cache, and two in the Manti.

Mortality Investigations

When a mortality signal was detected, the collar was located as quickly as possible. We aimed to find mortalities within 6-24 hours but some transmitters took longer to find due to rough terrain or because some lambs wandered too far to locate during the daily check and were found at a later date.

When a carcass was located, details of the location and condition of the carcass, and the distance from the main herd location was recorded. A field-necropsy was performed using methods derived from Bowns et al. (1973) and Palmer (2009), and instruction from US Department of Agriculture-Wildlife Services personnel. We classified lambs that died of causes other than predation as “non-predation”. These included lambs that died of disease, accidents, poisoning, dehydration, or other causes, and had no physical evidence of predation. We classified lambs that died of predation as “predation” and, if sufficient evidence was found, we identified the carnivore species responsible. Evidence used to identify carnivore species included presence and location of bite marks and wounds, hemorrhaging, manner of consumption, disposition of the carcass, location of predator fur, tracks, scat, and other signs. Occasionally a carcass would be determined to be a result of predation, but we lacked sufficient evidence to accurately determine the carnivore species responsible. If a carnivore was suspected but an accurate identification could not be made, a sample of the lamb remains was collected and frozen for analysis for carnivore DNA following methods described in Piaggio et al. (2020; see Appendix). Carcasses were marked “unknown” when we could not determine the cause of death, and “unknown-predator” when we could determine predation occurred but not the species of predator. Carcasses marked “unknown” occurred when the carcass was too decomposed, typically because we were unable to find the VHF frequency for multiple days due to terrain features or distance from the main herd. The heat was also a major factor accelerating decomposition.

Analysis

We estimated the proportional mortality rate (predation vs non-predation or unknown) for each sheep herd. We also estimated proportions of lambs lost to predation relative to total deaths and used Fisher's exact tests (Fisher 1934) to compare differences in predator to non-predator deaths among herds and between sites.

For the seven herds in the study, we constructed capture histories of collared lambs to estimate weekly survival probabilities (S) using the known-fate model in Program MARK (White and Burnham 1999). The known fate model is a logistic regression model, which is an extension of the Kaplan-Meier model (Kaplan and Meier 1958) and accommodates staggered entry and exit by censoring of marked animals (Pollock et al. 1989). We began the period for survival analysis when lambs for each herd were collared and monitoring began. The date of docking/collaring ranged from 24 April to 19 July, and the length of time lambs were monitored varied from 5-21 weeks. To account for differences in the start date, we include a start day (as Julian day) covariate for each herd. For the herds that we monitored for <21 weeks, we censored the data after monitoring ceased. We included the sex of each lamb as an individual covariate.

Model construction focused on our main goal, which was to determine if lamb survival varied among herds. To this end, herds were modeled as a group and we constructed models with survival being the same for all herds (null models; no difference in survival among herds) and models with survival different among the herds. To check whether differences between the 2 study sites (Cache and Manti) was more important than herd, we also included a model with site. For models with survival different among herds, we modeled weekly survival as constant (survival the same for each week) and as categorical (survival varies from week to week). We also included models with sex as an additive effect with herd. For (null) models without differences in survival among herds, we modeled weekly survival as constant and as categorical. Finally, we included a model with only the start day as explaining differences in survival. We used Akaike's Information Criterion adjusted for small sample sizes (AICc) and normalized AICc weights (wi) to rank models (Burnham and Anderson 2002).

To estimate survival over three months (i.e., 12 weeks), we took the product of the weekly survival estimate for 12 weeks. The weekly survival estimate was based on the top model (Table 2), which was weekly survival as constant for each herd. For example, the weekly survival was 0.997 for one herd in the study, while the 3-month survival was $0.997^{12} = 0.967$. We estimated the variance of the product using the delta method (Seber 1982), implemented in R (R Core Team 2021) using the emdbook package (Bolker 2020). The Jeffery's method was used to estimate the confidence interval (Brown et al. 2001).

