Risk assessment and management of brucellosis in the southern greater Yellowstone area (II):
Cost-benefit analysis of reducing elk brucellosis prevalence

Boroff, Kari¹, Mandy Kauffman², Dannele Peck^{3*}, Eric Maichak⁴, Brandon Scurlock⁴, and Brant Schumaker⁵

*Corresponding author: Tel: +01 307 766 6412. Fax: +01 307 766 5544.

Email: dpeck@uwyo.edu

¹Former Graduate Student, Department of Agricultural and Applied Economics, University of Wyoming, 1000 E. University Avenue, Laramie, WY, 82071.

²Western EcoSystems Technology, Inc., 200 South 2nd Street, Laramie, WY, 82071.

³Department of Agricultural and Applied Economics, University of Wyoming, 1000 E. University Avenue, Laramie, WY, 82071.

⁴Wyoming Game and Fish Department, 432 Mill Street, Pinedale, WY 82941.

⁵Department of Veterinary Sciences, University of Wyoming, 1174 Snowy Range Road, Laramie, WY, 82070.

Abstract

Recent cases of bovine brucellosis (*Brucella abortus*) in cattle (*Bos taurus*) and domestic bison (*Bison bison*) of the southern Greater Yellowstone Area (SGYA) have been traced back to free-ranging elk (*Cervus elaphus*). Several management activities have been implemented to reduce brucellosis seroprevalence in elk, including test-and-slaughter, low-density feeding at elk winter feedgrounds, and elk vaccination. It is unclear which of these activities are most cost-effective at reducing the risk of elk transmitting brucellosis to cattle. In a companion paper, a stochastic risk model was used to translate a reduction in elk seroprevalence to a reduction in the risk of transmission to cattle. Here, we use those results to estimate the expected economic benefits and costs of reducing seroprevalence in elk using three different management activities: vaccination of elk with *Brucella* strain 19 (S19), low-density feeding of elk, and elk test-and-slaughter. Results indicate that the three elk management activities yield negative expected net benefits, ranging from -\$2,983 per year for low-density feeding to -\$595,471 per year for test-and-slaughter. Society's risk preferences will determine whether strategies that generate small negative net benefit, such as low-density feeding, are worth implementing. However, activities with large negative net benefits, such as test-and-slaughter and S19 vaccination, are unlikely to be economically worthwhile. Given uncertainty about various model parameters, we identify some circumstances in which individual management activities might generate positive expected net benefit.

Keywords

Brucella abortus, cattle, economics, test-and-slaughter, strain 19 vaccination, low-density feeding

Abbreviations

WGFD = Wyoming Game and Fish Department

PHU = Pinedale Herd Unit

JCR = Job Completion Reports

NASS = National Agricultural Statistics Survey

Introduction

Bovine brucellosis, caused by the bacteria *Brucella abortus*, is prevalent in the greater Yellowstone area (GYA), where it can be found in free-ranging elk (*Cervus elaphus*) and bison (*Bison bison*). The disease persists in these two wildlife species despite ongoing efforts by state and federal agencies and the livestock industry to eradicate it. Although brucellosis does not threaten wildlife population-levels (Maichak et al., 2009; Cross et al., 2010), cattle (*Bos taurus*) and domestic bison do occasionally contract it from free-ranging elk and bison. This triggers quarantine, testing, and culling of infected domestic herds, which is costly to agencies and affected producers (Schumaker et al., 2012; Wilson, 2011).

Brucellosis is transmitted to susceptible individuals through aborted fetuses, placental membranes or fluids, and other vaginal discharges from an infected animal that has aborted or calved (Cook et al, 2002; Maichak et al., 2009). Transmission in the GYA is thought to occur between mid-winter and early summer, specifically between February and June (Shumaker et al., 2012). If infected free-ranging elk or bison abort on private land where domestic cattle or bison over-winter, or on public land where domestic cattle graze in the spring or early summer, transmission of brucellosis to domestic herds may occur. Our analysis focuses on transmission from free-ranging elk to domestic cattle on private or public lands.

Elk winter-feedgrounds play an important role in brucellosis dynamics within the southern GYA. The Wyoming Game and Fish Department (WGFD) operates 22 elk winter-feedgrounds in Teton, Sublette and Lincoln counties, in addition to the U.S. Fish and Wildlife Service's National Elk Refuge. These 23 feedgrounds increase elk survival through the winter, and reduce commingling of elk and cattle on private land (Dean et al., 2004). A large proportion of elk in the region spend November through March on these feedgrounds, a period that overlaps

with high-risk months for brucellosis-caused abortions (Dean et al., 2004). Because elk are concentrated on feedgrounds when these abortions tend to occur, brucellosis transmission and prevalence in elk herds are intensified (Scurlock and Edwards, 2010).

WGFD uses a number of elk management practices to try to reduce brucellosis prevalence and transmission. Some programs try to prevent cattle and elk from commingling, while others focus on reducing intra-specific disease transmission and resulting seroprevalence levels (as a marker of prevalence) in elk (WGFD, 2011). Here, we focus on three WGFD activities that aim to reduce seroprevalence in elk: 1) vaccinating elk with *Brucella* strain 19 (S19); 2) low-density feeding on elk winter-feedgrounds; 3) a pilot Test-and-Slaughter program in which feedground elk were bled and tested for brucellosis antibodies, and seropositive animals were lethally removed from the population (Scurlock et al., 2010; WGFD, 2011).

Wildlife managers, including those with WGFD, are often constrained by limited funds, as well as limited labor, equipment, and supplies. To maximize society's net benefit from these scarce resources, wildlife managers should weigh the relative social benefits and social costs of alternative management activities. Here, we approximate the social benefits and costs of three elk brucellosis management activities, with the goal of helping WGFD determine whether any of the activities generate positive net benefit. Benefits from the elk management activities take the form of reduced seroprevalence in elk, and hence a potential reduction in the risk of brucellosis transmission from elk to cattle. WGFD has monitored brucellosis seroprevalence in elk for nearly 30 years, including periods in which one or more of the elk management activities were implemented. Despite thousands of blood samples, we still lack conclusive evidence about the extent to which each management activity reduces seroprevalence. Similarly, costs have not been consistently documented for all three activities (Scurlock et al., 2010).

We address these information gaps by approximating the social economic cost of each management activity, including cash and non-cash costs incurred by WGFD and other public agencies, but not non-market costs (such as concerns about animal welfare or reduced wildlife viewing opportunities). Then we use the epidemiological results of a companion paper (Kauffman et al., 2016) to approximate the social economic benefit of each activity, including cash and non-cash benefits to cattle producers and animal health agencies, but not non-market benefits (such as reduced stress on ranch families from lower risks of a herd quarantine). Lastly, we identify some circumstances in which the three individual management activities are expected to generate positive net benefit. These insights will help WGFD and other wildlife agencies in the GYA narrow the list of potential management activities to those that are most likely to generate enough expected benefits to outweigh their cost of implementation.

Methods

Brucellosis risk model

Assessment of brucellosis risk both before and after a management activity is implemented is essential for understanding that activity's benefit. In a companion paper, Kauffman et al. (2016) presents a spatial risk model for the seasonal overlap of elk and cattle in the SGYA. This model estimates the risk of transmission from elk to cattle, which is reported as the expected number of years until the next spillover event occurs within a given elk herd-unit.

