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Original Article

Cost Effectiveness of Livestock Guardian Dogs for Predator Control

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ABSTRACT Predation threatens the economic viability of sheep operations in the United States. Many producers recognize the need to complement lethal control methods with nonlethal strategies such as the use of livestock guardian dogs (LGDs), but little information exists on benefits and costs. We report on a comprehensive benefit–cost analysis of the decision to incorporate LGDs onto a sheep operation in Mendocino County, California, USA, based on data collected during 2013–2017, where livestock predation by coyotes (*Canis latrans*) has been a persistent problem. We estimated that for a representative sheep operation with a breeding flock of 500 adult females (ewes), the use of 5 LGDs reduced lambs and ewes lost to coyote predation by 43% and 25%, respectively, for a total savings of US$16,200 over 7 years. However, we found that costs, which included acquisition and maintenance expenses, exceed benefits of this investment over the 7-year useful life of LGDs by US$13,413. Our results inform the adoption of LGDs, demonstrating that LGDs are only cost-effective for certain types of operations, namely those where LGDs are able to achieve high rates of predator protection efficacy. © 2020 The Wildlife Society.

KEY WORDS *Canis latrans*, coyotes, livestock guardian dogs, net present value, nonlethal control, predation, sheep.

Predation, particularly by coyotes (*Canis latrans*), has been an increasingly difficult and complex problem for sheep producers in the United States. Sheep and lamb predation by coyotes has been cited as a major factor impeding the economic viability of sheep operations in the United States for >4 decades and remains one of the primary reasons that sheep producers leave the business (Pearson 1975, Larson and Salmon 1988, Knowlton et al. 1999). According to the most recent sheep and lamb death loss report from the U.S. Department of Agriculture (USDA 2015), coyotes are responsible for the highest percentage of losses of any predator species—54.3% (33,498 head) of sheep losses and 63.7% (84,534 head) of lamb losses nationally in 2014. Although the direct (i.e., mortality) losses associated with coyote predation are economically substantial, indirect effects of these losses have persistent economic (e.g., losses of an animal's future genetic potential) and emotional effects for ranchers as well (Macon et al. 2018). To mitigate coyote predation losses, sheep operations have employed an extensive suite of lethal and nonlethal depredation tools and techniques.

Historically, a wide variety of lethal control methods have been used to control coyote predation including, but not limited to, aerial hunting (Wagner and Conover 1999), targeted removal of breeding pairs (Jaeger et al. 2001, Blejwas et al. 2002), spring-activated sodium cyanide ejectors (Connolly 1988), and leg-hold traps, snares, and poisons (Timm 2001). However, research suggests that the suppression of a coyote population, via lethal control, for an extended period of time does not cause the total population to decline in the long run (Connolly and Longhurst 1975, Sterling et al. 1983, Connolly 1995). Improved reproductive success and pup survival have been shown to occur when significant population reductions have been conducted (Connolly 1995, Crabtree and Sheldon 1999), such that populations return to precontrol densities within 3–5 years (Connolly 1995). Thus, sizeable lethal predation control efforts are unlikely to reduce predator pressures to acceptable levels. This and other factors are reasons that opponents of using lethal control measures argue that it is not an economically justified means of mitigating predation losses (Shwiff and Bodenchuk 2004).

Public concern over the nature and extent of lethal predator control activities, which has persisted for decades, places additional pressure on ranchers to adopt nonlethal tools. Opponents of lethal control, including some conservation biologists, wildlife advocacy groups, and animal rights activists, have become increasingly vocal in the 21st century. In response, some jurisdictions have implemented programs to promote use of nonlethal tools to mitigate losses from predation. One such example is Marin County, California, USA, where the Board of Supervisors voted to discontinue the County's contract with the USDA Wildlife

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Services federal trapper and use the savings to initiate a cost-share program with ranchers who wanted to begin using, or make improvements to, their nonlethal tools (e.g., improved fencing, purchases of livestock guardian dogs; Fox 2015). In recent years, wildlife advocacy groups have filed lawsuits challenging the renewal of contracts between counties (e.g., Mendocino County in northern CA) and USDA Wildlife Services, the federal organization providing trapper services, in an attempt to limit lethal control activities in areas where public support of wildlife advocacy groups has not been strong enough to eliminate the use of lethal control by government organizations (Fimrite 2015).

