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Cost–benefit analysis of coyote removal as a management option in Texas cattle ranching

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Abstract: The monetary value of livestock losses attributed to coyote (*Canis latrans*) predation in North America has increased during the past 20 years. In Texas, USA alone in 2011, these loses were estimated at $6.9 million. To mitigate coyote-related livestock losses, several lethal and nonlethal control methods have been developed. However, there remains a need for better information to guide management decisions regarding cost-effective predator control strategies for livestock production systems. We acquired data, which was used in the model, from published literature from 1960 to present day, subject matter experts, and anecdotal information on coyote ecology. We developed a systems dynamics simulation model to evaluate the economic impact of coyote control on an average-sized cattle (*Bos* spp.) operation (1,000 ha) for a conceptual 10-year period in Texas. We conducted a sensitivity analyses to validate the model and identify the most sensitive parameters. We tested 88 scenarios using common coyote management methods (i.e., aerial gunning, M-44 devices, snares, livestock guard animals (LGAs), calling and shooting, and foothold traps), combinations of multiple management methods, and number of applications per year (once per year, twice per year, continuous). Several management methods were cost effective at reducing calf predation when applied sparingly and under assumptions of skillful and dedicated application of coyote control methods. The most cost-effective method of coyote control to reduce calf depredation was the combined use of snares and LGAs. When applied 1 month prior to the primary calving month, the snare/LGA combination showed an 81% decrease in overall costs of calf loss and predator management during the 10-year period, respectively. Cost effectiveness of methods deteriorated as the number of applications per year increased. While these are useful results, the intangible values of coyotes through grazing benefits (i.e., fewer prey species such as lagomorphs on the landscape to compete for forage with cattle) and ecological benefits (i.e., mitigation of meso-predator release) were not included in the model. However, these benefits should be considered by ranchers before implementing lethal coyote management.

Key words: *Bos* spp., *Canis latrans*, cattle depredation, control, cost–benefit, coyote, removal, Texas, Vensim

Coyotes (*Canis latrans*) are a canid native to North America. Coyotes are a highly versatile species whose range has expanded amidst human population expansion (Fener et al. 2005). Initially the coyote distribution was restricted to the Great Plains states. However, with coyote's commensal abilities and the eradication of wolves (*Canis* spp.), coyotes now range from coast to coast and from Alaska, USA to Panama (Moore and Parker 1992, Bekoff and Gese 2003, Ripple et al. 2013).

Coyotes are known to eat a variety of food items in relation to changes in availability. Food items that they consume range in size from fruit and insects to large ungulates and livestock (Bekoff 1978, Andelt et al. 1987). Meinzer et al. (1975) reported that in Texas, USA, vegetation and insects are relied upon heavily during periods when they are plentiful (May through December). Mesquite (*Prosopis glandulosa*) pods, juniper (*Juniperus* sp.) berries, prickly pear (*Opuntia* spp.) fruit, lotebush (*Ziziphus obtusifolia*) berries, and ironwood (*Ostrya* spp.) berries were the primary vegetation

consumed during those periods (Meinzer et al. 1975). Fruits accounted for 50–75% of coyote diets throughout their 2-year study, and the carnivorous and scavenger habits were most prevalent during periods of vegetation and insect scarcity (December through April; Meinzer et al. 1975). Meinzer et al. (1975) found dramatic increases in rodent predation during October, lagomorph consumption predominated coyote diet in February, and carrion accounted for approximately a quarter of coyote diets throughout the study. Meinzer et al. (1975) noted that when carrion was present or suspected in stomach or scat samples, carcasses of livestock were found in close proximity and local ranches reported no losses of cattle (*Bos* spp.) or calves to coyotes.

Andelt et al. (1987) demonstrated, on average, that coyotes consumed mammals, insects, and wild fruits, which constituted about 64%, 10%, and 20% of coyote diets, respectively. Coyote diet was seasonal with deer consumed from November through March and during June, fruit consumption peaked during April to May and July to August, and consumption of cattle occurred during winter; however, the study did not distinguish if cattle were scavenged or killed (Andelt et al. 1987).

According to the National Agricultural Statistics Service (NASS) the monetary value of cattle and calf losses because of coyote predation has increased 31% (range 10–45%) during the past 20 years (NASS 1996, 2001, 2006, and 2011). More importantly for this study, they show a 20% average increase (range 2–37%) in the number of cattle lost during the same period. The higher average increase of the value of depredated cattle is likely a result of the increase in the price of cattle. The latest report of cattle death loss reported coyote predation on cattle nationally accounted for $48.2 million of damage or 116,708 head of cattle (calves = 103,017; cattle = 13,691), of which 17,372 cattle (15%) were lost (calves = 16,040, 16%; cattle = 1,332, 10%) because of coyote depredation for a value of $6.9 million in Texas (NASS 2011).

Although coyotes are consistently considered the top cause of predator-related cattle deaths, their damage is substantially less than several nonpredator-related causes of death, such as respiratory problems, digestive problems, calving problems, weather-related problems, and other nonpredator-related problems. Comparatively, respiratory problems are the single largest mortality issue that the cattle industry faces, costing the industry $750 million annually (Schneider et al. 2009).

Table 1. List of some lethal and nonlethal coyote (*Canis latrans*) control methods supported in the published literature.

Lethal	Nonlethal
Aerial shooting (helicopter or fixed wing) [1,2]	Calving synchronization[3,4]
Foothold trap[1,2]	Fencing[3,4]
Snare[1,2]	Frightening devices[3,4]
Call and shoot[1,2]	Carcass removal[3,4]
Denning[1,2]	Guard animals[3,4]
Livestock protection collars[1,2]	Herders[3,4]
M-44 devices[1,2]	Surgical sterilization[5,6]

[1]Mitchell et al. 2004
[2]Blejwas et al. 2002
[3]Knowlton et al. 1999
[4]Evans and Pearson 1980
[5]Till and Knowlton 1983
[6]Bromley and Gese 2001

Nationwide predator-related cattle losses (219,900) and nonpredator-related losses (3,773,000) were 0.2% and 4% of the nationwide cattle inventory, respectively (NASS 2010, 2011). Alternatively, Brewster (2018), in a survey of a sample of Texas ranchers, found that 22% of cattle ranchers who perceived coyotes to be the greatest threat also perceived that losses because of coyotes were >3% of their total herd, while 57% of respondents perceived losses to be <1% of their total herd.

There is potential for inflation of the threat of coyotes to cattle operations as depredations are commonly misdiagnosed as predation when actually the cow or calf carcass was scavenged after some other cause of death (J. Tomeček, Texas A&M AgriLife Extension Service, unpublished data). Further, with the high percent of cattle deaths because of illness, it is unknown how commonly a coyote may depredate a sick or nearly dead animal.

To mitigate coyote-related livestock losses, several lethal and nonlethal control methods have been developed (Table 1). Most of these methods are readily available to livestock producers; however, there are permit

requirements associated with the use of poisons in M-44 devices and livestock protection collars. Also, surgical sterilization is likely not widely employed by livestock producers (Shivik 2014).

The economic benefits of coyote management are typically measured by the value of reduced livestock losses against the associated costs of the management activities (Shwiff and Merrell 2004). There also are indirect and intangible benefits (i.e., benefits to surrounding community because of greater number of livestock sold; Shwiff and Bodenchuk 2004, Shwiff and Merrell 2004). Indirect costs also exist, such as cost of reduced forage for cattle because of increased lagomorph population when intensive coyote removal is applied and cost of increased disease prevalence because of lack of coyote scavenging (Henke and Bryant 1999, Beasley et al. 2015, Ranglack et al. 2015). These indirect benefits and costs deserve consideration when a cattle producer determines a tolerance threshold before implementing coyote management. Whether it is "…that coyotes kill [calves] or the number of [calves] killed that causes coyotes to be called a pest" (Hone 1994) is an important question when weighing costs and benefits.

Some of the controversy surrounding predation management today is focused on the economics of management efforts. Bodenchuk et al. (2000) estimated that predator management by U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Wildlife Services (WS) provided direct benefits by reducing calf predation by 2%. When including a 3x multiplier to account for indirect benefits to the wider cattle market, they estimated a maximum benefit of approximately $72.4 million for the national cattle and calf market. However, the individual rancher most likely will not experience the same multiplier to their expected financial condition, only the value of the additional 2% production increase over their condition without predator management.

The objectives of our study were to develop a theoretical mathematical model to outline, explain, and predict costs associated with various lethal and nonlethal coyote management techniques. This information could be useful to guide management decisions by promoting cost effective predator control strategies for cattle production systems.