In the present paper, we apply the risk model from Kauffman et al. (2016) to simulate our three elk management strategies. We achieve this by changing seroprevalence and other parameter values assumed in the model, and then calculating the resulting change in expected number of years until a spillover event occurs. To calculate the change in expected years until spillover, we need to know each activity's effectiveness. But this information is not known with

certainty. So a range of possible changes in seroprevalence were analyzed, including reductions of 1%, 5%, 10%, and 13% from the assumed starting seroprevalence of 18% (i.e., from 18% to 17%, 13%, 8%, and 5%, respectively). Our largest seroprevalence reduction, from 18% to 5%, is based on the lowest seroprevalence achieved at an elk feedground, following several years of an experimental test-and-slaughter program. Seroprevalence may have been reduced further had the program continued; however, it was discontinued after the agreed-upon duration of five years. We therefore assume a maximum possible effectiveness of 13% (in a single year) for test-and-slaughter, as well as strain 19 vaccination, and low-density feeding.

The effect of elk test-and-slaughter on the risk of brucellosis transmission to cattle was modeled by removing enough females from the feedground to achieve the target change in seroprevalence. Proportion of females in the elk population was also reduced, such that fewer potentially-infected elk overlapped with cattle in the model. Test-and-slaughter was assumed to occur on three elk feedgrounds in the model (Table 1), to reflect how the pilot program was actually implemented. To model vaccination of elk with S19, seroprevalence was reduced, but the number of animals in the elk herd unit remained the same. Lastly, low-density feeding was modeled by reducing seroprevalence at just two of the three feedgrounds in the Pinedale elk herd unit (Table 1), the only locations where low-density feeding is technically feasible.

For each management activity and effectiveness scenario, we re-evaluate the risk model under the new set of conditions to generate a new estimate of expected years until the next spillover occurs. This new estimate is then compared to the original number of years (as reported in our companion paper). Table 2 reports expected number of years until next cattle infection (i.e., predicted outbreak frequency) for each management activity under initial versus reduced seroprevalence levels (i.e., before and after a single elk management activity is implemented).

Note that we do not attempt to model combinations of multiple elk management activities, due to insufficient experimental or empirical data.

Economic benefit of reducing seroprevalence

The benefit of reducing elk seroprevalence is a decrease in the number of transmissions to cattle over a given time period, or equivalently, an increase in the number of years until the next spillover is expected to occur. This should give individual cattle producers more time to accumulate the funds that will be needed to cover the cost of an eventual outbreak in their herd. Because a producer can spread the cost of an outbreak over more years, the annualized cost of an outbreak is lower. This lower annual cost represents the benefit of reducing elk seroprevalence. More specifically, the annual expected-benefit (EB) is calculated as follows (equation 1).

$$EB = \frac{\text{Cost of Cattle Herd Becoming Infected}}{\text{Years Until Next Infection w/Current Elk Seroprev}} - \frac{\text{Cost of Cattle Herd Becoming Infected}}{\text{Years Until Next Infection w/↓Elk Sero}} \quad (1)$$

Equation 1's numerator—the cost of a cattle herd contracting brucellosis—is based on Wilson (2011), who estimated the cost of a hypothetical cattle outbreak that involves just one infected herd, containing 400 bred cattle, 80 replacement yearling heifers, 23 bulls, and 280 yearling steers and heifers. Though herd sizes vary throughout the region, our assumption is consistent with the typical herd size reported in two separate surveys (J. Hewlett, unpublished data; D. Peck, unpublished data). Wilson (2011) assumes the infected herd is detected on January 1st and tests out of quarantine in twelve months at a total cost of \$143,013 (using prices from the year 2010). We adjust this estimate to \$146,299 to account for a regulatory change in the age at which reproductively-intact animals become test-eligible, from 12 months to 6 months. More specifically, we add costs for three rounds of brucellosis testing for 180 heifer calves that, under new regulations, become test-eligible during the quarantine period. Our revised estimate of the

total cost of a cattle case includes the producer's private costs of feeding and caring for their quarantined herd, plus testing costs for all eligible animals (incurred primarily by state or federal animal health agencies), and spaying costs for yearling heifers (incurred in part by agencies). Quarantine costs will, in reality, depend greatly on the timing and duration of a quarantine, the price and quantity of additional hay needed, the affected herd's size, and the number and value of animals culled. These sources of variability should be considered when adapting our results to new outbreak scenarios.

Not included in the estimate above are the costs to test and quarantine any contact herds (i.e., herds that have interacted with the infected herd). This is due to the unpredictable and highly variable nature of contact herd costs, depending on the number of contact herds involved, the size of those herds, and their quarantine duration. For example, the cost of quarantine for a single contact herd is estimated to be \$2,235 for a standard 30-day quarantine, but may be as high as \$49,054 for a six-month quarantine (Wilson, 2011). Some cattle outbreaks might involve no contact herds, while others could involve a dozen or more. For simplicity, we choose to exclude the costs associated with contact herds. This comes at the risk of underestimating total cost of an outbreak in cattle, and thus underestimating the benefit of elk management activities that might delay the next spillover event. To mitigate this risk, we calculate a "breakeven outbreak cost" for each elk management activity; that is, the cost of an outbreak that results in the economic benefit of an activity being just equal to its implementation cost. This breakeven cost could be associated with outbreaks of various forms, e.g., a larger herd with few contact herds, or a smaller herd with several contact herds.

Equation 1's denominators—years until the next cattle infection under current versus reduced elk seroprevalence—are estimated using the spatial risk model described in our

companion paper. Current seroprevalence levels on all elk feedgrounds in Wyoming are estimated, on average, to be 18% (Scurlock and Edwards, 2010), which our risk model predicts will cause one cattle outbreak every 18.08 years (the median). If we assume there is an equal probability each year of this outbreak occurring, the expected annual cost of an outbreak equals $\$146,229/18.08$, or \$8092. In essence, if a producer (or society) were to set aside \$8092 each year for 18.08 years, they will accumulate just enough money to pay for one case of brucellosis in a 400-head cattle herd. Note that in this example, we make the simplifying assumption of a 0% interest rate (or discount rate). In our actual calculations, we assume a 2.08% interest rate.

For demonstrative purposes, imagine an elk management activity increases the number of years until the next cattle outbreak, from 18.08 to 20.08 years. Then the cost of the outbreak can be spread over two additional years, which reduces the expected annual cost of brucellosis from \$8092 to \$7286 (i.e., $\$146,299/20.08$). The activity's benefit is thus calculated as the difference between the expected annual cost imposed by the disease before (\$8092) versus after (\$7286) the management activity has been implemented. Expected benefit (EB) is thus the amount of money saved each year, \$806 in this example, due to reduced cattle risk resulting from reduced elk seroprevalence.

Expected benefit of a management activity should then be compared to the costs of implementing it. A reliable way to compare them is to calculate expected *net* benefit, which is simply the activity's annual expected benefit minus its annual cost. Three elk seroprevalence reduction activities and their associated costs are explained next. Detailed budgets for each activity are provided in a supplementary appendix.

Economic cost of elk management activities

For each elk management activity, we develop an enterprise budget to describe the quantity and cost of inputs required. Some of the activities can be implemented in different ways, in which case we provide multiple cost estimates. Management activity descriptions and technical specifications are based largely on information provided by WGFD personnel and feedground managers, though citations are provided for all sources. Prices for inputs were obtained from online and local retailers, as detailed in each activity's budget. All prices are adjusted to the same year, 2010, using producer price indices from the 2010 and 2011 Wyoming Agricultural Statistics yearbooks. By adjusting all prices to US\$2010, our cost estimates for elk management activities can be compared to cost estimates for cattle management activities as reported in Roberts et al. (2012) and Ruff et al. (2016).