Regardless of the public rhetoric surrounding the use of lethal removal, many sheep operators have come to the stark realization that lethal control alone is often insufficient to reduce sheep and lamb predation to acceptable levels, and have thus incorporated a variety of nonlethal depredation techniques on their operations (USDA 2015, Macon et al. 2018). A wide range of nonlethal depredation tools have been developed and tested (e.g., night penning, electric fences, fladry; Macon et al. 2018). In 2014, 58% of sheep operations in the United States used ≥1 nonlethal tools to protect their flocks from predators, with the vast majority of ranchers using multiple tools in concert (USDA 2015). Livestock guardian dogs (LGDs) are among the most common nonlethal tools employed on sheep operations in the United States and have been shown to be the most effective nonlethal tool available across different operational sizes (Gehring et al. 2010*a*). Use of LGDs is often successful at reducing coyote predation while facilitating increased use of pastures and grazing areas that would otherwise be underutilized because of predation risks (Webber et al. 2015, Eklund et al. 2017).

The general consensus, both anecdotally and in the literature, is that LGDs are effective at reducing predation by coyotes (e.g., Andelt 1992, Andelt and Hopper 2000, Smith et al. 2000, van Bommel and Johnson 2012); however, little work has been done to quantify, in monetary terms, benefits associated with incorporating this nonlethal tool onto sheep operations. Further, no studies to date have conducted a comprehensive economic assessment that compares the benefits and costs of LGDs on the same operation.

We conducted a comprehensive benefit–cost analysis of the decision to incorporate LGDs onto a sheep operation in Mendocino County, California, where livestock predation by coyotes has been a persistent problem. Most closely related to our study, van Bommel and Johnson (2012) estimate the effectiveness of LGDs at reducing predation, particularly as the flock-to-dog ratio changes, and perform a simple benefit–cost analysis based on producer survey responses in Australia. Our analysis improves upon this research in multiple ways: 1) we utilized detailed data from a university research center, as opposed to survey responses, which enables us to more precisely quantify benefits and costs; 2) our evaluation incorporates benefits and costs not previously considered, namely costs associated with mortality and culling of LGDs; and 3) we provide the first estimates of cost-effectiveness in a United States context.

Although some argue that costs associated with the use of nonlethal depredation strategies only play a minor role in producer decision-making, United States sheep operations are often economically at risk and need information about the true potential economic consequences associated with their decisions (Shwiff and Bodenchuk 2004). Our results inform the adoption of LGDs and support the economic viability of sheep operations more generally.

STUDY AREA

The Hopland Research and Extension Center (HREC) has long been the University of California's sheep research facility. Located on approximately 2,145 ha in the North Coast region of California (Mendocino County), HREC was home to the University's sheep research flock, which consisted of an average of 459 breeding females (ewes) during the study period 2013 to 2017. The HREC experienced a typical Mediterranean climate with mild winters (average rainfall of 92 cm/yr) and hot summers where it was typical to have no precipitation during July and August. Average daytime high temperatures ranged from 13° C in winter to 33° C in summer. Elevation across HREC varied from 152 to 914 m.

Like most commercial sheep operations in California, HREC was dependent on rain-fed, pasture-based forage for the majority of its feed and used a "mob-" type rotational grazing strategy to utilize available forage across space and over time. Coyote predation at HREC was a chronic and documented problem since as early as the 1970s (Scrivner et al. 1985). Large pastures, coupled with densely vegetated terrain, have always made utilizing the available grazing area at HREC a challenge. This is consistent with the findings of Robel et al. (1981) that indicated that as pasture size increased, so too did rates of losses attributed to predation. Larger areas may provide more opportunities for separation from the flock, making kills easier for predators. During the study period, the breeding ewe flock was only able to graze on <50% (~769 ha) of the available rangeland as result of historical losses from predation in specific pastures and consistent predator pressure from coyotes.

A typical reproductive schedule was followed at HREC to produce feeder lambs for market—ewes were bred in July with most lambs born in December and January. Lambing occurred in a barn with ewes and lambs kept together in individual pens inside the barn for about 2 days before being turned out together on pasture. Lambs were typically weaned and sold as feeder lambs in May each year at a mass of approximately 29.5 kg. Flocks were checked daily but were not accompanied by a herder.

Across California, 66.4% of total sheep and lamb losses were attributable to coyote predation (USDA 2015). These losses were understated for western states given that ranchers report lamb losses to the USDA following marking, docking, or branding. Yet, the pressure at HREC seemed to be more intense, with 89% of the known predator kills caused by coyotes (Scrivner et al. 1985). Although there was evidence that coyote predation pressure at HREC was significant, it is beyond the scope of this paper to attempt to estimate coyote populations in Mendocino County.