To obtain cause-specific mortality we first calculated the proportion of lambs killed by each predator species. Next, we used a 1-KM approach, described in Koen et al. (2007). This approach involves running a survival analysis but with all mortalities that are not the cause of interest being censored at the time of mortality - instead of listed as a mortality - to estimate a mortality rate for each cause, independent of the other causes. We looked specifically at mortalities caused by cougars and coyotes using a Cox proportional hazard model. We used the survminer (Kassambara et al. 2021) and survival (Therneau and Grambsch 2000; Therneau 2022) packages in program R (R Core Team 2021), testing cause of death (cougar or coyote) and for an interaction of cause of death with site (Manti or Cache). We could not use a model with herd identification instead of site because it failed to converge due to low numbers of lamb mortalities by cougars or coyotes.

Table 2. Model selection results for known-fate survival analyses of VHF collared domestic lambs, April–August 2021 in Utah, USA.

Model[a]	*K*	AIC_c	ΔAIC_c	w_i
S(herd)	7	643.03	0.00	0.664
S(.)	1	646.32	3.29	0.128
S(herd+sex)	9	646.89	3.86	0.097
S(site)	2	647.94	4.91	0.057
S(startday)	2	648.30	5.27	0.048
S(herd+week)	29	652.58	9.55	0.006
S(week) PIM	21	655.38	12.35	0.001
S(herd × week)	147	834.90	191.87	0.000

[a] Key to model notation: K = number of parameters; AIC_c = Akaike Information Criteria corrected for small sample size and lack of model fit; ΔAIC_c = difference between the model listed and the AIC_c of the best model; w_i = model weight based on model AIC_c compared to all other model AIC_c values; startday = Julian day when lambs were collared and monitoring began; week = weekly survival modeled as categorical; '.' = weekly survival modeled as constant; herd = survival different among the 7 different herds, site = survival different between the Cache and Manti study sites.
[b] Herd or site by itself indicates survival is constant from week to week, but different among the ranches or sites.

RESULTS

We documented 51 mortalities of collared lambs, for which 28 were determined to be from predation, 12 from non-predatory causes, and 11 from unknown causes (Table 1). Predators responsible for the 28 deaths included coyotes, cougars, and bobcats. Potential non-predatory mortalities included infection from docking or other wounds, poisoning from noxious plants, dehydration, snakebite, injury during transport, and a fall. The overall proportionate mortality rate from predators was 55%, primarily by coyotes and cougars (Table 3). Results from the Fisher's exact tests showed there were significant differences among herds in the proportion of deaths caused by predators versus other causes (p= 0.006; Fig. 3), but no significant difference between sites (p= 0.264; Fig. 4). The Cox Proportional Hazard model indicated no difference in proportion of predator mortality (z= -1.572, p= 0.1160) or cause of mortalities (z= -1.132, p= 0.2577) between the Cache and Manti study sites; however, there was an interaction between site and predator with cougar mortality being higher in the Cache study site compared to the Manti site (z= 2.371, p= 0.0177, Likelihood ratio test= 8.91 on 3 df p= 0.03).

The top two models for the estimated 3-month survival of lambs each had a ΔAICc <2, and a combined model weight of 0.749 (Table 2). The top model using herd as a covariate had a model weight of 0.534. We found no significant effect for start day, sex, or time of year in our models. The estimated 3-month survival of lambs for each herd is illustrated in Figure 5.

Table 3. Proportionate mortality rate of all known predator-caused deaths of radio-collared lambs by cause and predator species during spring and summer grazing season 2021, Utah, USA.

Proportionate Mortality Rate (%)	
Predation	54.9
Cougar	17.7
Coyote	25.5
Bobcat	7.8
Unknown-predator	3.9