Study area

Texas is a large state (i.e., 691,027 km^2) that comprises 10 ecoregions (i.e., Pineywoods, Gulf Prairies and Marshes, Post Oak Savannah, Blackland Prairie, Crosstimbers, South Texas Plains, Edwards Plateau Rolling Plains, High Plains, and Trans-Pecos; https://tpwd.texas.gov/). Each ecoregion has unique features, but in general annual precipitation ranges from <30 to 82 cm from west (i.e., Trans-Pecos ecoregion) to east (i.e., South Texas Plains) with high evaporation rates throughout the state. Soils range from course sands to clays, but clay soils tend to be predominant in areas of cattle production. Greatest livestock production occurs in the South Texas Plains, Rolling Plains, and Trans-Pecos ecoregions, which are characterized as a mix of grassland and shrubland. However, livestock occur through the state. Common vegetation within these ecoregions are mesquite, prickly pear, juniper, and yucca (*Yucca* spp.).

We assumed such an evaluation of the costs and benefits associated with coyote removal would be useful to the cattle ranching community in Texas. We used a hypothetical cattle operation with calf losses from coyote depredation. Gleaton and Robinson (2016) reported that most ranches in Texas were considered small (i.e., average size of 212 ha). However, this estimation did not report the primary livestock produced. With a focus on cattle ranches, we used a hypothetical cattle ranch of 1,012 ha based on survey data from 460 Texas ranchers (Brewster 2018). This acreage size was selected because it was considered to be an average size cattle operation in Texas (Brewster 2018) and large enough to support a stable coyote population (Knowlton 1972, Andelt 1985).

Methods

Model overview

Conceptual and quantitative development. We acquired data from the published literature (i.e., 1960 to present day), subject matter experts, and anecdotal information on coyote ecology and behavior. We constructed a conceptual population dynamics model that estimated coyote population trends under commonly applied coyote control methods (see coyote control methods in model development section) as related to cattle production. We manipulated the month of management application (1 month/

year, 2 months/year, and monthly throughout the year) along with lethal and nonlethal methods of management used and combinations of these methods. The model followed a similar population modeling approach used for coyotes (Glasscock 2001) and other wildlife species (Wuellner et al. 2017) to establish a stable simulation of coyote population. The model included age class stocks for pups (0–8 months), yearlings (9–21 months), and adults (>21 months) as well as a stock representing the local ecosystems resource constraint; flows (transfer of information into or out of the stocks [i.e., aging to different age classes, natural mortality, human induced mortality, and immigration]); and auxiliary variables (i.e., reproductive rates, survival, recruitment delays, and environmental limitations' influence on reproduction and survival).

The costs and benefits of coyote management in the model included stocks for total costs and total benefits driven by flows for cost generation and savings generation because of coyote management and resulting livestock gains. Benefit auxiliary variables (i.e., value of saved calves and value of increased weaning weight) influence the flows of financial resources. Each coyote control method had auxiliary variables that represented its associated costs, month(s) of application, and percentage of the coyote population removed. As each control method is employed, benefit accrued based on the number of calves, value of calves (dollars per head), percentage of calves lost to coyote predation, benefit from reduced coyote population, and weight gain increases from reduced coyote population. The model was created using the system dynamics modeling software Vensim (Ventana Systems Inc, Harvard, Massachusetts, USA).

Model development and specification

The model used difference equations (Appendix A) to calculate population sizes on an annual basis (i.e., time step [Δt] of 12 months/1 year). The equations included stocks or quantities (i.e., coyotes, costs, benefits), their rates of change (i.e., inflows/outflows), and the intermediate variables that influence the rates of change over time. The model framework was based on links among the described population, cost, and benefit parameters.

Population composition, mortalities, and recruitment. We assumed that a conservative hypothetical population of 4 coyotes, comprised of 3 adults and 1 yearling, was the beginning population. Because 1,012 ha is roughly 10 km^2, this is a reasonable starting population as coyote populations in Texas generally are between 0.12 and 2.3 individuals/km^2, of which the high end of that range can be found in parts of south Texas (Knowlton 1972, Bekoff and Gese 2003). Mortality was calculated as the age class stock value multiplied by the mortality rate (Windberg et al. 1985). The mortality rate variable was dependent on a density dependent or carrying capacity variable, which consisted of total coyote population subject to a resource constraint. As the carrying capacity variable approached 1 (1 = at carrying capacity), the mortality of yearlings and adults increased. Recruitment was calculated as the age class stock value divided by the recruitment delay.

Reproduction. Yearling and adult breeding auxiliary variables accounted for reproduction in the coyote population. Breeding consisted of yearling and adult litter survival rates (60% and 75%, respectively; Knowlton 1972), and yearling and adult litter size (6 and 4, respectively; Knowlton 1972). Similar to the mortality variable, the litter survival rates also were tied to the density dependence variable where survival decreased as the total coyote population approached carrying capacity. While carrying capacity interactions are very complex, this model simplifies those interactions, as is sometimes necessary to achieve reasonable model boundaries. A minimum of 2 coyotes (adult and/or yearling) was required for the breeding equations to be active, which assumed 50% sex ratio. Natality was calculated as the product of the age class stock value multiplied by the female proportion (50%; Knowlton 1972, Windberg and Knowlton 1988), litter size, and litter survival rate (Crabtree and Sheldon 1999). The breeding month for yearlings and adults was set to occur at month 1, and whelping occurred after a 2-month fixed delay (April; Andelt 1985) in the total litter variable; as expected, this whelping activity significantly increased the number of individuals in the system (Knowlton 1972).

Immigration and emigration. Immigration is an important consideration when coyote removal is conducted. Transient coyotes or yearlings dispersing from surrounding areas are known to

quickly fill the empty spaces created by coyote removal (Gier 1968, Knowlton 1972, Henke and Bryant 1994, Blejwas et al. 2002). We assumed an immigration delay of 3 months, although there is potential for replacement to happen more quickly (Blejwas et al. 2002). Immigration flowed into the yearling age-class stock to account for dispersing individuals using a fixed delay triggered by reduced density in the carrying capacity variable. Emigration was set to occur in December with a flow out of the yearling stock at a rate of 55% per month when the number of yearlings in the yearling stock was >2.

Coyote control methods. We used 6 different coyote control methods in this model that accounted for the most commonly used means to reduce coyote populations and/or calf depredations in Texas (NASS 2011, Brewster 2018). Lethal methods included aerial gunning by helicopter, use of M-44 devices, calling and shooting, snares, and foothold traps. Additionally, use of snares in combination with net wire fences was retested for increased efficiency at reducing coyote populations (M. Bodenchuck, Wildlife Services, personal communication). The nonlethal method included was use of donkeys (*Equus africanus*) as livestock guard animals (LGA), as donkeys are commonly used as guard animals in Texas and the maintenance costs of guard donkeys is less than that of guard dogs (*C. familiaris*).

The model assumed landowner responsibility for the costs in USD of coyote control. The cost of aerial removal by helicopter ($650 per hour at 4 hours) was estimated from communication with private helicopter service operators in Texas. The cost of M-44 devices was calculated at $200 per week ($800 per month) for WS to conduct (D. Trevino, Wildlife Services, personal communication). This cost was used as it is assumed that many landowners do not have a pesticide applicators license or the desire to obtain one and adhere to the associated regulations to possess sodium cyanide capsules. The cost of snares was calculated at $2 per snare at 40 snares (Coyote Eliminator Snares, Wildlife Control Supplies, East Granby, Connecticut, USA) with labor costs estimated at $10 per hour at 32 hours per month. The cost of traps was calculated at $15.75 per trap at 40 traps (Bridger #3 Dogless Coil Spring Trap [Offset Jaws], Wildlife Control Supplies, East Granby, Connecticut, USA) with labor costs estimated at $10 per hour at 192 hours per month, which accounted for regulations in Texas that require traps to be checked every 72 hours. Calling and shooting costs included estimates for cost of ammunition ($30) and labor at $10 per hour at 12 hours per month (M. Bodenchuck, Wildlife Services, personal communication, based on 6 locations for 1 hour per location x 2 days per month). Livestock guard animal (donkey) cost was calculated at $200 per animal plus $100 per year maintenance cost (Walton and Field 1989, Bureau of Land Management 2017).

Control method effectiveness was synthesized through literature (Windberg and Knowlton 1990, Henke and Bryant 1994, Sacks et al. 1999) and verified against mental models (Jones et al. 2011) of subject matter experts in the form of percentage of coyote population removed (M. Bodenchuck, Wildlife Services, personal communication). The percent of the coyote population lethally removed was calculated as a random variable with the following means used for each method: aerial gunning (75%); M-44 (45%); snare (15%); snare used in conjunction with net wire fencing (60%), referred to as Snare+; foothold trap (10%); calling and shooting (35%); and LGA (0%). Percent removed variables were connected to a percentage of population removed variable, which was tied to outflows from the yearling and adult stocks in the form of treatment removal. A random variable divided the proportion of yearlings and adults removed (estimated averages of 35% adults and 65% yearlings). The use of LGAs (i.e., donkeys) did not remove any of the coyote population from the system.