Timm and Schmidt (1989) assert that one of the likely causes of increased predation at HREC during the 1970s and 1980s was because ranches on the adjacent 3 sides of HREC exited the sheep business and discontinued predator control efforts. This is consistent with work that has shown predator populations rapidly immigrate into areas where lethal removal had been conducted, especially when predators had aggregated in a high-prey-density area (Norrdahl and Korpimäki 1995, Henke and Bryant 1999, Salo et al. 2010). Some of the studies examined herein focus on other predators, but the Conner and Morris (2015) meta-analysis suggests that individual species responded to harvest pressure in similar fashions. This confluence of factors contributed to the significant and persistent predator pressure experienced at HREC from the 1970s to today, as well as the willingness of the HREC Director to invest in LGDs to protect the ewe flock. We used this decision to acquire and maintain LGDs to estimate benefits associated with increased flock protection and costs associated procurement and maintenance of LGDs.

As a research facility, HREC data availability and record keeping surpassed that of many commercial sheep operations. Thus, this partnership provided access to a rich data set on losses due to coyotes, acquisition and maintenance costs for LGDs, and labor hours associated with the use of nonlethal tools.

METHODS

Net present value (NPV) calculations, which discount the future stream of expected net benefits, are commonly used to determine the economic viability of investments (Boardman et al. 2017). In this setting, we compared the present value of expected future benefits (i.e., reduced lamb and ewe losses) with the present value of costs associated with investing in and maintaining LGDs using proprietary data from HREC to ascertain economic feasibility. Specifically, the NPV was calculated with the following formula:

$$\text{NPV} = \sum_{t=0}^{t=T} \frac{\text{Benefits}_t}{(1+r)^t} - \sum_{t=0}^{t=T} \frac{\text{Costs}_t}{(1+r)^t}$$

where benefits and costs for each time period $t \in [0, T]$ were discounted to the present at rate r. We discounted future expected benefits and costs to the present to compare values that occur in different time periods, capture the opportunity cost of money, and reflect time preferences (Boardman et al. 2017). To generalize our conclusions beyond HREC, we incorporated estimates from the existing literature on LGD effectiveness in various settings into the framework to simulate other production settings that may be more representative of commercial sheep operations in other areas of the United States.

The general approach to the economic valuation had 3 steps. First, we quantified the present value of the reduction in predator-associated losses that could be attributed to LGD protection. Second, we estimated both the capital or fixed (i.e., investment) and variable (i.e., maintenance) costs associated with the use of LGDs as a nonlethal depredation tool. Finally, we combined the benefit and cost information to identify conditions under which using LGDs as a nonlethal depredation tool was cost-effective; that is, when the NPV was positive. To enhance the robustness of the NPV analysis, we incorporated uncertainty about future outcomes and modeling choices, and included a sensitivity analysis to identify which factors most influence the NPV calculations.

Confidential data from HREC used in this analysis consisted of 4 years of detailed production and cost data related to the operation and management of an average of 459 breeding ewes from 2013/2014 to 2016/2017. This facility was regularly used for research purposes, so each animal was tagged and tracked such that it was known which lambs were born to which ewes; this enabled us to accurately measure reproductive rates as well as losses due to both coyotes and natural causes. Furthermore, complete production data allowed for a reliable economic valuation associated with those savings. Given masses and market values available in these data, we estimated revenues associated with both ewes and lambs to paint an accurate picture of changes in net profits due to anticipated changes in flock size. Last, detailed cost data on feed, fencing, veterinarian expenses, and labor costs allowed us to precisely estimate all costs associated with LGD use. A variety of predator effect studies have been criticized because they rely upon rancher (i.e., self-reported) losses associated with predation, with critics asserting that ranchers are more likely to overstate losses they suffer. Further, given that few operations keep detailed records, recall of past losses may also lead to biases in self-reported estimates. Our study benefited from not having to rely on survey data that involved rancher self-reporting, eliminating potential sources of bias.

Throughout the subsequent analysis, we used data from HREC to construct a representative commercial sheep operation. We assumed that this operator has a flock consisting of 500 breeding ewes with a reproductive rate of 1.12. Livestock guardian dog ability to protect a flock varies based on many factors including size of pasture, change of elevation within pasture, and tree and shrub cover, but guidance from the literature suggested that adequate protection can be achieved, on most operations and landscapes, with 1 LGD/100 ewes (van Bommel and Johnson 2012). Based on this guidance, we based calculations for the representative operation on the purchase of 5 LGDs to protect the 500-ewe breeding flock.