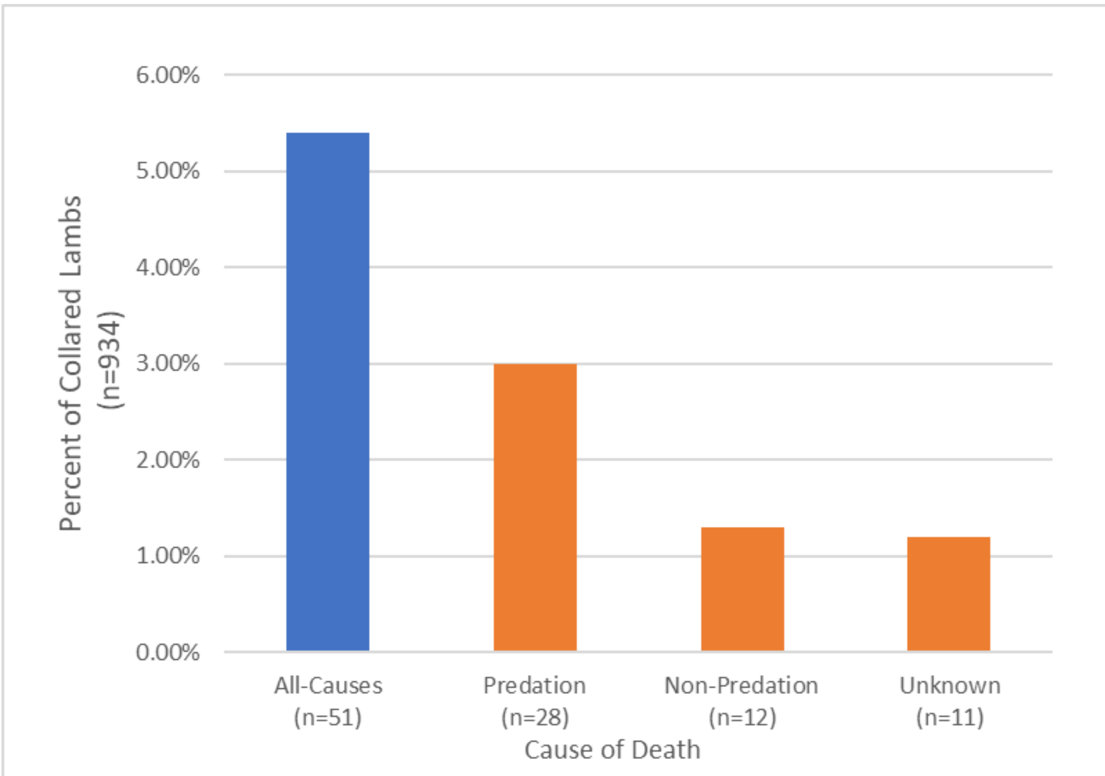

Figure 2. Percent mortality from all causes and by cause-specific mortality for VHF-collard domestic lambs monitored during the spring and summer grazing season of 2021 from two sites in Utah, USA.