All three elk management activities involve a one-time purchase of at least some inputs that are used over multiple years. These upfront input costs need to be annualized—spread over the lifespan of the purchased item—using the following formula (equation 2).

$$R = \frac{V_0 * i}{[1 - (1+i)^{-n}]}, \quad (2)$$

V_0 is the value of the item at time of purchase, i is the discount rate (0.0208, or 2.08%), and n is the item's useful life-span. The discount rate represents the price of borrowing money, which is based on bank-reported interest rates. A rate of 2.08% was chosen—the five-year CD rate in 2010—to be consistent with Roberts et al (2012) and Wilson (2011).

Low-Density Feeding

Under the traditional method of feeding free-range elk during the winter, hay is spread in a continuous line across the feedground. Low-density feeding, in contrast, places hay in multiple

piles, dispersed along multiple rows of feed lines that are adjacent to each other. This feeding pattern significantly reduces contact between elk and elk fetuses, and is thought to reduce elk-to-elk transmission by up to 67% (Maichak et al., 2009; Creech et al., 2012).

Low-density feeding requires more space, though, than traditional feeding. Each feedground's physical space and topography are unique; therefore, not every feedground is amenable to low-density feeding. Feeding is traditionally done using a team of horses that pull a sleigh, with the guidance of a person who typically feeds by themselves, under contract with WGFD. Low-density feeding may require another person to be hired, particularly if a calm and experienced horse team is unavailable (WGFD, unpublished data). Under the best circumstances, when space to feed is ample, terrain is accessible, and horses are performing well with little direction from the feeder, low-density feeding may only require more of the feeder's time.

On most feedgrounds, elk are fed seven days a week from late November to mid-April (WGFD 2004). In recent years, WGFD has paid feeders \$36 per day for their labor to feed up to two tons of hay. If hay fed exceeds two tons per day, feeders are paid an extra \$5 per ton fed. When hay tonnage is averaged across years and feedgrounds, the average amount fed is less than two tons, although feeding more than two tons is not uncommon. Using historical data on hay tonnage, elk fed, and labor costs, we calculate average feeding cost per year for each feedground. Note that WGFD is currently redesigning contracts with feeders to move away from tonnage-based pay (WGFD, unpublished data).

Although feeders are not paid on a per hour basis, and are not paid extra for low-density feeding (WGFD, unpublished data), the extra time they spend feeding represents a cost to society because that labor could otherwise be allocated to the next most-valuable use. To understand the value of extra time spent feeding, we estimate the per hour wage of feeders. WGFD estimates

that it takes two hours to feed 500 elk using the traditional method, with an extra hour (an additional 50% of time for traditional) required for low-density feeding. The 10-year average for the number of elk fed in the Pinedale herd unit is 575. Proportionally, traditional feeding of 575 elk should take 2.3 hours, and low-density feeding should take 3.5 hours. Given the feeding time assumptions described above, feeders would receive \$11.94 per hour for traditional feeding. We therefore assume \$11.94 is the appropriate hourly wage to use when calculating additional labor costs for low-density feeding.

Assuming a feeder traditionally uses two horses and a sleigh, directed only with their own labor, the least-expensive approach to low-density feeding is simply to take more of the existing feeder's time. Under this simplest and cheapest method (assuming it is feasible at a given feedground without first having to pack down deep snow with a Snowcat), no other costs in the elk-feeding budget are affected by switching to low-density. For example, we do not consider the cost of hay fed to elk because these costs do not change under traditional versus low-density feeding (WGFD, unpublished data).

A summary of costs associated with low-density feeding can be found in Table 3. Detailed descriptions of all components of the elk winter-feeding budget, under traditional versus low-density methods, can be found in the supplementary appendix. The cost of traditional versus low-density feeding under alternative assumptions, such as feeding with a tractor and Snowcat, are also provided and explained in the appendix.

Strain 19 Vaccination

In 1985, WGFD began vaccinating elk at the Greys River feedground with strain 19 delivered remotely via biobullets (Dean et al., 2004). The program expanded to twenty other

feedgrounds by 1997, excluding Dell Creek feedground, which served as a control to test vaccine efficacy. Elk on all other feedgrounds were vaccinated annually in January and February of each year, using air-powered rifles fired from hay sleds. All elk on a given feedground were targeted during the first year or two of the vaccination program, with a coverage rate of between 80 and 100%. Thereafter, only juveniles were targeted (WGFD, unpublished data). The vaccination program was discontinued in 2015, however, because the manufacturer of biobullets ceased production. WGFD had an opportunity to purchase the rights to the biobullet technology, but has thus far declined to do so, in part because of the low efficacy of strain 19 in elk.

Strain 19 prevents abortion in approximately 20% of vaccinated elk, but does not provide protection against brucellosis infection (Roffe et al., 2004). Theoretically, fewer abortions should reduce the number of infected elk fetuses on the feedground, and hence the probability of elk being exposed to the bacteria. However, a growing body of evidence suggests it has little impact on herd-level seroprevalence (Dean et al., 2004; Roffe et al., 2004; Olsen et al., 2006).

An activity with low effectiveness should not automatically be dismissed; after all, if its cost is also low, it may actually generate positive net benefit. We therefore proceed to estimate the cost of vaccinating elk with strain 19, using information from WGFD documents about the number of elk vaccinated each year, as well as the quantity and cost of vaccine, equipment, and labor. With regards to labor, WGFD employees spent time organizing vaccination efforts as well as training and assisting feeders, who were paid extra to administer the vaccine (WGFD, unpublished data). Cost of the strain 19 vaccine itself was provided by the National Vet Services Lab in Ames, Iowa (S. Carter, personal communication).

Job completion reports (JCRs) from WGFD provide the total number of vaccines given to juveniles and adult females at each feedground during each year of the vaccine program. Total vaccinations given, divided by the number of years vaccination occurred, provides an average number of elk vaccinated at each feedground per year. Recent JCRs do not report vaccination numbers for the Pinedale Herd Unit (PHU), though, because vaccination was stopped after 2004, in preparation for the test-and-slaughter program. For these feedgrounds, Dean et al. (2004) provides the total number of vaccinations given at each feedground since the start of the program. Based on feedground populations, and 90% coverage of adult female elk, we estimate yearly PHU vaccine requirements of 770. In comparison, we estimate 2,144 vaccines would be necessary each year to vaccinate at all feedgrounds in the Pinedale region.

To calculate costs, we first distinguish between two different levels of geographic analysis: (1) all feedgrounds in the Pinedale region, and (2) only Muddy, Scab and Fall Creek feedgrounds within the PHU (see Kauffman et al., 2016, for a map of the PHU). Cost for the three PHU feedgrounds was calculated separately from the greater Pinedale region to enable later comparisons with test-and-slaughter and other management strategies occurring exclusively in the PHU. Furthermore, vaccination costs in the PHU may differ from other herd units because the regional office in Pinedale is closer to the PHU, which reduces travel costs.

Regarding labor costs, three WGFD employees spent 17 to 18 days vaccinating each year, and three to four days preparing and organizing materials and equipment for vaccination (WGFD, unpublished data). Wildlife biologist wages are obtained from the Bureau of Labor Statistics (2010). The cost of elk feeders' additional time, while helping administer the vaccine, is not compensated per hour, but instead per elk they vaccinate (WGFD, unpublished data).

To estimate WGFD transportation costs, mileage from the Pinedale Field Office to each feedground was found using Google Earth. Total, average, and median distances were calculated for both PHU and regional feedgrounds. We do not include transportation costs for elk feeders because they vaccinate in conjunction with feeding; therefore, vaccination does not require any additional miles of travel for them.