Using average ewe and lamb prices and sale masses from the 4 marketing years (2013/2014 to 2016/2017) for which we had data, we calculated LGD effectiveness at reducing coyote predation of ewes and lambs by comparing the pre-LGD "base" period (marketing years 2012/2013 and 2013/2014) with the post-LGD "treatment" period (2014/2015 and 2015/2016). The use of a marketing year basis was required given that the breeding schedule for ewes spans 2 different calendar years (i.e., ewes are bred in July of year x and lambs are born and sold in year $x + 1$). We discounted benefits and costs using a rate of 3%, which is the farm loan rate minus the rate of inflation (Kauffman and Kreitman 2018).

RESULTS

Calculations of economic benefits and costs for our representative flock included all direct economic considerations associated with the use of LGDs as a nonlethal depredation tool. We compared the stream of benefits and costs over time by discounting annual estimates to present value terms over the 7-year useful life of LGDs. We summarized annual estimates and a timeline for when each component enters the NPV equation (Table 1). Subsequently, we tested the sensitivity of our results with a simulation that varied the magnitude of different benefit and cost components to speak to the generalizability of this analysis to areas outside California.

Benefits Associated with Livestock Guardian Dogs

As early as the 1980s, HREC began attempting to use LGDs to reduce predation losses (Timm and Schmidt 1989). Following a 1.5-year observation period, Timm and Schmidt (1989) found that guard dogs had limited effectiveness due to a multitude of factors including, but not limited to, straying from the property, chasing and killing wildlife, and incompatibility with lethal predator control tools used on HREC at the time. Given these factors, LGD use was virtually eliminated until 2013. There were 2 LGDs on the HREC property prior to 2013/2014, they were kept exclusively in a small pasture with the operation's rams and not used to protect the ewe flock that was grazing on the extensive rangeland afforded by the field station. Thus, it was not until HREC invested in 3 additional LGDs and integrated them with the ewe flock that we estimate the depredation savings attributable to LGDs (2014/2015).

To estimate benefits associated with LGD use, we used changes in ewe and lamb losses attributed to coyotes in the pre-LGD period (2012/2013 to 2013/2014) for which we have data and compared that with the losses in the post-LGD period (2014/2015 to 2016/2017). Throughout this analysis, we focused exclusively on the "direct" benefits associated with nonlethal depredation management (i.e., animals saved from predation; Engeman et al. 2003, Shwiff and Bodenchuk 2004). However, we acknowledge that "indirect" benefits associated with rancher well-being, such as a reduction in psychological costs associated with livestock depredations, may be important as well.

Isolating predator losses required that we account for losses due to other causes for lambs and breeding ewes. Lamb losses due to nonpredator causes (e.g., infection, injury, white muscle disease, hemophilia) were typically static, while losses due to predation were often quite variable (Scrivner et al. 1985). At HREC, losses due to natural causes were very stable—3% of lambs born, on average—during the entire study period. Given our representative ewe flock of 500 with a reproductive rate of 1.12, we anticipated that 560 lambs will be born each year. With anticipated lamb losses from natural causes estimated to be 3% (i.e., 17 head/yr), the representative operation had 543 lambs to market or use as replacements in the flock, assuming no predator-associated losses. Using the difference between pre-LGD and post-LGD period averages, we estimated that the use of LGDs reduced lambs lost to coyote predation by 43% each year (i.e., 27 lambs/yr). Average predation losses prior to incorporating LGDs on HREC were 11.8%/year. In the post-LGD period, average lamb predation losses dropped to 6.9%/year. This estimate rests on the assumption that all other factors that affected the effectiveness of LGDs, such as changes in predator density and pressure and changes to infrastructure and terrain, remained constant over the pre- and post-LGD time periods. During the study period, the average sale price for feeder lambs was US$3.02/kg and lambs were sold at an average mass of 29.5 kg. Thus, each year that LGDs were in place, we estimated savings from reduced lamb predation to be US$2,404.35.

The pattern of ewe losses, due to nonpredator causes, observed at HREC is typical of most commercial sheep operations and was small, with most ewes being culled from the flock before mortality was realized (Timm 2001). However, ewes were susceptible to predation by coyotes. Again, using the difference between pre-LGD and post-LGD period averages, we estimated that LGDs reduced ewe predation losses by 25%/year (i.e., on the representative operation, 4 ewes saved from predation each year). In the pre-LGD period, an average of 3.2% of breeding ewes were lost to predation each year. After LGDs were incorporated with the flock, ewe losses due to predation dropped to 2.3%. We value the estimated savings

Table 1. Timeline and values for components of benefits and costs (US$) from using livestock guardian dogs to protect domestic sheep lambs and ewes, based on data from Hopland, California, USA, 2013–2017.