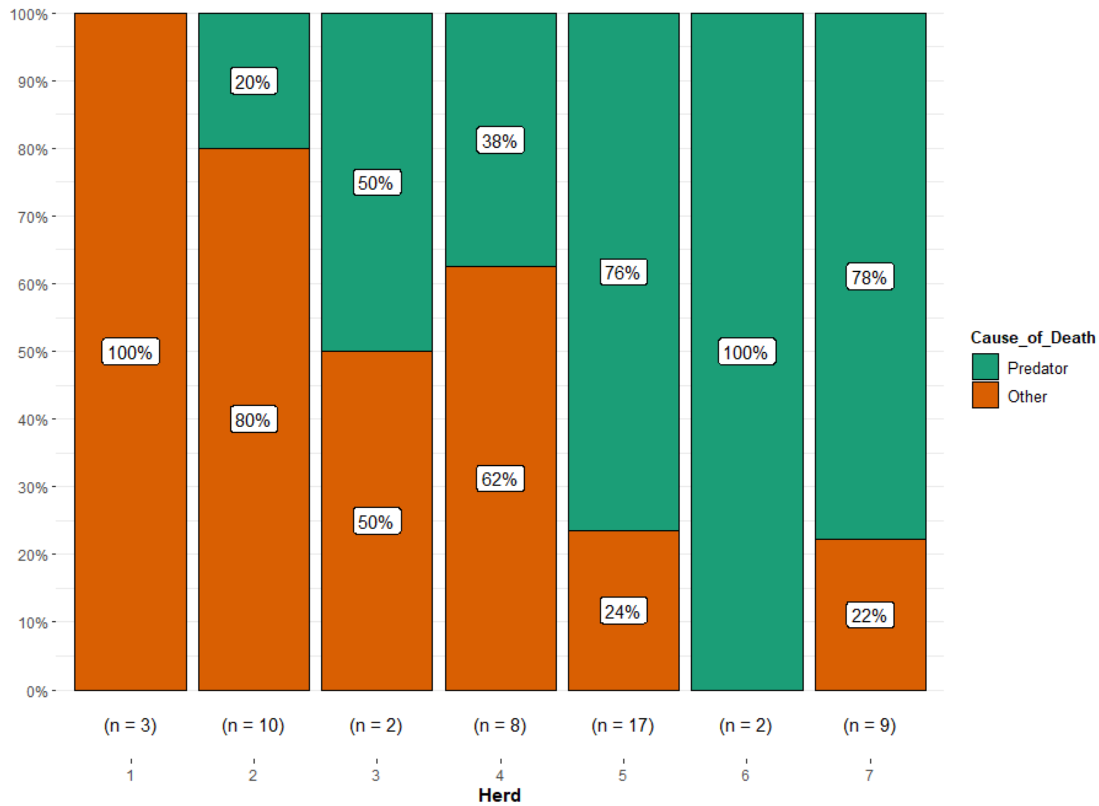

Figure 3. Cause of death (predator vs. other cause) by herd, for VHF-collared domestic lambs monitored during spring and summer grazing sea.

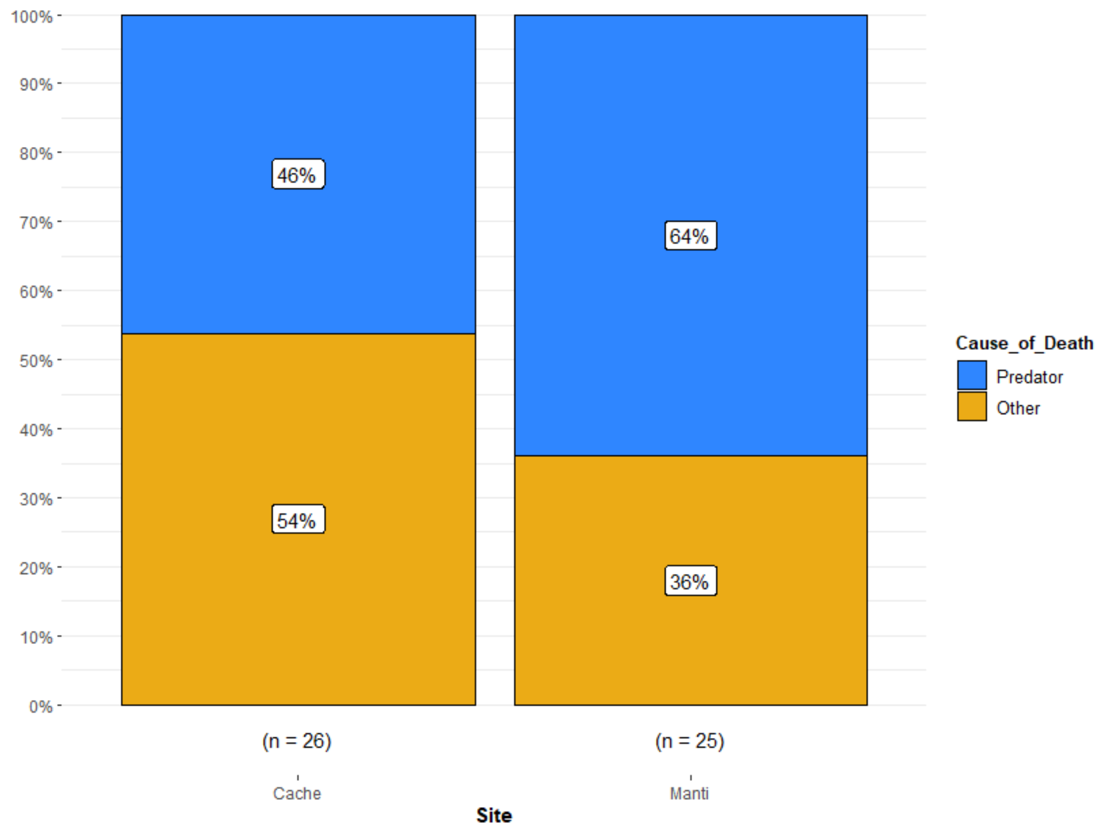

Figure 4. Cause of death (predator vs. other cause) by study site, for VHF-collared domestic lambs monitored during spring and summer grazing season of 2021, Utah, USA.