Calves and calf loss. Using survey data from Brewster (2018), an average herd size of 122 cows was estimated for this hypothetical ranch with a 75% calving rate and a 100% weaning rate producing 91 calves each year. Calving was split with 75% winter calving (February) and 25% summer calving (June), as this is a typical operation in Texas (A. Ortega-S., Texas A&M University–Kingsville, unpublished data). Calf loss was estimated from the same survey data with a mean calf loss because of coyote depredation of 2.8% ± 6.2%.

Benefits. The benefits assumed for coyote control is measured in the form of saved livestock (Bodenchuk et al. 2000). Saved calves, or reduced calf loss, is the idea that some calves that would

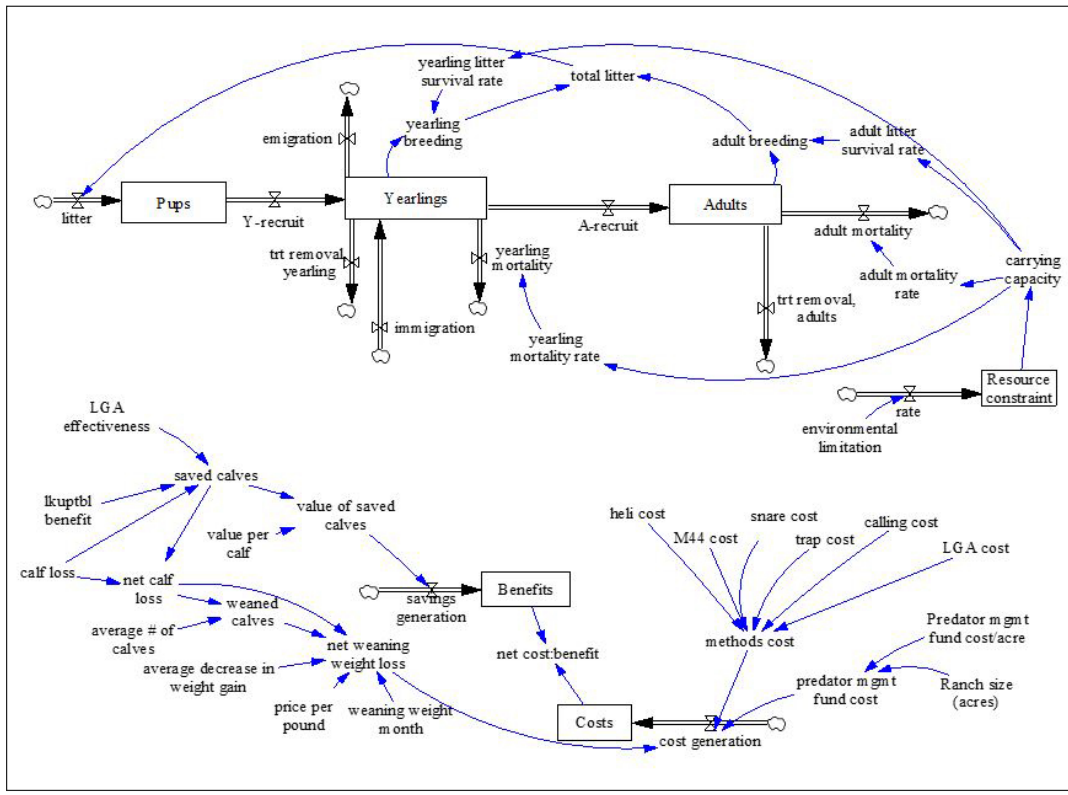

Figure 1. Simplified dynamic systems model of coyote population dynamics and cost–benefit dynamics of coyote (*Canis latrans*) removal in Texas, USA. Simulations were conducted during 2016–2018.

have been killed by coyotes were saved from depredation because of coyote control activities. The number of saved calves via lethal methods of coyote control was calculated as a function of the total coyote population. As the coyote population was reduced, the estimated equation resulting from regressing the number of calves lost on the number of coyotes removed declined in a fashion characteristic of a Poisson distribution. Since the use of LGAs did not affect the coyote population, LGA effectiveness was calculated as a random variable with an average of 60% reduction (min = 30%, max = 80%, mean = 60%) in calf loss (Green 1989, Andelt 2004). Livestock guard animal effectiveness was reported while protecting sheep and goats; thus, higher effectiveness when protecting less vulnerable cows and calves is possible. A market price of $715 for 227–271 kg weaned calves ($143 per cwt; U.S. Department of Agriculture 2017) was used to calculate the value per head of calves saved. The value of saved calves entering the savings generation flow was aggregated in the benefits stock.

Other costs and considerations. Other potential costs of coyote predation that may have a role in assessing the costs and benefits of predation management are payments to predator management funds and weaning weight loss. Ramler et al. (2014) found that Montana, USA cattle herds with a confirmed wolf (*Canis lupus*) depredation experienced an average loss of 10 kg on calf weight across the herds, presumably because of inefficient foraging behavior and/or stress to mother cows. Kluever et al. (2008) also found increased vigilance and reduced foraging in mother cows after losing a calf to mountain lion (*Puma concolor*) or wolf predation. Because coyotes are known to occasionally kill calves and yet no data exists that shows coyote predation has similar effects on weaning weight loss, we estimated a portion of this loss (5 kg per calf). Additionally, ranchers in many parts of Texas are known to contribute to predator management funds (Brewster 2018). An average cost per hectare from that survey was included as a cost in the model.

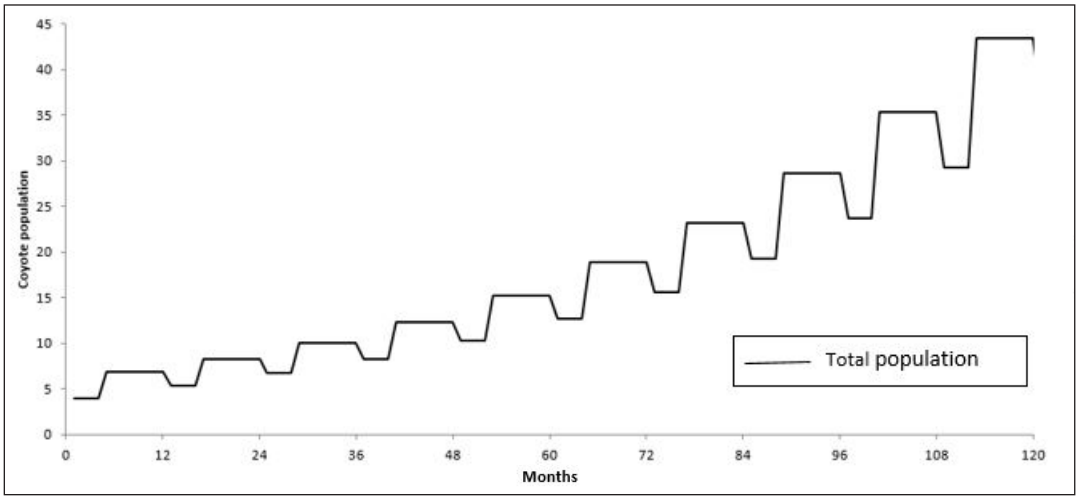

Figure 2. Initial evaluation of model output from the theoretical coyote (*Canis latrans*) population model in Texas, USA with no coyote mortality during a nondescript 10-year period. Simulations were conducted during 2016–2018.

Model testing

The model was calibrated and evaluated relative to model output behavior based on information available in the literature and knowledge of the species and system dynamics (Grant et al. 1997, Turner et al. 2016*a*). Coyote population dynamics were tested using 0% mortality in the population model and no coyote removal to test for exponential growth over time, which indicates a reasonable and accurate representation of population dynamics (Grant et al. 1997).

Sensitivity analysis

Sensitivity analysis is a model evaluation technique used to determine the sensitivity of model output to particular model parameters (Grant et al. 1997). Model parameters are varied one at a time and the simulation output is compared to the baseline results (Grant et al. 1997, DeMaso 2008, Turner et al. 2016*b*, Wuellner et al. 2017). The sensitivity analysis was conducted by varying model parameters by ± 50% (e.g., mortality, immigration, emigration, effectiveness of coyote control method [i.e., percent of population removed], calf price, and number of calves lost) to evaluate their effect on changes in total population and net benefits of control efforts. Model parameters were selected for sensitivity analysis based on reports in the literature about their influence on coyote population dynamics (Knowlton 1972, Henke and Bryant 1999, Blejwas et al. 2002, Andelt 2004) and from *a priori* knowledge of the system structure.