Components	Value in year	Time periods
Benefits		
Reduced lamb predation	$0–2,404	50% in Year 2, 100% in Years 3–7
Reduced ewe predation	$0–979	50% in Year 2, 100% in Years 3–7
Costs		
Investment	$2,000	Year 0
Food	$3,265	Years 1–7
Veterinary	$1,050	Years 1–7
Labor	$0–2,625	Years 1–7
Fencing	$0–3,450	Years 1–7
Replacement	$89–148	Years 1–7 (11% mortality rate in first 38 months and 5% thereafter)

associated with reduced ewe predation by using breeding ewe sales prices that HREC received during the study period. These prices, which averaged US$244.75/head, capture the average value of ewes when incorporated into a commercial breeding flock, meaning these prices reflect the net (i.e., after cost) value of their remaining useful life as a capital asset, which includes producing lambs and wool, and their salvage value (i.e., value at time of cull and slaughter). On net, expected benefits associated with reduced predation of ewes (4 head) totaled US$979/year.

Given that LGDs are investments that have an average useful life of 7 years, all expected future benefits associated with investment in, and maintenance of, LGDs must be calculated over that same time period with appropriate adjustments for the time value of money. The estimated present value of the savings associated with reduced lamb predation over the 7-year period totaled US$11,512. Net savings for reduced ewe predation in present value terms over the 7-year period was US$4,687. Thus, the grand total of anticipated benefits associated with using LGDs as a nonlethal depredation tool over the investment's useful life was US$16,200.

Attribution of losses due to predators is not an exact science and frequently lambs and ewes that were unaccounted for were losses due to predators (Scrivner et al. 1985). For example, Scrivner et al. (1985) estimated that 45% of the lambs that were categorized as "missing" were in fact losses due to coyote predation. Given that we did not include "unattributable" lamb and ewe losses to predation, our estimated benefits associated with LGDs should be considered conservative.

Costs of Acquiring and Maintaining Livestock Guardian Dogs

Costs associated with the use of LGDs as a nonlethal depredation tool include the 1) initial investment to purchase the dogs, and 2) variable costs that are required to maintain the dogs each year. These annual variable costs include dog feed, veterinarian costs, replacement costs, and labor costs associated with feeding, caring, and training LGDs.

Use of LGDs is considered to be a capital investment for sheep operations, which depreciates over the useful life of the asset. Each LGD is estimated to have an average useful life of 7 years. For the purposes of this analysis, the purchase cost (i.e., investment) is incurred in the initial period (i.e., year 0) of the analysis and was thereby not discounted. Costs of purchasing LGDs vary by breed and age at purchase. Hopland Research and Extension Center LGDs were purchased initially at prices that ranged from US$300 to $1,000/dog, which was roughly consistent with estimates in the literature. Andelt (1985) reported that the average cost for a guardian dog pup is US$240, but adults averaged US$690/dog. Van Bommel and Johnson (2012) reported that the average cost of purchasing a LGD was AU$600, with additional costs for initial veterinarian services (e.g., neutering and vaccinations) of AU$340. Gehring et al. (2010*b*) and VerCauteren et al. (2008) use initial prices of US$400 and $500–700/dog, respectively. Pups were less expensive than adults, but they involved much greater labor costs associated with training in the first year.

The representative operation is assumed to purchase LGDs as puppies at a cost of US$400/each, resulting in an initial capital expenditure of US$2,000. This *de novo* approach to incorporating LGDs onto an operation is not how HREC approached using this nonlethal depredation tool. In the 2012/2013 production season, HREC began utilizing 2 LGDs to protect ewes on the property and increased the number of LGDs utilized over time. At the conclusion of this phase-in period, 6 LGDs were with the breeding ewe flock at HREC in 2016/2017. The average cost across the 6 dogs purchased was $786. It is likely that each sheep operation would approach investment in LGDs differently, but we modeled an initial investment in a sufficient number of dogs to protect the flock such that we were able to provide a comprehensive accounting of all costs associated with using LGDs on a sheep operation. If an operator incorporates LGDs into their operation by investing in puppies, the benefits associated with flock protection are not immediate. Following van Bommel and Johnson (2012), we assumed that young LGDs were not effective at reducing predation in the first year and were "half effective" in the second year (i.e., a LGD would achieve roughly 50% of their potential adult effectiveness).