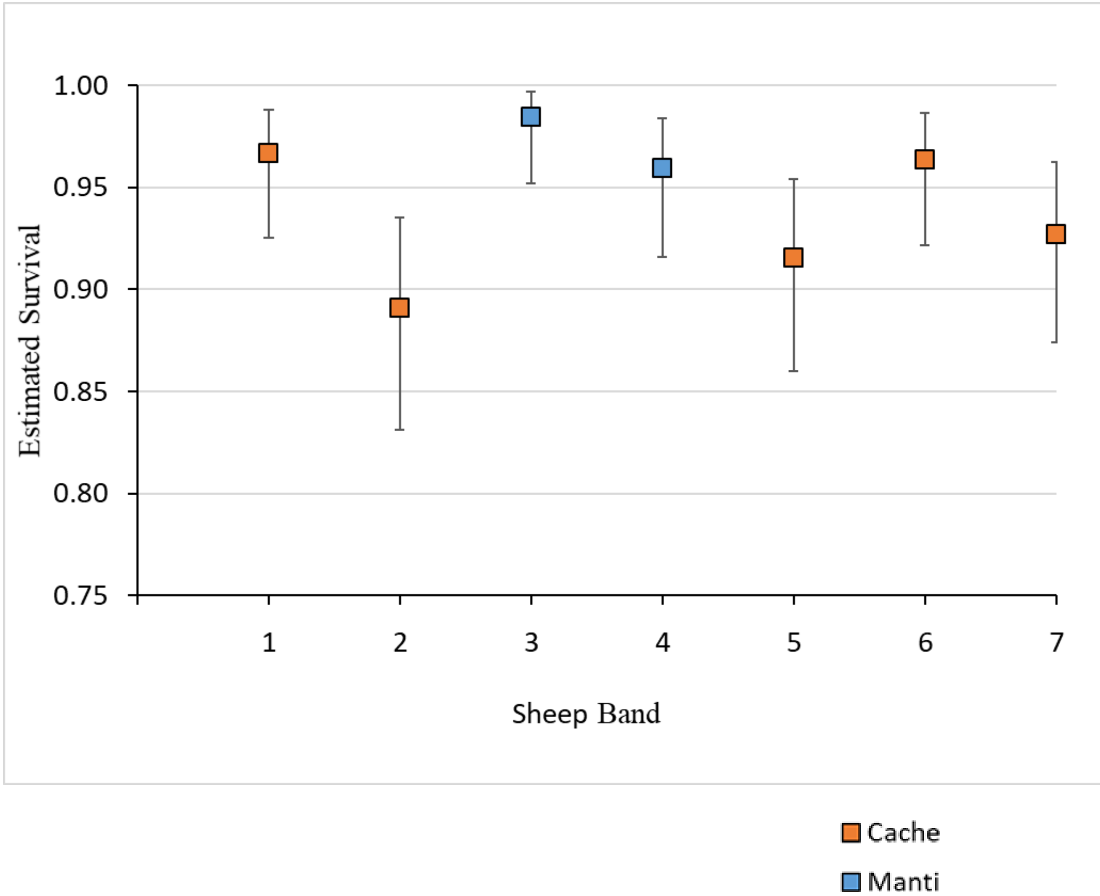

Figure 5. Three-month survival of VHF-collared domestic lambs (known fate); estimated from the top model, S(herd), for seven herds in Utah monitored during the spring and summer grazing season of 2021. Variance was estimated using the delta method. Confidence intervals estimated using Jeffery's method.