Model simulations

We tested simulations of 6 control methods (i.e., aerial gunning from helicopter, use of M-44 devices, snares [2 levels of effectiveness, Snare and Snare+], foothold traps, calling and shooting, and use of LGAs) and combinations of control methods. Two-way combinations of control methods and a 3-way combination were simulated. The 3-way combination of snare, trap, and call/shoot was simulated because Texas ranchers suggested common use of these methods in a survey of predator control (Brewster 2018).

We also simulated seasonal timing of control method application. Control methods were simulated to occur once per year (1 month prior to the primary calving month), twice per year (1 month prior to the primary and secondary calving months), and continuous (control methods applied each month). The use of LGAs in simulations was assumed to occur each month as the ownership and maintenance of the LGA predicates the application of this method.

Results

Initial model evaluation

We ran the first model (Figure 1) under a test simulation of 0% mortality. The model output exhibited behavior that was consistent with exponential growth (Figure 2). The results of this test suggested an overall accurate representation of the system with 0% mortality.

Our base run with no coyote control efforts (Figure 3) showed costs of calf loss, reduced

weaning weights, and contributions to predator management funds. The costs in the base run totaled $79,852 during the 120-months (10-year) period. We compared the simulations (N = 88; Table 2) to the base run to assess effectiveness in reducing overall costs of predation when the costs of control methods were included. The top 3 most effective methods and/or combinations are discussed for each seasonal application strategy.

Single application of coyote control method(s). When coyote control was simulated to occur one month prior to the primary calving month, the top 3 most effective methods to reduce overall costs associated with coyote predation on calves were Snare+ and LGA combination, snare and LGA combination, and trap and call/shoot combination (Figure 3A). The results of the simulation of Snare+ and LGA combination and the snare and LGA combination showed that the predation costs were reduced by 81% and 80% from the base run, respectively, with ending loss value to $15,456 and $15,846. The third most effective method for the single application of control was trap and call/shoot combination, which showed a 76% benefit by reducing overall predation expensed to $18,838 during the 120-month period. Other methods and combinations showed a reduction in net losses from coyote predation with aerial gunning and any combination that included aerial gunning as the least successful at reducing economic losses (i.e., 38% reduction in net loss from the base run) because of the high input costs of that method.

Multiple applications of coyote control method(s). For simulations where coyote control was applied 1 month prior to the primary calving month and 1 month prior to the secondary calving month, the top 3 control methods were Snare+ and LGA combination, snare and LGA combination, and call/shoot (Figure 3B). The benefit from the Snare+ and LGA combination and the snare and LGA combination was reduced to 77% for each combination or overall costs accounting for $18,537 and $18,710, respectively. The simulated call/shoot method showed a benefit of 69% and an overall cost of $25,139. Again, the least successful method at reducing net losses was aerial gunning. In this scenario, aerial gunning applied twice per year resulted in an 8% reduction in net losses. In some cases when aerial gunning was combined with other methods, net losses actually increased because of the high costs to aerial gunning.

Continuous application of coyote control method(s). Continuous applications were assumed for simulations where coyote control methods were applied each month. The 3 most effective control methods were the call/shoot method, call/shoot and LGA use combination, and the LGA use method, which showed a 52%, 49%, and 46% benefit in reduced costs, respectively (Figure 3C). Overall costs associated with predation and control efforts during the 120-month period resulted in $38,421, $40,621, and $42,748, respectively. When methods were simulated to be applied continuously, most of the scenarios were not cost effective, as net economic losses increased with coyote control methods (i.e., the costs of treatments increasingly outpaced the gains in livestock productivity). Previously, aerial gunning showed the lowest level of effectiveness but still maintained some level of cost effectiveness. While use of aerial gunning each month is not realistic in real-world applications, the scenario resulted in a 318% increase in net losses.

Sensitivity analysis

The 4 model parameters found to have the greatest influence (>15% change in total population during the 10-year period) on coyote populations (Table 3) were environmental limitation (Table 3; Figure 4A), emigration (Table 3; Figure 4B), aerial gunning effectiveness (Table 3; Figure 4C), and adult mortality (Table 3; Figure 4D). Each of these directly influenced the outflow of coyote stocks.

A second sensitivity analysis was conducted, which identified 4 model parameters that had the greatest influence on cost effectiveness (Table 4), cattle price (Table 4; Figure 5A), percentage of calves depredated by coyotes (Table 4; Figure 5B), aerial gunning effectiveness (Table 4; Figure 5C), and LGA effectiveness (Table 4; Figure 5D). The cattle price and percentage of calves depredated by coyotes are economic/productivity related that directly influence the benefit stock. Aerial gunning effectiveness and LGA effectiveness indirectly influence the benefit stock through influence on coyote population, indicating that tight coupling/feedback between components.

The other variables we tested were less

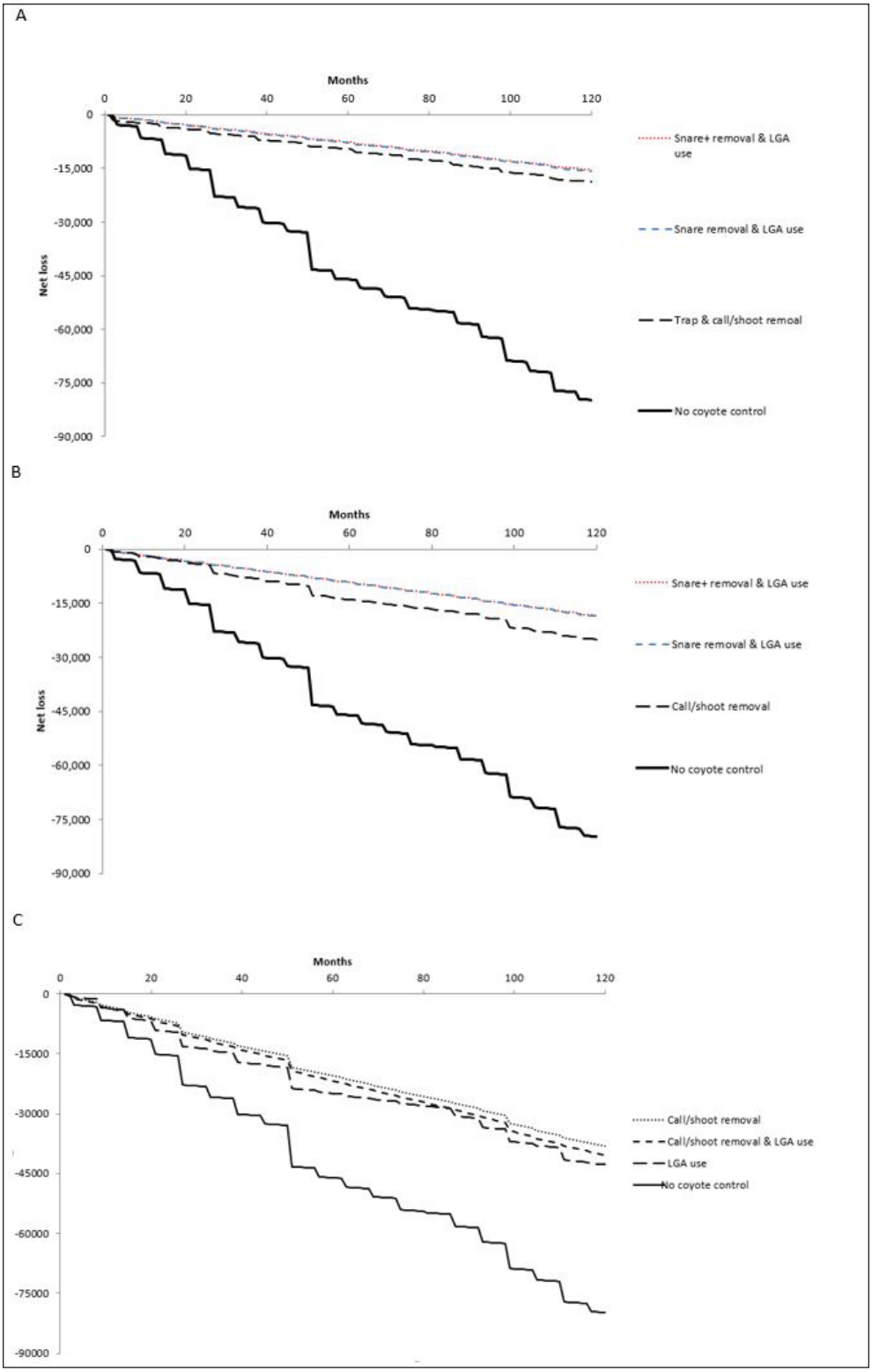

Figure 3. Simulation output from a theoretical coyote (*Canis latrans*) removal model for the top 3 most effective coyote control methods when applied once per year (1 month prior to the primary calving month; panel A); twice per year (1 month prior to the primary calving month and 1 month prior to the secondary calving month; panel B); or applied every month (panel C), Texas, USA, during a nondescript 10-year period. Simulations were conducted during 2016–2018.