The strain 19 vaccine itself is delivered in the form of a biobullet, a small capsule of hydroxypropyl cellulose that contains the vaccine. Fired from air-powered rifles from a range of up to 40 meters, they dissolve in the targeted muscle over time, subsequently releasing the vaccine. Including clip-related costs, vaccine production cost (in 2010 dollars) is estimated to be \$5.14 per biobullet (S. Carter, personal communication).

The ballistic system used to deliver the vaccine to elk consists of a CO₂ rifle, hose regulator, air tank, backpack, and gun sleeve. WGFD currently has 21 ballistic systems in working condition, roughly one per feedground (WGFD, unpublished data). The purchase price of one of these ballistic systems is \$1950 (M. Straka, personal communication). However, it lasts 15 to 20 years (M. Straka and S.A. Shwiff, personal communication), so its annualized purchase price is \$104 per system per year. All costs associated with the strain 19 vaccination program are summarized in Table 4.

Test-and-Slaughter

Test-and-slaughter was a five-year pilot program conducted on three feedgrounds (Muddy Creek, Scab Creek, and Fall Creek) within the PHU. The program required WGFD to construct a large elk trap at each of the participating feedgrounds. Elk were lured into the trap with hay, then antlerless individuals were funneled into squeeze-chutes, where a blood-sample was drawn, a metal ear tag with unique identification number was attached, and a visibility-collar

with a unique identifier was slipped on. Elk were returned to the trap and held overnight until the results of a blood test for antibodies to brucellosis were revealed. Seropositive elk were then sorted from the herd, loaded into trailers, and sent to a slaughter facility in Idaho (Scurlock et al., 2010).

Test-and-slaughter costs include: 1) trap construction, 2) snow removal so feedgrounds are accessible to vehicles and trailers, 3) personnel travel to Pinedale, 4) travel from Pinedale to the feedgrounds, 5) transportation of blood samples to Laramie and costs for overnight testing, 6) hauling elk to slaughter and delivering meat to participating charities, 7) all equipment and vehicle usage, 8) fuel costs, and 9) personnel labor. WGFD kept detailed records of many of these project-specific costs, and also recorded the number of elk tested and removed from each feedground each year.

The cost to construct a single elk-trap is \$100,010 (US\$2010), but that trap should last 15 years (WGFD, unpublished data). Because this represents a multi-year cost, we annualized it using equation 2. Test-and-slaughter also requires extensive snow and ice removal, both from the traps and from roads into the target feedgrounds to allow a truck and trailer to remove seropositive elk for slaughter (Scurlock et al., 2010). WGFD's records did not include information about road plowing costs because Sublette County provided this service free of charge. Although WGFD was not charged for this service (i.e., it was not a cash cost), valuable resources were used (e.g., fuel, wear-and-tear on equipment, and a driver's time), and are therefore included in our cost estimate for test-and-slaughter. Based on machinery use rates and distances traveled, we estimate a per-trapping cost of \$225 to plow Fall Creek feedground, \$333 to plow to Scab Creek feedground, and \$150 to plow to Muddy Creek feedground.

During the five-year pilot project, test-and-slaughter occurred in all five years at Muddy Creek, but only in two years at Fall Creek and Scab Creek. Therefore, in 2009, test-and-slaughter occurred at three feedgrounds; in 2008 and 2010, it occurred at two; and in 2006 and 2007, it occurred at only one. Due to differences in the number of feedgrounds trapped per year, we report most costs on a per-feedground basis. This makes sense for most expenses, such as labor, lab costs, vehicle use, meat processing, and fuel for travel. But this results in multiple budgets, depending on whether two or three feedgrounds are trapped per year (Table 5). Each test-and-slaughter budget accounts for annual depreciation and maintenance of all three traps, regardless of whether every feedground is trapped every year. Other costs, however, increase as the number of feedgrounds trapped increases (e.g., labor, lab work, fuel). Detailed cost estimates are provided in the supplementary appendix.

Economic net benefit

Having described methods for estimating each activity's benefits and costs, we calculate next the relative economic performance of our three elk management activities—measured in terms of expected net benefit (i.e., expected annual benefit minus annual cost). An alternative measure is a benefit-cost ratio, which is a popular way to compare projects, and can be easily calculated for projects of the same size (i.e., with similar total costs). However, benefit-cost ratios for projects of different sizes may provide misleading relative-rankings (Workman, 1986). Expected net benefit is a less error-prone measure when the cost of activities vary widely, as they do for the elk management activities analyzed here.

Breakeven cost of a cattle outbreak

The scope of a brucellosis outbreak among cattle varies depending on the index herd's size, the number and size of contact herds involved, the duration of quarantines, whether

quarantine-eligible pastures are available, and whether hay prices are high or low. Given these sources of variability, an alternative way to frame our economic question is to determine how costly a cattle outbreak would have to be for an elk management activity (assuming some fixed level of effectiveness) to just break-even. We calculate this “breakeven outbreak cost” by setting the expected annual benefit (EB) of an activity just equal to its expected annual cost (EC), as shown in equation 3.

$$EB \equiv \frac{C_{outbreak}}{\text{median years to cattle case (current)}} - \frac{C_{outbreak}}{\text{median years to cattle case (activity)}} = EC \quad (3)$$

By solving for $C_{outbreak}$, we get equation 4, which identifies the minimum outbreak cost required for the expected benefit of an activity to just equal its expected cost.

$$C_{outbreak} = \frac{EC}{\frac{1}{Y_c} - \frac{1}{Y_A}} \quad (4)$$

Y_c = median years to cattle case under current elk seroprevalence, and Y_A = median years to a cattle case under reduced elk seroprevalence due to the management activity.

Breakeven number of years until next cattle outbreak

Given uncertainty about each management activity’s effectiveness, additional insights may be gained by calculating the number of years each activity would have to delay the next cattle outbreak for that activity to break-even economically. Using equation 5, we solve for the median “breakeven number of years” until the next outbreak under a management activity (Y_A) assuming a cattle outbreak costs \$146,299.

$$Y_A = \frac{-\$146,299}{EC - \left(\frac{\$146,299}{Y_c}\right)} \quad (5)$$

Results and Discussion

Economic net benefit of elk management activities

Expected annual benefits and costs of the three elk management activities are presented in Tables 6 and 7, respectively; expected net benefits are presented in Table 8. Expected net benefit is negative for each of the three elk management activities at all levels of effectiveness (seroprevalence reduction) considered and across all measures of variability from the spatial risk model (median, 5% confidence interval, 95% confidence interval).

Among the three modeled elk management activities, test-and-slaughter has the highest expected annual benefit, but it also has the highest annual cost. In sum, its annual cost far exceeds its expected annual benefit. Low-density feeding is the least-expensive strategy considered, and is thought to be effective at reducing the number of elk that contact aborted fetuses (Maichak et al., 2009). Yet even at the highest levels of potential effectiveness modeled (reducing seroprevalence from 18% to 5%), expected net benefit of low-density feeding is approximately -\$1,500 per year per herd unit. Similarly, strain 19 vaccination generates a net benefit of approximately -\$3,000 per year per herd-unit.

Despite negative expected net benefit for all three elk management activities, they should not be dismissed without also considering the risk preferences of wildlife managers, or more appropriately, the public they serve. If wildlife managers adopt a risk-neutral attitude, only the mean outcome (i.e., expected outcome) of elk seroprevalence reduction matters. In such case, they should discontinue all three elk management activities because the expected outcome is

negative net benefit (i.e., a net loss). They would be better-off, on average, not implementing any of the management activities. In contrast, if wildlife managers adopt a risk-averse attitude (i.e., they are willing to pay more than the expected annual cost of a brucellosis outbreak to reduce the risk of such an outbreak occurring), the three elk management activities may deserve further consideration, particularly those with an expected net benefit close to being positive (e.g., low-density feeding).