DISCUSSION

Our goal was to determine the cause-specific mortality of domestic sheep, with specific interest in identifying what proportion are lost to predators, and what predator species are responsible when there is a depredation. We chose study sites that were representative of sheep grazing in Utah and the Intermountain West. Overall, our mortality numbers fall within the range of previous studies in Utah. Like Palmer et al. (2010), we found a higher proportion of lambs killed by cougars in our study than those found in the 20th century. This it to be expected given the corresponding increase in cougar numbers across the West during this time. It is important to note that our results are not annual mortality rates, but only the rates we observed during the time the lambs were monitored on our study. Therefore, its likely that deaths from all causes could be higher were all the lambs monitored from birth to the point when our monitoring began. Survival analysis indicated that the biggest predictor of lamb survival is the herd to which it belongs. Since the herds were located in the same habitats, and often in neighboring locations, the most likely explanation for the differences in predation between herds were the differences in animal husbandry. This is especially likely as we saw variation between herds for all causes of death, not just deaths from predation. Such differences in husbandry are important to consider, as they are likely to influence an animal's behavior (Nevalainen 2014), and therefore what occurs on the landscape. Since we could not control for the individual husbandry practices of each herd, we cannot say for sure which husbandry differences may contribute to our results. Some likely factors include herder experience level, herding and bedding practices, the presence of guardian animals, precipitation history, the presence and location of water sources, preventative medical care, and individual predator behavior.

While monitoring the collared lambs, we found that the herders and ranchers often believed that all sheep in their herds were accounted for even when our monitoring showed otherwise. There were often individuals or groups of sheep in different locations from the main herd, and they would stay separated for weeks at a time. Since herding and livestock guardian animals have both been found to reduce predation (Bruns et al. 2020; Andelt 2004), it is likely that sheep and lambs separated from the main herd, herder, and guardian animals are at a much higher risk for predation than those located with most of the other sheep (Shivik 2004). Similarly, we observed collared lambs that were left behind when the herd moved locations or that wandered extreme distances (e.g., ≥4km from the main herd); these lambs were likely at a much higher risk for death, especially from predation. In fact, predators were the cause of death for all mortalities of collared lambs >2km from the herd (n=5). However, we were unable to record distance from the herd for all mortalities because of herd movement, so some of the ~11% of mortalities that were unknown or non-predator could have also been at >2km from the herd.

While we had a robust sample size of herds and lambs monitored within each herd, all of the data were collected in one grazing season. Weather and environmental conditions limit our scope of inference, especially because the presence and abundance of water directly affect sheep movements (Dwyer 2008; Baum 2021). Our study coincided with historic drought conditions across both study areas, which impacted water availability and forage quality. When water became scarce, we often observed ewes and their lambs wandered off from the rest of the herd, presumably in search of additional sources of water. This behavior was common, and changes in climate, including higher temperatures, will likely increase these behaviors. Further, about half of the herds were removed from grazing allotments earlier than in most previous years, while other herds were smaller than normal. Ranchers opted to decrease herd size, with one rancher stating the herd was ~80% its normal size, to proactively account for less forage. One herd on our study (herd 6) had to be removed and relocated to another area outside of our study areas, and the collars removed and replaced on another herd, so the monitoring time on that herd was very short. We controlled for final date of monitoring in our analysis, but mortality rates may have been lower than in years where all sheep remain on allotments for the entire grazing season (i.e. 4-months) because the risk of depredation has been found to be greater on public lands used as grazing allotments relative to grazing on fenced, private lands (Stone et al. 2017).

In addition to differences in animal husbandry practices, predation rates might also be impacted by the preferences or characteristics of individual predators. In one instance during our study, five collared and two uncollared lamb mortalities were found and confirmed in a nine-day period. The timing and location of the kills strongly indicate that ~2 or fewer individual cougars were responsible. While we had other cougar-caused mortalities, these were the only instances where we had multiple confirmed collared lamb mortalities from the same individual predator(s) (i.e., single cougar or cougar mother with kittens). This suggests that the presence of an individual predator that has developed a preference or a specialization for lambs is more of a factor than the presence of the predator on the landscape. Studies on cougar predation, have found that individual cougars do learn to specialize on prey species, and one individual can have outsized impacts on prey populations (Ross et al. 1997; Festa-Bianchet et al. 2006). Thus, in areas with high mortalities and management that allows for removal of predators after a depredation is confirmed would likely benefit more from targeted removal of offending individuals than from simply targeting a certain species. This strategy has been used effectively when managing vulnerable bighorn sheep populations at risk of cougar predation (German and Stephenson 2018).