Table 2. Results of simulations tested during 2016–2018. All base comparison values are compared to the net costs of the base run without coyote (*Canis latrans*) management ($79,852). Numbers in parentheses represent negative values, Texas, USA.

Once per year			Twice per year			Continuous		
Simulation method	Net costs (10 yrs)	Base comparison	Simulation method	Net costs (10 yrs)	Base comparison	Simulation method	Net costs (10 yrs)	Base comparison
Snare60, LGA	$(15,456)	-81%	Snare60, LGA	$(18,537)	-77%	Call	$(38,421)	-49%
Snare, LGA	$(15,846)	-80%	Snare, LGA	$(18,710)	-77%	Calling, LGA	$ (40,621)	-47%
Trap, Calling	$(18,839)	-76%	Call	$(25,139)	-69%	LGA	$(42,844)	-44%
M-44, LGA	$(20,274)	-75%	Trap, Calling	$(26,501)	-67%	Snare60, LGA	$(50,238)	-34%
M-44, Snare60	$(21,204)	-73%	M-44, Snare60	$(27,034)	-66%	Snare, LGA	$(50,370)	-34%
M-44, Snare	$(21,271)	-73%	Calling, LGA	$(27,339)	-66%	Snare60	$(54,485)	-28%
Call	$(25,559)	-68%	M-44, Snare	$(27,573)	-65%	Snare	$(59,804)	-21%
Snare60	$(26,788)	-66%	Snare60	$(28,051)	-65%	Calling, Snare60	$(72,317)	-5%
Calling, LGA	$(27,759)	-65%	M-44, LGA	$(28,067)	-65%	Calling, Snare	$(75,987)	0%
Calling, Snare60	$(28,305)	-65%	Calling, Snare60	$(30,704)	-62%	Trap	$(99,395)	31%
Calling, Snare	$(28,790)	-64%	Snare	$(31,451)	-61%	Trap, Calling	$(99,484)	31%
Snare	$(30,169)	-62%	Calling, Snare	$(31,423)	-61%	Trap, LGA	$(101,595)	34%
M-44	$(31,721)	-60%	M-44	$(37,779)	-53%	M-44, LGA	$(101,842)	34%
M-44, Calling	$(33,179)	-58%	Trap	$(40,075)	-50%	M-44	$(114,064)	50%
Snare60, Trap	$(33,786)	-58%	M-44, Calling	$(40,438)	-49%	M-44, Calling	$(129,889)	71%
Trap	$(34,093)	-57%	Snare60, Trap	$(41,264)	-48%	Snare60, Trap	$(131,657)	73%
Snare, Trap, Calling	$(35,520)	-56%	Trap, LGA	$(42,275)	-47%	Snare, Trap	$(136,532)	80%
Snare, Trap	$(35,645)	-55%	Snare60, Trap,Calling	$(42,427)	-47%	M-44, Snare60	$(137,340)	81%
Snare60, Trap, Calling	$(35,785)	-55%	LGA	$(42,844)	-46%	M-44, Snare	$(137,709)	81%

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Trap, LGA	$(36,293)	-55%	Snare, Trap	$(43,409)	-46%	Snare60, Trap, Calling	$(149,652)	97%
M-44, Trap	$(38,581)	-52%	Snare, Trap, Calling	$(44,374)	-44%	Snare, Trap, Calling	$(149,954)	97%
Heli, M-44	$(39,641)	-50%	M-44, Trap	$(51,165)	-36%	M-44, Trap	$(189,820)	150%
LGA	$(42,844)	-46%	Heli, M-44	$(73,300)	-8%	Heli	$(333,569)	339%
Heli	$(49,832)	-38%	Heli	$(73,745)	-8%	Heli, LGA	$(335,762)	342%
Calling, Heli	$(50,072)	-37%	Heli, LGA	$(75,945)	-5%	Calling, Heli	$(351,793)	363%
Heli, Snare60	$(51,363)	-36%	Calling, Heli	$(76,507)	-4%	Heli, Snare	$(372,016)	390%
Heli, LGA	$(52,032)	-35%	Heli, Snare60	$(79,665)	0%	Heli, Snare60	$(372,047)	390%
Heli, Snare	$(52,989)	-34%	Heli, Snare	$(80,050)	0%	Heli, Trap	$(410,976)	441%

influential on coyote and cost effectiveness stocks. Those variables likely did not have as great an impact on the coyote population or cost effectiveness because of their lower base values. For example, the baseline mean effectiveness for aerial gunning was 75% population removal while the coyote control method with the next highest baseline effectiveness was M-44 with 45% population removal.

Discussion

The results of the model simulations suggested that many methods of coyote management available to rancher application can be cost effective at reducing net losses associated with calf depredation. Whether or not a particular cattle breeding program incorporates a second calving season, the method that showed the greatest cost effectiveness is the use of snares 1 month prior to those respective calving seasons and continuous use of LGAs. The model assumed rancher responsibility to pay for reasonable labor, equipment, and service costs for coyote management activities. Some counties in Texas have WS contracts, which provide government trappers to conduct coyote management at no direct cost to the rancher. If the government pays for coyote control, then any option could be beneficial to the rancher.

Additionally, there is a recreational value associated with coyote removal. If a rancher derives recreational value from participating in coyote removal, some or all of the assumed labor costs could be negated (as long as those efforts are effective and do not train coyotes to avoid similar removal efforts in the future). Anecdotally, we encountered multiple accounts of individuals highly experienced at removing coyotes willing to pay ranchers for access to hunt coyotes or act as volunteers to hunt coyotes. In a case where skilled shooters pay a rancher a fee to stay at a ranch, provide their own guns and ammunition, and also pay for a helicopter service to conduct aerial gunning, there is little question with regard to cost effectiveness in this scenario if calf depredation is problematic. One helicopter service that we spoke to said that they maintain a short list of experienced shooters who are willing to volunteer as a shooter for aerial gunning flights. These comments highlight the existing recreational value from coyote removal.

Coyote management incorporated in this model

Table 3. Results of coyote (*Canis latrans*) management model sensitivity analysis of 13 model parameters varied by ±50% and their effect on coyote population, Texas, USA, 2016–2018.

Parameter	Variation	Total population 5 yrs	Total population 10 yrs	Absolute difference from baseline model (10 yrs)	Percent difference from baseline model (10 yrs)	Avg. percent difference	*F* (df = 1,240)	*P*
Environmental limitation	50%	3.2	3.1	1.6	35%	-6%	102	<0.0001
	-50%	6.5	6.9	-2.2	-46%		149	<0.0001
Adult mortality	50%	4.3	4.5	0.2	4%	-14%	0.86	0.36
	-50%	5.3	6.2	-1.5	-32%		41	<0.0001
Yearling mortality	50%	4.4	4.5	0.1	4%	-3%	0.02	0.88
	-50%	4.7	5.0	-0.3	-6%		3.27	0.07
Immigration	50%	4.3	4.7	0.0	0%	0%	0.13	0.71
	-50%	4.2	4.7	0.0	0%		0.14	0.71
Emigration	50%	3.4	3.7	1.0	21%	-4%	3	0.077
	-50%	5.5	6.1	-1.4	-29%		19	<0.0001
Aerial gunning effectiveness	50%	5.1	5.7	-1.0	-22%	-16%	32	<0.0001
	-50%	4.8	5.1	-0.5	-10%		0.07	0.79
M-44 effectiveness	50%	4.7	5.0	-0.3	-7%	-4%	1	0.25
	-50%	4.7	4.7	-0.1	-1%		0.21	0.65
Snare effectiveness	50%	4.7	4.7	0.0	0%	-1%	0.11	0.74
	-50%	4.4	4.8	-0.1	-2%		0.05	0.83
Trap effectiveness	50%	4.7	4.9	-0.3	-6%	-2%	0.17	0.68
	-50%	4.3	4.6	0.1	1%		0.06	0.81
Call/shoot effectiveness	50%	4.8	5.1	-0.4	-9%	-6%	0.008	0.93
	-50%	4.3	4.8	-0.1	-3%		0.0001	0.99
Cattle price	50%	4.3	4.7	0.0	0%	0%	-	-
	-50%	4.3	4.7	0.0	0%		-	-
Percentage of calves predated by coyotes	50%	4.3	4.7	0.0	0%	0%	-	-
	-50%	4.3	4.7	0.0	0%		-	-
Baseline		4.3	4.7					