Beyond accounting for the initial investment, it was also necessary to take into account the risk and expected expense associated with mortality and necessary culling. This cost aspect has heretofore not been included in any of the research in this area. A long-term study of LGD culling and mortality, which includes a variety of LGD breeds and considers different locations (e.g., farm and range settings), suggested that 45% of LGDs were either culled or died over their useful life (Lorenz et al. 1986). Lorenz et al. (1986) also found that risks associated with mortality were greater in younger dogs. As such, when we estimated replacement costs associated with LGD mortality and culling, we assumed that the risk of death or culling was independent in each year and varied by age of the LGD. For dogs in their first 38 months of life, we followed guidance from Lorenz et al. (1986) and calibrated our calculations such that the probability that a dog was culled or died was 11% in any given year, while dogs older than 38 months of age had a probability of cull or mortality of 5%. The authors indicated that greater levels of mortality and culling in younger dogs were attributable to greater rates of accidents including being hit by vehicles, being shot, and eating poison. Also, owners identified behavioral problems (e.g., killing livestock, being inattentive to livestock) that made dogs inappropriate for LGD duties. This suggested that if a rancher acquired 5 dogs as puppies initially, then at the end of the 7-year useful life, the rancher would have needed to replace roughly 2 of those dogs during that time. This increased the costs associated with using LGDs as a nonlethal tool that some operations may fail to adequately internalize. The present value of expected replacement costs for LGD mortality and culling totaled US$728 (i.e., 36% of the total initial purchase cost).

Maintenance costs include dog food and veterinary costs. At HREC, during the period over which we have data, veterinarian costs averaged US$211/dog/year and food averaged US$654/dog/year. These costs are slightly larger than those reported in past studies; both Gehring et al. (2010*b*) and VerCauteren et al. (2008) estimate annual maintenance (food and veterinarian) costs of US$600/dog/year. Other costs associated with the use of LGDs came from breeding ewes and lambs being saved from predation. These additional costs, such as increased labor hours to handle larger flock size are discussed and included in the subsequent portions of the analysis. Thus, the total discounted present value of anticipated costs associated with using LGDs as a nonlethal depredation tool over the investment's useful life totaled US$29,612. This estimate excludes labor costs addressed in subsequent sections of the paper.

Net Present Value Results and Sensitivity Analysis

Based upon the foregoing analysis of the benefits and costs associated with using LGDs as a nonlethal depredation tool on the representative operation described (Base Scenario), we found costs exceeded benefits by US$13,412 over the 7-year period. The expected future benefits associated with reduced predation were economically significant—US$16,200—but costs of investing in and maintaining LGDs exceeded the benefits at the rates of predator-protection efficacy experienced at HREC (43% [25%] reduction in predation for lambs [ewes]) during the study period (Fig. 1). Yet this anticipated negative return on investment was inconsistent with some estimates from the literature, namely van Bommel and Johnson (2012) and Andelt and Hopper (2000), with one of the primary factors that drove these differences being the predator-protection efficacy rates experienced after LGDs were put into place. However, it should be noted that Palmer et al. (2010) observed that the use of LGDs on operations they surveyed declined substantially since the 1970s. The authors were agnostic as to whether the dogs were ineffective or too expensive to maintain.

To broaden the applicability of our results to other production scenarios, we conducted several simulations to calibrate our detailed cost information to alternative benefit scenarios from the literature. van Bommel and Johnson (2012) reported that for 68% of their survey respondents, predation ceased to occur after LGDs were employed (i.e., 100% efficacy was achieved). Further, the authors estimated that if the number of stock per dog was <100 to 1, all predation could be eliminated. If LGDs were able to prevent predation entirely, the expected present value of expected future benefits exceed costs by US$16,853 over a 7-year period (Fig. 1, Scenario 1). In this scenario, 65 [16] lambs [ewes] would have been saved by LGDs from coyote predation. Over the 7-year period, the present value of these benefits totaled US$46,465.