Early in our study, when the lambs were still very young (< 2 months old), we found and confirmed four collared lambs that had been killed and eaten by bobcats. On one occasion, two collared lambs were found on the same day several kilometers apart, and it is unclear if this was the same or multiple bobcats because home ranges vary from ~2-100 km^2 (Lawhead 1984; Litvaitis et al. 1986; Miller 1980). The lambs killed by bobcats were almost entirely consumed except for the head and part of the neck, which were cached and buried completely under vegetation. Without the VHF collars, it is highly doubtful that these mortalities would have been found. While there have been some studies on bobcat depredation of sheep (Neale et al. 1998) and confirmed examples of bobcat kills (Klebenow and MacAdoo 1976), this cryptic caching behavior might mean that most herders and ranchers do not detect these carcasses so they are undocumented. However, the sheep herd where the bobcat depredations occurred was the first and earliest on the range, and the other lambs on our study were not docked and collared until they were older and larger, and therefore a potentially less attainable prey item for bobcats. Husbandry techniques that lamb earlier or wait longer before lambs are on open range may therefore, eliminate the risk of bobcat depredations.

Despite our early bobcat mortalities and small size of lambs in early season, we found no support for changes in risk or frequency of predation over time. This is interesting as others have found risk of predation by coyotes increased during the time of year when pups are being reared (Sacks et al. 1999). Smaller lambs are generally more at risk of predation (Dwyer 2008), but we saw no difference in predation as the lambs grew. This may be due to predators selecting the smallest lamb in relation to others, rather than absolute size of the lamb being the deciding factor. Alternatively, predators may have been avoiding herds because of the presence of the herders and guard animals (Bruns et al. 2020; Andelt 2004) and taking advantage of alternative prey items. For example, mule deer fawns are also highly abundant and a common prey item of these predators during the same time of year (Hamlin et al. 1984). Further studies that integrate native and domestic prey availability (e.g., Nelson et al. 2016) would improve our understanding of mechanisms that make lambs vulnerable to predation.

IMPLICATIONS

As large carnivore populations continue to increase and expand their range, human-predator conflict will likely also increase. Drought and other environmental disruptions increase movement behavior of sheep that may put them at greater risk of depredation. Drought also can reduce forage quality, which impacts market value of sheep and therefore compounds the detrimental effects of predation. Rancher's and wildlife managers are limited in their ability to manage predators and to protect livestock and must focus on methods that maximize their effectiveness. Our results indicate that livestock husbandry practices and targeted removal of confirmed predators may be the most effective areas on which to focus their efforts. Further study that integrates more information on predator movement and native prey availability, while continuing to monitor domestic livestock, could further increase the understanding of the effects of predators on livestock. GPS ear tags and integrated long-range wireless area networks could be used in future studies and have promising implications on livestock monitoring and management.

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APPENDIX

DNA SAMPLING AND ANALYSIS

If a carnivore was suspected during our mortality investigations, but an accurate identification could not be made, a sample of the lamb remains was collected and frozen for analysis for carnivore DNA. To maximize the chance that predator DNA would be obtained during sampling, we would select an area of skin containing a wound and cut out a section of skin around the wound. To eliminate possible scavenger DNA and to ensure we only included wounds caused by the suspected predator, we only sampled wounds that exhibited signs of hemorrhaging. Hemorrhaging is a sign the wound formed while the lamb was still alive. Once the section of skin was removed, we folded the sample on itself and placed it in a sealed bag, ensuring as much air as possible was removed from the bag. The samples were then frozen.

At the conclusion of our monitoring period, all samples were shipped to the genetics laboratory at the USDA National Wildlife Research Center in Fort Collins, Colorado, USA. The staff analyzed our samples for carnivore DNA according to methods described in Piaggio et al. (2020).

Unfortunately, despite extra efforts, the lab was unable to amplify any carnivore DNA. This is likely due to the degraded nature of the samples. While we attempted to preserve the quality of the samples, the decay already present, the amount of time it took to transport the samples to a freezer for storage, and the time the frozen DNA was stored likely resulted in degradation of the samples. Future efforts to obtain predator DNA from depredated carcasses would likely benefit from fresher samples, and more rapid analysis, to reduce the degradation caused by decomposition and storage.