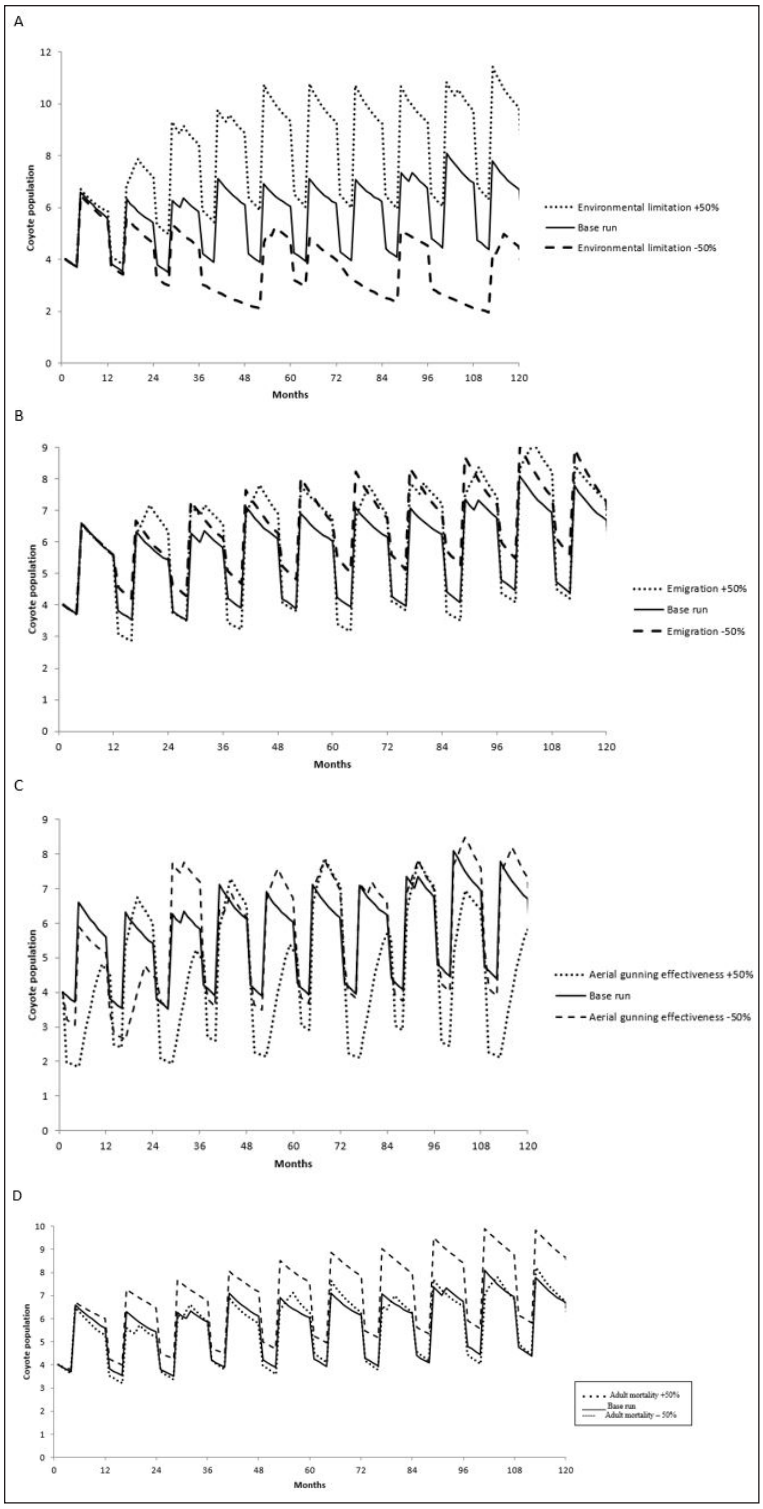

Figure 4. Sensitivity analysis simulation output from a theoretical coyote (*Canis latrans*) removal model for effects on coyote population resulting from varying levels of environmental limitations (base environmental limitation = 7 ± 2 coyotes; panel A); emigration (base emigration = 50%; panel B); aerial gunning effectiveness (aerial gunning effectiveness = 75% ± 5%; panel C); and adult mortality (base adult mortality = 2%; panel D), Texas, USA, during a nondescript 10-year period. Simulations were conducted during 2016–2018.

was assumed to be used as part of focused efforts to reduce depredation. The simulations would likely not maintain the same level of cost effectiveness with less focused efforts similar to that of opportunistic coyote removal. The intelligence of coyotes is well researched (Darrow and Shivik 2009, Gilbert-Norton et al. 2009, Shivik 2014, Blackwell et al. 2016), and coyotes can learn to avoid removal efforts if they are not removed on early attempts. Therefore, it is important to learn to apply these methods correctly to achieve the most humane and economically successful coyote management. Correctly applying coyote removal methods may include accurate snare and trap sets, proper use of calling equipment and effective shooting, and accurate shooting while aerial gunning.

Additionally, the effectiveness of guard animals can be increased by appropriate selection of individuals with a protective nature and with correct acclimation and bonding with the herd. While livestock producers cannot manage individual coyote behavior that may influence the efficacy of nonlethal methods (Blackwell et al. 2016), correct selection and handling of LGAs is within rancher control. The wide disparity shown in the LGA sensitivity analysis (Figure 5D) suggests that appropriate guard animal selection coupled with

Table 4. Results of coyote (*Canis latrans*) management model sensitivity analysis of 13 model parameters varied by ±50% and their effect on cost effectiveness, Texas, USA, 2016–2018. Numbers in parentheses represent negative values.

Parameter	Variation	Total population 5 yrs	Total population 10 yrs	Absolute difference from baseline model (10 yrs)	Percent difference from baseline model (10 yrs)	Avg. percent difference	*F* (df = 1,240)	*P*
Environmental limitation	50%	$(46,121)	$(79,852)	$ -	0%	0%	<0.0001	1
	-50%	$(46,121)	$(79,852)	$ -	0%		<0.0001	1
Adult mortality	50%	$(46,121)	$(79,852)	$ -	0%	0%	<0.0001	1
	-50%	$(46,121)	$(79,852)	$ -	0%		<0.0001	1
Yearling mortality	50%	$(46,121)	$(79,852)	$ -	0%	0%	<0.0001	1
	-50%	$(46,121)	$(79,852)	$ -	0%		<0.0001	1
Immigration	50%	$(46,121)	$(79,852)	$ -	0%	0%	<0.0001	1
	-50%	$(46,121)	$(79,852)	$ -	0%		<0.0001	1
Emigration	50%	$(46,121)	$(79,852)	$ -	0%	0%	<0.0001	1
	-50%	$(46,121)	$(79,852)	$ -	0%		<0.0001	1
Aerial gunning effectiveness	50%	$(24,569)	$(47,099)	$(32,752)	41%	39%	48	<0.0001
	-50%	$(25,739)	$(50,430)	$(29,421)	37%		40	<0.0001
M-44 effectiveness	50%	$(16,418)	$(31,365)	$(48,487)	61%	59%	130	<0.0001
	-50%	$(17,953)	$(34,735)	$(45,117)	57%		114	<0.0001
Snare effectiveness	50%	$(14,196)	$(28,610)	$(51,242)	64%	63%	144	<0.0001
	-50%	$(15,617)	$(30,377)	$(49,475)	62%			
Trap effectiveness	50%	$(17,836)	$(33,833)	$(46,019)	58%	57%	117	<0.0001
	-50%	$(18,068)	$(34,053)	$(45,799)	57%		115	<0.0001
Call/shoot effectiveness	50%	$(13,504)	$(25,432)	$(54,420)	68%	66%	172	<0.0001
	-50%	$(15,004)	$(28,463)	$(51,389)	64%		154	<0.0001
LGA effectiveness	50%	$(9,542)	$(17,327)	$(62,525)	78%	51%	233	<0.0001
	-50%	$(36,488)	$(60,377)	$(19,474)	24%		12	0.0007

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Cattle price	50%	$(61,077)	$(104,061)	$24,209	-30%	0%	14	0.0003
	-50%	$(31,165)	$(55,643)	$(24,209)	30%		25	<0.0001
Percentage of calves predated by coyotes	50%	$(60,801)	$(103,616)	$23,764	-30%	5%	13	0.0003
	-50%	$(27,866)	$(47,740)	$(32,112)	40%		44	<0.0001
Baseline		$(46,121)	$(79,852)					