Andelt and Hopper (2000) surveyed ranchers in Colorado, USA, that used LGDs on their operations in both fenced pasture and open range settings. They found that producers who did not use LGD lost 5.9 and 2.1 times greater proportions of lambs to predators than did producers who were using LGDs in 1986 and 1993, respectively. The authors did not find a significant change in the predation losses for ewes. So, the number of ewes lost to predation remained the same as in the pre-LGD period. For our representative

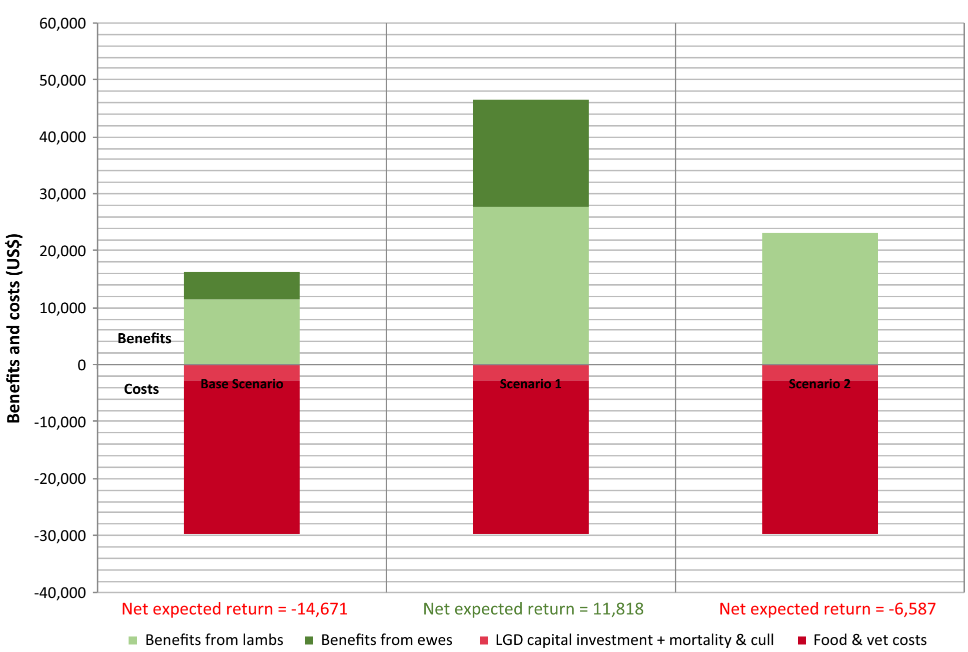

Figure 1. Net present value of expected benefits and costs from using livestock guardian dogs to protect sheep lambs and ewes, based on data from Hopland, California, USA, 2013–2017. For all 3 scenarios, a representative flock of 500 breeding ewes is modeled. Five livestock guardian dogs are used to protect the flock and achieve reductions in lamb [ewe] predation of 43% [25%] in the Base Scenario, 100% [100%] in Scenario 1, and 83% [0%] in Scenario 2.

operation, these results would have translated into lamb predation reductions of 83% and 52%, respectively. Given that the second of the 2 estimates (52%) is close to our baseline predation reduction figures, we simulated the 83% reduction as Scenario 2. In this situation, LGDs were predicted to have saved 54 lambs from predation, resulting in an expected present value of expected future benefits that totaled US$23,025 (Fig. 1, Scenario 2). Thus, overall, the anticipated net loss from investing in LGDs totaled US $6,587, roughly half of the net loss associated with our baseline scenario.

To further test the robustness of our main conclusions, we expanded our characterization of predation effects to include both direct and indirect factors. Throughout the previous analysis, the focus was exclusively on the direct costs (i.e., death loss) associated with predation. Yet, it may be that the indirect costs associated with predator presence and pressure are more significant than the direct costs of predation (Ramler et al. 2014, Macon et al. 2018). These indirect costs include, but are not limited to, lower reproductive rates, reduced body condition, and stress to the flock associated with confinement that is often used as a depredation strategy. Further, the loss of a particular animal represented a loss of future genetic potential, which in some cases may have been the result of years of investment and effort on the part of the rancher (Naughton-Treves et al. 2003).

Data availability and challenges associated with continuously tracking the location of predators and livestock make estimation of indirect impacts challenging at best. Further, we did not have access to data sufficient to estimate the indirect effects associated with predator pressures at HREC and, as a consequence, benefits associated with LGDs in this study are likely understated. Ramler et al. (2014) is the only study known to the authors that has estimated indirect costs associated with predator pressure, namely the reduction in calf weaning mass caused by the presence of wolves (*Canis lupus*) in western Montana, USA. Although this is only one aspect of indirect costs possibly suffered by ranchers, and is clearly not directly analogous to a sheep operation, it is our only available estimate. If predator pressures are assumed to affect calf and lamb masses in a similar fashion, Ramler et al. (2014) suggests that lamb masses at marketing would be 3.5% greater than if predators were not present. With lambs weighing an additional 0.91 kg on average, the present valued of expected future benefits over the 7-year period increased slightly to US$16,554 in total, and costs of LGDs still exceeded the anticipated benefits by US$13,058.