There are at least three legitimate reasons wildlife managers might consider adopting a risk-averse attitude, and therefore consider implementing one or more of the management activities, despite their negative net benefit. First, our analysis does not consider the indirect economic impacts that a case of brucellosis in cattle might cause. For example, a rural community's ranch-supplies store might lose business if a ranch undergoing a protracted quarantine goes bankrupt and is subsequently sold into development or to someone who does not contribute as much to the local economy.

Second, our analysis does not consider the risk of brucellosis expanding geographically if elk seroprevalence is not actively managed. Such an expansion could force state veterinarians in affected states to widen the boundaries of their Designated Surveillance Areas, or face additional inter-state trade restrictions, both of which would impose additional costs on cattle producers. For example, in 2012, the WGFD detected brucellosis exposure in hunter-killed elk serum samples in Wyoming Elk Hunt Area 40 in Big Horn County, outside of the current Wyoming Designated Surveillance Area boundary (WGFD, 2016). In response to this finding, the states of Montana, North Dakota and South Dakota have required (as of August, 2016) an additional import-test for all cattle originating from Big Horn County (WLSB, 2016). At this time, the connection between elk exposure to brucellosis in Big Horn County and seroprevalence of elk on

feedgrounds in Teton, Sublette and Lincoln counties is still being investigated. Genomic evidence suggests that elk dispersing from the National Elk Refuge are likely responsible for spreading the disease eastward (Kamath et al., 2016). Future research should therefore determine the extent to which reductions in seroprevalence among feedground elk could slow the diffusion rate of brucellosis. If the three management activities we analyzed here could slow diffusion, our benefits estimates would need to be revised upward. Until this information becomes available, our current estimates indicate how large these additional benefits would need to be for the individual activities' expected net benefit to become positive.

Third, by undertaking one or more of these elk seroprevalence reduction activities, WGFD may be able to engender goodwill (i.e., sociopolitical capital) amongst cattle producers. If producers feel WGFD is doing its part to manage brucellosis, they may be more willing to take on additional cattle management activities for brucellosis risk reduction. Goodwill may also generate benefits outside the realm of brucellosis, such as additional habitat improvement projects on private land, which benefit a variety of wildlife species and hence the general public.

Breakeven cost of a cattle outbreak

In light of several sources of variability and uncertainty underlying our analysis, we feel compelled to check the robustness of our main conclusion—that all three elk management activities generate negative expected net benefit—under more extreme economic and epidemiologic conditions.

First, we calculate the cost of a cattle outbreak necessary for each activity's expected benefit to just equal its expected cost (Table 9). This “breakeven cost of a cattle outbreak” addresses the concern that we may have underestimated the true cost of a cattle outbreak. To

favor the activities as much as possible in this part of analysis, we also assume they achieve the maximum potential effectiveness considered in our study (i.e., reducing seroprevalence from 18% to 5%). This favorable assumption reduces the breakeven cost of a cattle outbreak even further. The question then is whether this conservative breakeven cost of a cattle outbreak could realistically be observed during an actual outbreak. If so, then the elk management activity may in fact have the potential to generate enough expected benefits to outweigh its costs (assuming it is actually effective enough to reduce seroprevalence from 18% to 5%).

For low-density feeding to break-even, it would need to be highly effective (reducing 18% seroprevalence to 5%) and a cattle outbreak would need to cost a minimum of \$224,431 (median). Recall that our original cost estimate for a cattle outbreak is \$146,299. If a wildlife manager believes that a cattle outbreak could be \$78,132 (53%) more expensive than our original estimate, and that low-density feeding could indeed be this effective, then they may believe that low-density feeding could break even. For strain 19 vaccination, assuming it were highly effective (reducing 18% seroprevalence to 5%), a cattle outbreak would have to cost \$263,215 for the vaccine to break even. Finally, for test-and-slaughter, assuming it were effective enough to reduce seroprevalence from 18% to 5%, a cattle outbreak would have to cost \$15.5 million for its expected annual benefit to outweigh its annual cost.

It is reasonable that believe that a cattle outbreak could rise in cost from our original estimate of \$146,299 to the breakeven levels of \$224,431 or \$263,215. A quarantined cattle herd need only be 1.5 to 1.8 times larger than the herd we originally assumed. Alternatively, the length of quarantine could be longer, or the price of hay higher. Therefore, it may be possible for low-density feeding and strain 19 vaccination to generate positive expected net benefit. It is less clear, however, whether they are effective enough in reality to reduce seroprevalence from 18%

to 5%, in which case the cost of a cattle outbreak would have to be even larger to justify implementation. It is more difficult to imagine the cost of a cattle outbreak rising to several million dollars, as is needed for test-and-slaughter to break even, even if it were capable of reducing seroprevalence from 18% to 5% in a single year.

Breakeven number of years until next cattle outbreak

To address any concern that we may have systematically underestimated the ability of elk management activities to delay the next cattle outbreak (i.e., the activities' epidemiological benefit for cattle producers), we calculate the size of delay that would be necessary for an activity's expected annual benefit to just offset its annual cost (assuming an outbreak cost of \$146,299) (Table 10).

Low-density feeding requires an increase in the “number of years until the next cattle outbreak” from the current median of 18.08 years (Y_C) to a post-activity median of 37 years (Y_A) to achieve an expected net benefit of zero. Recall from Table 2 that, under the highest level of effectiveness analyzed (reducing seroprevalence from 18% to 5%), low-density feeding increased the years to next cattle outbreak from a median of 18.08 to 27.18. To break even, it would need to increase the latter number from 27.18 to 37 years. For strain 19 vaccination to break even, it would need to increase the years to next cattle outbreak from a median of 18.08 to a median of 114 years. Our most generous estimate for strain 19 vaccination, assuming it was highly effective (reducing seroprevalence from 18% to 5%), was an increase in years to 33.56. It is difficult to imagine strain 19 vaccination being effective enough to increase this even further to 114 years, and thereby break even.

No breakeven value could be calculated for test-and-slaughter because the annual cost of implementation, \$601,164, exceeds the maximum possible expected annual benefit of \$8092

(\$146,299/18.08). That is to say, under current elk seroprevalence levels, the expected annual cost of brucellosis is \$8092 (assuming one cattle herd is infected every 18.08 years), so the best an activity can do is eliminate this expected annual cost by preventing brucellosis entirely (i.e., stretching the years until the next cattle case from 18.08 to infinity). If test-and-slaughter were capable of achieving an infinite delay, the expected annual benefit (\$8092) is still outweighed by the annual cost of implementation (\$601,164).

The previous statement assumes that annual implementation of test-and-slaughter would be necessary to ensure the infinite delay of the next cattle case. It is unclear whether this would be necessary in reality. The test-and-slaughter pilot program ended in 2013, per the agreed-upon five-year timeframe; seroprevalence has since rebounded to pre-program levels. Had the program continued, seroprevalence theoretically could have been driven to zero on target feedgrounds.

If brucellosis were eradicated from target feedgrounds, brucellosis management costs would theoretically decrease to zero (although monitoring costs would likely continue for several years), and the benefits of brucellosis management would continue far into the future. Based on management challenges encountered in recent decades, however, this scenario seems infeasible. For example, unless test-and-slaughter were expanded to all 22 state feedgrounds, plus the National Elk Refuge and Yellowstone National Park, brucellosis would likely be reintroduced to “clean” herds from neighboring herds that were not subject to test-and-slaughter.