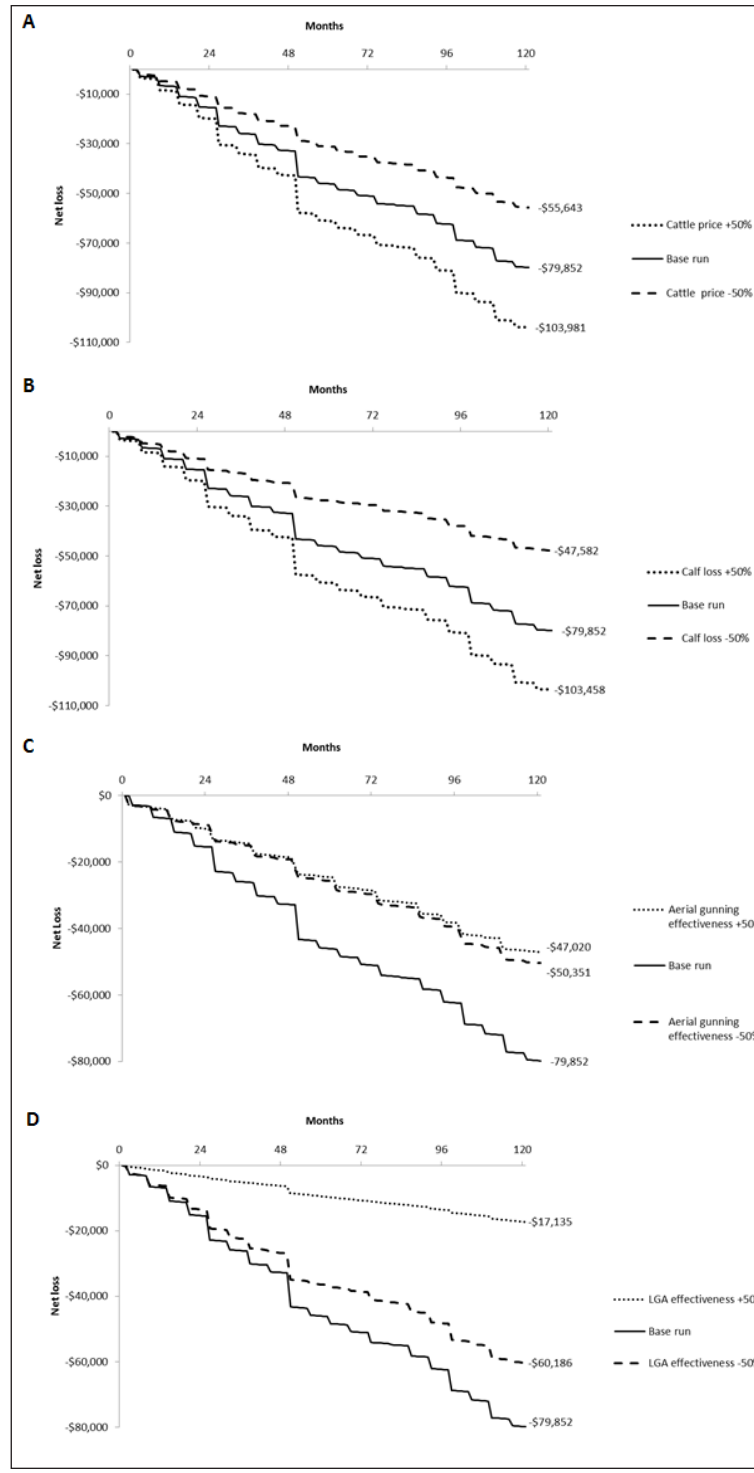

Figure 5. Sensitivity analysis of simulation output from a theoretical coyote (*Canis latrans*) removal model for effects on financial net losses resulting from varying levels of cattle (*Bos* spp.) price (base cattle price $715 for 227–271 kg weaned calves; panel A); percentage of calves depredated (base calf loss = 2.8% ± 6.2%; panel B); aerial gunning effectiveness (base aerial gunning effectiveness = 75% ± 5%; panel C); and livestock guarding animal effectiveness (base LGA effectiveness = 60% ± 5%; panel D), Texas, USA, during a nondescript 10-year period. Simulations were conducted during 2016–2018.

better husbandry can reduce coyote predation as well as enhance herd productivity.

The ecological value of coyotes is an example of a parameter outside the scope of this model that also may be considered before beginning lethal coyote management. Lagomorphs are significant forage competitors on rangelands (Ranglack et al. 2015) and are a major food source for coyotes (Rosen 2000, Bartel and Knowlton 2005). As forage competitors, approximately 30 jackrabbits (*Lepus californicus*) can account for 1 animal unit or 1 454-kg cow (Currie and Goodwin 1966, Fulbright and Ortega-S. 2013). The grazing effect of small herbivores is commonly overlooked (Rebollo et al. 2013), with significant increases in jackrabbit density associated with intense coyote removal as demonstrated by Henke and Bryant (1999). Such grazing effects should not be disregarded. As coyotes function as a keystone predator (Henke and Bryant 1999, Ripple et al. 2013), coyotes may offer ecological benefits to cattle producers through increased forage, which may refute some of the economic benefits of coyote removal suggested by this cost effectiveness model.

Ranchers employing opportunistic coyote removal methods to reduce livestock depredation may seek these methods as a feel-good activity, which generates feelings that the actions are doing something to solve the problem even though it may not be cost effective. The idea of "know your enemy" may be worth consideration in these cases. As coyotes are removed, others soon resettle the territory and the predatory behavior of those individuals is unknown.

The sensitivity analysis of the model revealed that cattle price and percentage of calves depredated were the most sensitive parameters to cost effectiveness. This suggests that as the price of calves decreases, the basis for coyote management is weakened. While calf price was a sensitive parameter, adjustments of calf price revealed that a dramatic drop in calf price would be required to reach a break-even point with the most cost-effective coyote management method (Snare+ and LGA). The current market value for a 227–271 kg calf is approximately $715. The break-even point with the most cost-effective method is $60.50 per calf.

Another sensitive parameter, the random variable for percentage of calves depredated (min = 0%, max = 30%, mean = 2.8%), was derived from survey results of Brewster (2018). That estimate used reflected a large number of calves depredated. It is likely that many cow-calf operations may not experience direct losses from coyotes. However, many ranchers may perceive that coyote depredation causes significant economic losses (Conover et al. 2018). Thus, it is important to determine the cause of death of calves as definitively as possible to avoid the misdiagnosis of scavenging activity as depredation. Some experienced wildlife managers and specialists hold mental models that concede that coyote depredation of calves does occur, but likely much less often than commonly reported. This highlights the importance of capturing the mental models of stakeholders in the same problem-situation, as these differences in mental models can result in significant differences in both real-world behavior and model outcomes.

Our model is not a model of economic choice, but rather a presentation of net savings that a cattle rancher could expect under a range of predetermined, commonly used management options for coyote control. Doing so allows for post-estimation comparison of benefits and costs across the range of management options. The frequency of management is an exogenous decision and the simulations reflect a rigid control plan (i.e., single application, dual application, or monthly application). Although our model used information about cattle production from the southwestern United States, we believe the basic concept of the model can be applicable throughout the United States. Our model does assume that coyotes do not adapt to control methods, which is possible when carried out by experienced personnel (Henke and Bryant 1999). For example, Henke and Bryant (1999) had a 97% kill rate when conducting coyote removal every 3 months for 2 years, which resulted in approximately a 50% reduction in the coyote population. In this study, naïve coyotes emigrated into the control area and did not adapt to the control methods. However, coyotes can quickly adapt if given the opportunity to learn to avoid control methods (Bekoff 1975, Bekoff and Gese 2003). If this occurs, then the benefits to cattle ranchers provided by the various methods of coyote control will be greatly reduced, potentially to the point where coyote control is only a cost and not a benefit. Additionally, our model did not include discounted values through time to account for potential inflation,

risk, or the time value of money, which means that the financial results could mask the true preference of 1 control practice over another. Nevertheless, if the costs of control methods and the value of calves rise proportionally, then the relative value of coyote control should remain as determined. However, if rising costs in future control methods exceed the potential rising value of calves or if calf value remains fairly stable through time, then coyote control options may not be economically feasible. Ranchers need to determine their individual level of economic tolerance between the costs of coyote control and value loss of calves.