Overall, our baseline results and simulation analysis suggested that the key factor for a sheep operation considering the use of LGDs is the operation-specific factors that will determine a dog's predator protection efficacy. Given that site-specific factors such as pasture size, changes in elevation, and tree and shrub cover influence ability to protect a flock, ranchers should consider these environmental factors before making the economically significant investment in LGDs. If efficacy of ≥90% can be achieved on an operation of comparable scale to that considered herein, incorporating LGDs on the ranch would likely contribute to profitability.

DISCUSSION

Conservation biologists and wildlife conservation activists are increasingly concerned about livestock–predator conflicts and maintaining ecosystem diversity. Yet, the cost of nonlethal depredation strategies are most often borne by producers whose economic viability is threatened either by losses of livestock to predators or by employing nonlethal depredation strategies that may be cost-prohibitive for their operation. We found that LGDs are not a prudent investment for all types of sheep operations seeking to mitigate predation losses from coyotes. Beyond the operation-specific factors that must be considered to determine whether LGDs can be successful at protecting livestock, a number of other factors must also be top of mind for operators charged with making this investment decision.

The most variable, and often substantial, LGD maintenance costs are labor-related expenses, which include time spent training, feeding, and supervising. One of the advantages associated with using data from HREC, a university-owned research facility, was the tracking of data including labor hours associated with specific segments of the operation. At HREC during the study period, labor costs averaged US$1,584/dog/year and increased with the number of LGDs employed to guard the flock. Based on the US$1,584/dog/year, over the 7-year useful life of 5 LGDs, labor-related expenses were estimated to total $49,344. Yet, this single point estimate (i.e., average cost per dog) does nothing to communicate the underlying variability or challenges associated with using and interpreting these data. For example, we did not have access to the number of hours or wage rate details associated with the total labor costs in the LGD budget category. This means that some of the variability in total labor costs was likely to be driven by wage changes (increases), rather than more hours of time being spent on LGD maintenance. Further, given that this is a University-owned and -operated facility, wage and benefit rates paid to employees were likely to exceed that which a ranch operator would expect to attribute to their own labor. Finally, communication with HREC personnel suggested that the study period included ≥2 incidents involving LGDs that would likely increase labor-related expenses; one LGD had to have hip surgery and associated recovery and another dog suffered an accident and died.

Yet, the experience at HREC should not be ignored. Any operation should consider the possibility that time and costs associated with labor dedicated to LGD-related issues will be needed to varying degrees while dogs are being utilized. For comparison, Gehring et al. (2010*b*) estimated training costs to be US$4,000/dog during the first year and VerCauteren et al. (2008) reported that supervising, feeding, and training LGDs required 7–50 hours/month during the first year, and 10–11 hours/month afterward.

Given the terrain and existence of natural barriers, fencing may also be needed to effectively use guardian dogs. Gehring et al. (2011) argued that fencing could be crucial for successful implementation of LGDs because socialization with sheep was not always enough to prevent the dogs from roaming. However, operations that already have adequate fencing or use temporary electric fencing would not have to incur these additional costs. During the study period, 2,039 m of fencing was installed or replaced at HREC. Thus, fencing costs were high, averaging US$3,450/year for fiscal years 2012–2015. At HREC, fencing costs were greater than other costs associated with LGDs. We hypothesized that this was driven by the exceptionally large grazing space, where sheep grazed approximately 809 ha of rangeland. Regardless of size and extent of fencing, inclusion of fencing costs in the analysis reinforced the main finding that LGDs were not cost-effective at HREC. Although the large grazing size and substantial fencing expenses may not be representative of the average sheep operation, it remains an important consideration for producers.

MANAGEMENT IMPLICATIONS

The use of LGDs on sheep operations in the western United States has been shown to be an effective way to reduce lamb and ewe predation by coyotes. However, care should be taken to consider the true economic costs associated with using this nonlethal tool to reduce predation. Profitability of this management decision depends critically upon site-specific factors that will determine the potential efficacy of protection. As pressure to reduce or eliminate forms of lethal control increase, ranchers need to make use of all tools available to remain economically sustainable. Yet, our results suggested that LGDs will not increase profitability on all operations and should be carefully considered on a case-by-case basis.

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