Additional modeling is needed to explore the possibility of achieving eradication (at least locally) through test-and-slaughter. In the meantime, our annual analysis suggests that even the highest level of effectiveness (delaying a cattle outbreak into infinity) would be insufficient for test-and-slaughter to be economically worthwhile.

In case any doubts still linger, we go one step further to consider the extreme circumstances (in multiple dimensions of the problem) necessary for test-and-slaughter to generate enough expected annual benefit to equal (or outweigh) its annual cost. We begin by assuming that a cattle outbreak occurs in the PHU *every* year, rather than every 18.08 years. Given this hypothetically high Y_C , an outbreak would have to cost \$601,164 (median), rather than \$146,299, for the expected annual benefit of test-and-slaughter to outweigh its annual expected cost. Even then, test-and-slaughter would have to completely eliminate the risk of a cattle outbreak during that year to just break even.

The breakeven analyses described above assume a specific return-frequency for brucellosis in cattle, a specific number of cattle herds involved in an outbreak, a specific cost of an outbreak, or a specific level of activity effectiveness. If any of these assumptions differ in reality from those assumed in our analysis, then the expected net benefit of the elk management activities will also differ. For example, if the number of infections per year increases in the future, such that Y_C decreases, then the expected annual cost of brucellosis will increase, and hence the expected net benefit of management activities will increase. Within the southern GYA, 3 cattle outbreaks have occurred in the last 24 years (as of Spring 2016), for an average sample return-frequency of 8 years (more frequent than our modeled estimate of 18.08 years). Note, however, that cases within individual herd units such as the PHU are less frequent. Similarly, suppose the number of cattle herds involved in an outbreak or per-herd cost of an outbreak increases. Then the expected annual cost of brucellosis will increase, and thereby increase the expected net benefit of management activities. Finally, if future research indicates a higher level of effectiveness for any of our elk management activities, then their expected net benefit will be larger than our reported estimates.

Limitations

Our cost estimates are based on a specific set of assumptions about the location at which management activities are implemented, and the way in which they are implemented. Costs are likely to change with location and approach. We modeled several different approaches for each activity, then chose a “most likely” approach for each, which was used in the net benefit analysis. We also calculated minimum and maximum costs. Maximum cost was roughly 55, 20 and 524 percent greater than the minimum cost for test-and-slaughter, strain 19 vaccination, and low-density feeding, respectively. Minimum cost for test-and-slaughter included County-provided plowing and implementation at two feedgrounds, while the maximum cost was based on private contract plowing and trapping at all three feedgrounds in the PHU. For the expected net benefit estimate, we assume the County plows the roads and trapping occurs at all three feedgrounds. For low-density feeding, the “most likely” cost happened to also be the minimum cost. For S19 vaccination, the “most likely” cost corresponded to the maximum cost because expected costs for the PHU were higher than for surrounding regional feedgrounds. However, even if minimum cost for S19 vaccination were used instead, net benefit would still be negative by roughly \$3000 to \$6000.

Another limitation of our analysis is that costs are based on US\$2010 prices. If real prices (i.e., nominal prices with inflation removed) change, due to shifts in market demand or supply, costs will need to be re-estimated. Some prices fluctuate more dramatically than others, such as fuel prices, and some management activities are more fuel-dependent than others. An increase in the real fuel price, holding all other costs constant, could therefore cause one management activity to suddenly become more or less attractive than another, changing the relative ranking of activities.

One final limitation of our analysis is that the expected benefits of elk management activities depend largely on the cost of a cattle outbreak. As mentioned before, our cost of a cattle outbreak is based on Wilson (2011), who assumes a hypothetical cow/calf/yearling herd with 400-head of bred cows that are quarantined for 12 months, undergo 3 rounds of testing, and results in 2 cows being culled before being released from quarantine. One limitation of this cost estimate is that Wilson (2011) does not include the potential for contact herds because the associated costs are so variable. However, these costs could be large if multiple contact herds are affected. On the other hand, some infected herds in the GYA have recently spent only 6 months in quarantine rather than 12 months, achieving release after all eligible animals tested negative after calving. This shortened quarantine period reduces outbreak costs significantly (from \$146,299 to \$53,490) because a herd can be turned out to summer pasture instead of being confined and fed hay, which is expensive. If this shortened quarantine period becomes the norm, the economic consequences of brucellosis in cattle will be lower. Consequently, the benefits of elk management activities will be lower, and their net benefit will become even more negative.

Conversely, if an outbreak were longer (e.g., if it was detected several years after initial exposure occurred, such that several cows were infected), or the affected herd is larger, or the herd is under quarantine for more than a year (or culled rather than quarantined), or hay prices are higher, or APHIS imposes statewide testing in response to an outbreak, then outbreak costs may be larger, thereby increasing the expected benefit of brucellosis management activities. This brief discussion illustrates a number of possible scenarios that may affect the expected cost of a brucellosis outbreak and hence the expected benefit of brucellosis management activities.

Conclusions

Our epidemiological and economic modeling results, along with several robustness checks, suggest that the three elk management activities of interest for reducing brucellosis seroprevalence [test-and-slaughter, strain 19 vaccination, and low-density feeding] yield negative expected net benefits, ranging from -\$1,447 per year for low-density feeding to -\$595,471 per year for test-and-slaughter. Society's risk preferences will ultimately determine whether activities with modestly negative expected net benefits are worth implementing, such as low-density feeding. However, activities with large negative annual net benefits, such as test-and-slaughter, or activities with low effectiveness relative to their implementation cost, such as S19 vaccination, are unlikely to be economically worthwhile.

If wildlife managers (or the general public they serve) decide that, despite negative expected net benefits, they wish to invest in management activities that reduce brucellosis seroprevalence in free-ranging elk, they must then decide how much to invest in each one. Our analyses provide a ranking of activities, based on their expected net benefit, but do not provide insights about the marginal benefits of doing more or less of an activity. Furthermore, our analyses do not explore the benefits of combining two or more elk management activities. Effectiveness of combining management activities is unknown at this time, but may be a useful avenue for future research.

As society debates the merit of investing in elk management activities to reduce seroprevalence, we should keep in mind that the success of brucellosis management is ultimately measured as a reduction in the number of infected cattle herds. Investment decisions should therefore also consider the relative net benefit of cattle management activities, not just elk management activities. Roberts et al. (2012) indicates that several livestock management activities may provide positive net benefits, even at low levels of effectiveness, such as hazing

elk from private cattle feedlines and fencing haystacks. In addition, adult-booster vaccination may be economically justifiable for herds that face sufficiently high risks of contracting brucellosis.

Many cattle producers have already undertaken fencing haystacks and calling WGFD to haze elk away. Adult-booster vaccination is increasingly being discussed. Other cattle management activities, such as delaying cattle grazing on summer range, hiring a rider to prevent commingling, or switching to stockers, are very expensive and therefore only economically justifiable if they are highly-effective and if the herd's background level of risk is very high (Roberts et al., 2012; Ruff et al., 2016). Additional research is needed to determine which combination of cattle and elk management activities would achieve society's brucellosis management goals at least-cost.

Acknowledgements

This work was completed under funding from Wyoming Wildlife Livestock Disease Research Partnership (WWLDRP) and USDA-APHIS-VS Cooperative Agreement #11-9756-2082-CA.