Management implications

Several of the management methods we evaluated were cost effective at reducing calf predation when skillfully applied. The most cost-effective method of coyote control to reduce calf depredation was the combined use of snares and LGAs. While results are useful, the intangible values of coyotes through grazing benefits (i.e., fewer prey species such as lagomorphs on the landscape to compete for forage with cattle) and ecological benefits (i.e., mitigation of meso-predator release) were not included in our models. The necessity is clear to navigate many value-based judgments and decision factors present before implementing a coyote management program. There is no single solution to manage coyote–calf depredation, and all factors should be considered to determine what may be most effective and suitable. Ranchers must find the combination of control methods that best fits their situation.

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Appendix A. Description of key variables in the cost–benefit model of coyote (*Canis latrans*) removal as a management option in Texas cattle ranching (Vensim, Ventana Systems, Inc., Harvard, Massachusetts, USA), Texas, USA, 2016–2018. Key: A = adult; Heli = helicopter/aerial gunning, a method of coyote removal; Imm = immigration; LGA = livestock guard animal, a method of depredation management; Lkuptbl = lookup table; Mgmt. = management; Trt = treatment; Y = yearling. Model uses the following sequence for each random number equation: RANDOM NORMAL ({min}, {max}, {mean}, {stdev}, {seed}) where, {min} = minimum value, {max} = maximum value, {mean} = average value, {stdev} = standard deviation around the mean, subject to bounds of minimum and maximum values within a biologically feasible range, and {seed} = any user defined value that is used to maintain objectivity between simulations so that the final results are comparable.

Variable name	Equation no.	Formal equation	Variable type	Units
A recruit delay	1	IF THEN ELSE(month counter=10,0.9,0)	Auxiliary	Dimensionless/Month
A-recruit	2	IF THEN ELSE(Yearlings>0, Yearlings*A recruit delay,0)	Flow	Head/Month
adult breeding	3	IF THEN ELSE(Adults>=2:AND:month counter=1, Adults*female proportion*adult litter size*adult litter survival rate, 0)	Auxiliary	Head
adult litter size	4	RANDOM NORMAL(3, 4, 3.5, 0.022, 908077)	Auxiliary	Dimensionless
adult litter survival rate	5	WITH LOOKUP (carrying capacity, ([(0,0)-(2,1)],(0,0.75),(0.7095,0.66),(1,0.35),(2,0.35)))	Auxiliary	Dimensionless
adult mortality	6	adult mortality rate*Adults	Flow	Head/Month
adult mortality rate	7	WITH LOOKUP (carrying capacity, ([(0,0)-(2,0.08)],(0,0.0166),(0.85,0.02),(1,0.04),(2,0.04)))	Auxiliary	Dimensionless/Month
Adults	8	INTEG (“A-recruit”-adult mortality-”trt removal, adults”, 3)	Stock	Head
Benefits	9	INTEG (savings generation, 0)	Stock	$
calf loss	10	RANDOM NORMAL(0, 0.3, 0.028, 0.062, 7107)*calving	Auxiliary	Head/Month
calling cost	11	call cost, electronic+((call ammo cost+calling labor)*calling month)	Auxiliary	$
calling % removed	12	(RANDOM NORMAL(0.2, 0.5, 0.35, 0.06, 8574))*calling month	Auxiliary	Dimensionless
carrying capacity	13	total population/Resource constraint	Auxiliary	Dimensionless
cost generation	14	methods cost+cost of calf loss+net weaning weight loss+predator mgmt fund cost	Flow	$/Month
Costs	15	INTEG (cost generation, 0)	Stock	$
Emigration	16	IF THEN ELSE(month counter=11:AND:Yearlings>=2, Yearlings*emigration rate, 0)	Flow	Head/Month
environmental limitation	17	RANDOM NORMAL(4, 12, 7, 2, 9500)	Auxiliary	Head
heli cost	18	(“heli, cost of ammo”+(heli cost per hour*heli hours))*heli month	Auxiliary	$

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Heli % removed	19	RANDOM NORMAL(0.65, 0.85, 0.75, 0.05, 5018)*heli month	Auxiliary	Dimensionless
imm condition	20	IF THEN ELSE(carrying capacity<0.55, 1, 0)	Auxiliary	Dimensionless/Month
imm delay	21	DELAY FIXED((1-carrying capacity)*imm condition, 3, (1-carrying capacity)*imm condition)	Auxiliary	Dimensionless/Month
LGA cost	22	LGA cost of animal+LGA maintenance cost	Auxiliary	$
LGA effectiveness	23	(RANDOM NORMAL(0.3, 0.8, 0.6, 0.05 , 54619))	Auxiliary	Dimensionless
LGA % removed	24	0	Auxiliary	Dimensionless
lkuptbl benefit	25	WITH LOOKUP (total population, ([(0,0)-(16,1)],(0,1),(1,0.9),(2,0.9),(3,0.85),(4,0.85),(5,0.7),(7,0.7),(9,0.5),(10,0.3),(15,0)))	Auxiliary	Dimensionless
M-44 % removed	26	(RANDOM NORMAL(0.3, 0.55, 0.45, 0.07, 857))*M-44 month	Auxiliary	Head
net calf loss	27	calf loss-saved calves	Auxiliary	Head/Month
net cost:benefit	28	Benefits-Costs	Auxiliary	$
net weaning weight loss	29	IF THEN ELSE(net calf loss>1, (weaned calves*average decrease in weight gain*price per pound)*weaning weight month, 0)	Auxiliary	Dimensionless
predator mgmt fund cost	30	(Predator mgmt fund cost/acre*Ranch size (acres))/12	Auxiliary	$
Pups	31	INTEG (litter-"Y-recruit", 0)	Stock	Head
Rate	32	(environmental limitation-Resource constraint)/adj rate	Flow	Head/Month
rdm % range of adults removed	33	RANDOM NORMAL(0.3, 0.4, 0.36, 0.05, 4011)	Auxiliary	Dimensionless
rdm % range of yearlings removed	34	1-rdm % range of adults removed	Auxiliary	Dimensionless
saved calves	35	IF THEN ELSE(Treatment number=0, 0, IF THEN ELSE(Treatment number=6,LGA effectiveness*calf loss, IF THEN ELSE(LGA treatment=1, MIN((calf loss*LGA effectiveness)+(calf loss*LGA effectiveness*lkuptbl benefit), calf loss), calf loss*(lkuptbl benefit))))	Auxiliary	Head
snare cost	36	(snares cost+snare labor)	Auxiliary	$
Snare effectiveness	37	(RANDOM NORMAL(0.1, 0.25, 0.15, 0.03, 7835))	Auxiliary	Head/Month
Snare effectiveness with net wire	38	RANDOM NORMAL(0.45, 0.65, 0.6, 0.09, 7835)	Auxiliary	Head/Month

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snare % removed	39	Snare effectiveness with net wire * snare month	Auxiliary	Dimensionless
total litter	40	DELAY FIXED((adult breeding+yearling breeding),2,(adult breeding+yearling breeding))	Auxiliary	Head/Month
trap cost	41	(traps cost+"labor, trap")	Auxiliary	$
trap % removed	42	(RANDOM NORMAL(0.08, 0.15, 0.1, 0.02, 973))*trap month	Auxiliary	Dimensionless
trt removal, adults	43	(Adults*percent of population removed)*rdm % range of adults removed	Flow	Head/Month
trt removal, yearling	44	IF THEN ELSE(Yearlings>0, Yearlings*percent of population removed*"rdm % range of yearling removal", 0)	Flow	Head/Month
value of saved calves	45	saved calves*value per calf	Auxiliary	calves/Month
weaned calves	46	average # of calves-net calf loss	Auxiliary	Head
Y recruit delay	47	IF THEN ELSE(month counter=10,1,0)	Auxiliary	Dimensionless/Month
Y-recruit	48	Y recruit delay*Pups	Flow	Head/Month
yearling breeding	49	IF THEN ELSE(Adults<2:AND:Yearlings>=2:AND:month counter=1, Yearlings*female proportion*yearling litter size*yearling litter survival rate, 0)	Auxiliary	Head
yearling litter size	50	RANDOM NORMAL(4, 6, 4.5, 0.25, 28097)	Auxiliary	Dimensionless
yearling litter survival rate	51	WITH LOOKUP (carrying capacity, ([(0,0)-(2,0.7)],(0,0.6),(0.737,0.25),(1,0),(2,0))) yearling mortality = MAX(yearling mortality rate*Yearlings,0)	Auxiliary	Dimensionless
yearling mortality rate	52	WITH LOOKUP (carrying capacity, ([(0,0)-(2,0.2)],(0,0.0333),(0.85,0.04),(1,0.068),(2,0.068)))	Auxiliary	Dimensionless/Month
Yearlings	53	INTEG (immigration+"Y-recruit"-"A-recruit"-"trt removal, yearling"-yearling mortality-emigration, 1)	Stock	Head

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