Literature Cited

- Cook, W.E., Williams, E.S., Thorne, E.T., Kreeger, T.J., Kreeger, Stout, G., Bardsley, K., Edwards, H., Schurig, G., Colby, L.A., Enright, F., Elzer, P.H. 2002. *Brucella abortus* strain RB51 vaccination in elk. I. Efficacy of reduced dosage. J. Wildl. Dis. 38(1), 18-26.
- Creech, T.G., Cross, P.C. Scurlock, B.M., Maichak, E.J., Rogerson, J.D. Henningsen, J.C., Creel, S. 2012. Effects of low-density feeding on elk-fetus contact rates on Wyoming feedgrounds. J. Wildl. Manage. 76(5), 877-886.
- Cross, P.C., Cole, E.K., Dobson, A.P., Edwards, W.H., Hamlin, K.L., Luikart, G., & White, P.J. 2010. Probable causes of increasing brucellosis in free-ranging elk of the greater Yellowstone ecosystem. Ecol. Appl. 20 (1), 278-288.
- Dean, R., Gocke, M., Holz, B., Kilpatrick, S., Kreeger, T., Scurlock, B., Smith, S., Thorne, E.T., Werbelow, S. 2004. Elk Feedgrounds in Wyoming. Wyoming Game & Fish Department Report, 26pp. Available at: https://wgfd.wyo.gov/WGFD/media/content/PDF/Wildlife/WY_ELKFEE_DGROUNDS.pdf (accessed October 26, 2015).
- Edwards, W. 2009. Iowa State University Extension: Estimating farm machinery costs. File A3-29. Available at: <http://www.extension.iastate.edu/publications/pm710.pdf> (accessed October 9, 2012).
- Kamath, P.L., Foster, J.T., Drees, K.P., Luikart, G., Quance, C., Anderson, N.J., Clarke, P.R., Cole, Eric, K., Drew, M.L., Edwards, W.H., Rhyan, J.C., Treanor, J.J., Wallen, R.L., White, P.J., Robbe-Austermann, S., Cross, P.C. 2016. Genomics reveals historic and contemporary transmission dynamics of a bacterial disease among wildlife and livestock. Nat. Comm. 7(11448), 1-10.
- Kauffman, M., Peck, D., Scurlock, B., Logan, J., Robinson, T., Cook, W., Boroff, K., Schumaker, B. 2016. Risk assessment and management of brucellosis in the southern greater Yellowstone area (I): A citizen-science based risk model for bovine brucellosis transmission from elk to cattle. Prev. Vet. Med. (In Press, same volume/issue).

- Maichak, E.J., Scurlock, B.M., Rogerson, J.D., Meadows, L.L., Barbknecht, A.E., Edward, W.H., Cross, P.C. 2009. Effects of management, behavior, and scavenging on risk of brucellosis transmission in elk of western Wyoming. *J. Wildl. Dis.* 45(2), 398-410.
- Olsen, S.C., Fach, S.J., Palmer, M.V., Sacco, R.E., Stoffregen, W.C., Waters, W.R. 2006. Immune responses of elk to initial and booster vaccinations with *Brucella abortus* Strain RB51 or 19. *Clin. Vaccin. Immunol.* 13(10), 1098-1103.
- Roberts, T.W., Peck, D.E., Ritten, J.P. 2012. Cattle producers' economic incentives for preventing bovine brucellosis under uncertainty. *Prev. Vet. Med.* 107(3-4), 187-203.
- Roffe, T.J., Jones, L.C., Coffin, K., Drew, M.L., Sweeney, S.J., Hagius, S.D., Davis, D. 2004. Efficacy of single calfhood vaccination of elk with *Brucella abortus* strain 19. *J. Wildl. Manage.* 68(4), 830-836.
- Ruff, S.P., Peck, D.E., Bastian C.T., Cook, W.E. 2016. Economics of transitioning from a cow/calf/yearling operation to a stocker operation. *J. Am. Soc. Farm Managers and Rural Appraisers* (in press).
- Schumaker, B.A., Peck, D.E., Kauffman, M.E. 2012. Brucellosis in the Greater Yellowstone area: disease management at the wildlife-livestock interface. *Hum.-Wildl. Interact.* 6(1), 48-63.
- Scurlock B.M., Edwards W.H. 2010. Status of Brucellosis in free-ranging elk and bison in the United States. *J. Wildl. Dis.* 46(2), 442-449.
- Scurlock, B.M., Edwards W.H., Cornish, T., Meadows, L. 2010. Using Test and Slaughter to reduce prevalence of brucellosis in elk attending feedgrounds in the Pinedale elk herd unit of Wyoming; results of a 5 year pilot project. Wyoming Game and Fish Department, Cheyenne, Wyoming. Available at http://www.wyomingbrucellosis.com/_pdfs/TestandSlaughterBCTreport_91510FINAL_.pdf (accessed October 26, 2015).
- United States Bureau of Labor Statistics. 2012. Occupational employment statistics, wildlife biologists. Online resource. Available at <http://www.bls.gov/oes/current/oes191023.htm> (accessed June 10, 2012).

Wilson, B.A. 2011. Regional economic impacts of bovine brucellosis under new federal regulations. Unpublished master's thesis. Department of Agricultural and Applied Economics, University of Wyoming, Laramie, Wyoming, USA.

Workman, J.P. 1986. Rangeland Economics. Macmillan Publishing Company, New York.

Wyoming Game and Fish Department (WGFD). 2011. Job completion report, Pinedale region, elk. Available at: https://wgfd.wyo.gov/WGFD/media/content/PDF/Hunting/JCRS/JCR_BG_PINE_ELK_2011.pdf (accessed October 26, 2015).

Wyoming Game and Fish Department (WGFD). 2016. 2015 Brucellosis Surveillance in Hunter-Killed Elk. Wyoming Game and Fish Department, Cheyenne, WY. Available at: <https://wgfd.wyo.gov/WGFD/media/content/PDF/Vet%20Services/2015-Hunter-killed-elk-brucellosis-report.pdf>. Accessed August 15, 2016.

Wyoming Livestock Board (WLSB). 2016. MT to require brucellosis testing on Big Horn County cattle prior to importation. Wyoming Livestock Board, Cheyenne, WY. Available at: [https://wlsb.state.wy.us/editable-page/home/downloadFile?filename=2016-06-07_MT-Import-Reqs-BH-Co-Cattle_Press-Release%20\(1\).pdf](https://wlsb.state.wy.us/editable-page/home/downloadFile?filename=2016-06-07_MT-Import-Reqs-BH-Co-Cattle_Press-Release%20(1).pdf). Accessed August 15, 2016.

Table 1. Description of the three elk winter-feedgrounds located within the Pinedale Herd Unit, including which elk management strategies are technically feasible at each.

Feedground	Average Elk Population ^{a/}	Management Strategies Available	Distance ^{b/}
Fall Creek	493	Low-density feeding, S19 vaccination, Test-and-slaughter	20
Muddy Creek	455	Low-density feeding, S19 vaccination, Test-and-slaughter	62
Scab Creek	773	S19 vaccination, Test-and-slaughter	48

a/ WGFD, unpublished data for years 2003 to 2012.

b/ Road-miles from WGFD Pinedale Office to each feedground (round-trip).

Table 2. Median (5%, 95%) years to expected cattle case under modeled management activities and various assumptions about the magnitude of seroprevalence reduction (Kauffman et al., 2016).

		Initial Seroprevalence (18%)	Expected Number of Years to Next Cattle Case when Seroprevalence is Reduced by –X%, to (Y%)			
			-1% (17%)	-5% (13%)	-10% (8%)	-13% (5%)
Strategy						
Test-and-slaughter						
	Median	↑	18.083	19.551	29.268	60.992
	5% ^{a/}		5.329	5.619	7.564	15.401
	95% ^{b/}		18.97	35.620	64.100	135.490
S19 vaccination						
	Median	18.08	18.808	22.505	29.474	33.559
	5%	5.33	5.364	5.476	5.482	5.485
	95%	32.22	33.883	44.283	75.153	99.085
Low-density feeding						
	Median	↓	18.083	18.718	21.705	27.180
	5%		5.329	5.359	5.475	5.480
	95%		32.223	33.641	41.435	62.062

a/ 5% represents the worst case (pessimistic) scenario.

b/ 95% represents the best case (optimistic) scenario.

Table 3. Costs for feeding elk with a team and sleigh, assuming traditional versus low density (L-D) feeding. Note: only labor costs differ across the feeding approaches; all other costs are the same.

	Traditional 1 Feeder	L-D 1 Feeder	L-D 2 Feeders
Draft Horses		\$215	
Vaccinations		\$190	
Veterinary		\$250	
Salt/Mineral		\$190	
Hoof Care	←	\$160	→
Water Tank		\$256	
Sleigh/Harness		\$295	
Winter Feed		\$1,021	
Spring Feed		\$122	
Summer/Fall Feed		\$365	
Labor	\$4,156	\$6,235	\$12,469
Total Yearly Costs	\$7,220	\$9,298	\$15,533

Table 4. Summary of strain-19 vaccination costs.

	3 PHU Feedgrounds	Per PHU Feedground
Ballistic System	\$313	\$104
Bio-bullet Cost	\$3,956	\$1,319
Shipping Cost	\$10	\$3
WGFD Labor	\$1,261	\$420
Feeder Labor	\$1,153	\$384
WGFD Transportation	\$116	\$39
Total Yearly Costs	\$6,808	\$2,269

a/ Costs are assuming Pinedale Herd Unit (PHU) elk numbers. Elk are not currently vaccinated in the PHU.

Table 5. Yearly test-and-slaughter costs assuming Sublette County plowing, and assuming two versus three feedgrounds trapped per year.

	Trapping Events per Year	
	2	3
Plowing Costs	\$443	\$664
Slaughter Costs	\$11,054	\$16,580
Yearly Costs of Elk Traps	\$25,891	\$26,334
All Other Yearly Costs	\$372,167	\$558,250
Total Yearly Costs	\$409,111	\$601,164

Table 6. Expected benefit of reducing elk seroprevalence using various management activities (=expected annual cost of brucellosis in a cattle herd under Current elk seroprevalence^{a/}-expected annual cost under reduced seroprevalence).

Activity ^{b/}	Reduction in elk seroprevalence by –X to (Y%)			
	-1% (17%)	-5% (13%)	-10% (8%)	to 5%
T&S				
Median	\$1	\$609	\$3,093	\$5,693
5%	-\$5 ^{c/}	\$1,412	\$8,107	\$17,949
95%	\$0	\$433	\$2,258	\$3,461
S19				
Median	\$0	\$1,591	\$3,128	\$3,732
5%	\$174	\$732	\$761	\$776
95%	\$223	\$1,237	\$2,594	\$3,064
LDF				
Median	\$1	\$276	\$1,351	\$2,709
5%	-\$5	\$149	\$727	\$751
95%	\$0	\$192	\$1,010	\$2,183

a/ Current management results in seroprevalance levels of 18%.

b/ Management activities include: elk test-and-slaughter (T&S), strain 19 vaccination (S19), and low density feeding (LDF).

c/ This negative expected net benefit is an unexpected artifact from the risk model, likely caused by an extreme value (i.e., data value outside model range) in a variable other than seroprevalence.

Table 7. Summary of cost estimates for elk management strategies.

Strategy	Minimum Cost	Maximum Cost	Unit	# Units Used Per Year	Annual Total Cost Assumed
Test-and-Slaughter	\$409,111	\$635,125	trapping at 3 feedgrounds	1	\$601,164 ^b
Strain 19 Vaccination	\$1,896	\$2,269 ^a	per feedground per year	3	\$6,807 ^c
Low-Density Feeding	\$2,078	\$12,985	per feedground per year	2	\$4,156 ^d

a/ Cost in bold are assumed for net benefit analysis for strain 19 vaccination and low density feeding.

b/ Expected test-and-slaughter costs include Sublette county plowing and for trapping at all 3 feedgrounds. Minimum value is trapping at two feedgrounds with Sublette County plowing costs, while the maximum value represents trapping at three feedgrounds with private contract plowing.

c/ Assumed vaccination cost occurs on 3 feedgrounds within the Pinedale Herd Unit, with each feedground incurring a cost of \$2269 which is the 'maximum' cost but also the most likely scenario, based on feedground and elk population characteristics.

d/ Low density feeding costs account only for additional expenses incurred due to low density feeding, as compared to traditional feeding. Minimum and assumed cost reflects feeding with a team and sleigh, while maximum cost assumes using a tractor and feeding implement.

Table 8. Expected net benefit of reducing elk seroprevalence under various activities and reduction scenarios.

		0% (18%)	-1% (17%)	-5% (13%)	-10% (8%)	-13% (5%)
T&S						
Median	n/a	-\$601,163	-\$600,555	-\$598,071	-\$595,471	
5%	n/a	-\$409,116	-\$407,700	-\$401,005	-\$391,162	
95%	n/a	-\$635,125	-\$634,692	-\$632,867	-\$631,664	
S19						
Median	n/a	-\$6,807	-\$5,216	-\$3,679	-\$3075	
5%	n/a	-\$1,722	-\$1,164	-\$1,135	-\$1,120	
95%	n/a	-\$2,046	-\$1,032	\$325	\$795	
LDF						
Median	n/a	-\$4,155	-\$3,881	-\$2,805	-\$1,447	
5%	n/a	-\$4,162	-\$4,008	-\$3,430	-\$3,405	
95%	n/a	-\$25,636	-\$25,444	-\$24,626	-\$23,453	

Table 9. Minimum cost of cattle outbreak required for management activities to be economically justifiable (expected annual net benefit=0) under modeled and current seroprevalence levels.

		Current	Reduction of seroprevalence by -X% to (Y%)			
		-18%	-1% (17%)	-5% (13%)	-10% (8%)	-13% (5%)
T&S						
Median	n/a	\$65,514,980,968	\$144,460,028	\$28,433,609	\$15,448,471	
5%	n/a	\$0	\$62,299,041	\$10,848,970	\$4,900,005	
95%	n/a	\$208,047,843,323	\$202,924,040	\$38,945,584	\$25,412,744	
S19						
Median	18.08	> ∞	\$617,462	\$314,056	\$263,215	
5%	5.33	\$5,646,549	\$1,342,406	\$1,290,829	\$1,266,538	
95%	17.72	\$4,408,199	\$794,243	\$378,727	\$320,613	
LDF						
Median	n/a	\$452,921,767	\$2,204,513	\$449,910	\$224,431	
5%	n/a	-\$118,045,237	\$4,093,441	\$836,409	\$809,267	
95%	n/a	\$1,438,287,783	\$3,170,121	\$602,106	\$278,483	

Table 10. Minimum number of years cattle outbreak must be extended for a management activity to be economically justifiable (i.e., for expected annual net benefit = 0), assuming an outbreak cost of \$146,299.

	Current Years (Yc)	Break-even # Years Until Cattle Case (Y _A) ^{a/}		
		T&S	S19	LDF
Median	11.3	> ∞	106	37
5% ^{/b}	7.75	> ∞	7	6
95% ^{/c}	17.72	> ∞	95	36

a/ Calculated using equation 5.

b/ 5% represents a best-case (optimistic) scenario.

c/ 95% represents a worst-case (pessimistic) scenario.