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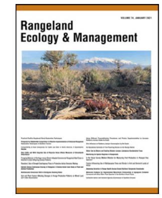

Evaluating Prairie Dog–Cattle Competition from the Perspective of a Ranching Enterprise in the Western Great Plains: Economic Analysis of Potential Effects on Long-Term Profitability

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ABSTRACT

Prairie dogs and livestock have long been viewed as competitors for forage resources, causing widespread exterminations of prairie dogs, resulting in the decline of other threatened and endangered wildlife species. In this study we model the impacts that prairie dogs exhibit on the long-term profitability and cow herd dynamics of a ranch over a 40-yr production period on a representative cow-calf ranch operation in the Thunder Basin Ecoregion of Wyoming. More specifically, we evaluate the effects of prairie dogs on a cow-calf operation through two forage/livestock use assumptions; the first is simply loss of forage due to prairie dog consumption, and the second scenario assumes there is no available forage for livestock on prairie dog colonies. We also include three different potential prairie dog population dynamic scenarios: unmanaged prairie dogs, unmanaged prairie dogs with increased colony expansion during drought, and prairie dogs managed for a target colony size. As expected, our results indicate that prairie dogs decrease forage availability for grazing, thus reducing the average cow herd size on a ranch, the annual returns from livestock sales, and the maximized net present value of annual returns. Further, the magnitude of these impacts and the financial feasibility of managing prairie dogs largely depends on the effects prairie dogs exhibit on forage resources and how cattle use these forage resources.

The black-tailed prairie dog (BTPD, *Cynomys ludovicianus*), one of five subspecies of prairie dogs found in North America, inhabits mixed-grass and short-grass prairies of the Great Plains region (Biggs et al. 2006). Prairie dogs once inhabited a large region of central North America stretching from southern Canada into the grasslands of northern Mexico. Because of habitat conversion, direct extirpation, introduced disease, and other factors, prairie dogs occupied only a small fraction of their historical extent by the end of the 19th century (Knowles et al. 2002). Most of the remaining large complexes of prairie dog colonies occur in four states: Colorado, Montana, South Dakota, and Wyoming (McDonald et al. 2015).

The prairie dog is a keystone species and ecosystem engineer with major impacts on the ecology of the grasslands they inhabit (Miller et al. 2007). In disturbance-dependent North American grasslands, prairie dog colonies create unique habitats that support high levels of biodiversity, including specialist species that are rare elsewhere in the landscape (Ceballos et al. 2010; Davidson et al. 2012; Augustine and Baker 2013; Davidson et al. 2018; Duchardt et al. 2019). Although they provide habitat and food for numerous other species, BTPD also compete with livestock for rangeland forage. Derner et al. (2006) showed that where prairie dogs exceed 30% of total pasture area in the shortgrass steppe of Colorado, they can suppress the weight gain of yearling steers and reduce livestock value by up to \$38 per steer and \$5.58 per hectare for the summer grazing season. Subsequent analyses showed slightly lower estimates, indicating that prairie dog occupancy of 30–60% of a pasture could induce 4–8% loss in yearling steer weight gain during the growing season (Augustine and Derner 2021). Losses of this magnitude can undermine the long-term sustainability of extensive agriculture in rangelands, where economic margins are already low (Dunn et al. 2010; Rolfe et al. 2016).

Due to the perceived competition between prairie dogs and livestock, prairie dogs were labeled as an agricultural pest, which

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led to widespread population control methods, including extensive rodenticide applications using zinc phosphide (Collins et al. 1984; Knowles et al. 2002). The US Department of Agriculture estimates that 10 000–25 000 kg of poisoned bait and 1–2 million fumigant tablets were deployed annually to control BTPDs on western rangelands during the early 1990s (Forrest and Luchsinger 2006). By the late 1990s, rodenticide applications on BTPD colonies led to low densities and a scattered distribution of the species, leaving prairie dogs unable to perform their ecosystem functions in many regions (Miller at al. 2000; Soule et al. 2005; Proctor et al. 2006). The emergence of the non-native sylvatic plague within populations has also resulted in rapid population declines (Cully et al. 2010) and extreme boom-bust population cycling dynamics that are undesirable for both livestock management and wildlife conservation objectives (Johnson et al. 2011; Davidson et al. 2022). In some cases, lethal control can be an economically viable option, but the cost of controlling prairie dogs may also exceed financial losses due to forage reduction from prairie dogs; a better understanding of these thresholds is critical for effectively managing livestock production in landscapes with prairie dogs (Miller et al. 2007; Delibes-Mateos et al. 2011; Davidson et al. 2012; Augustine and Derner 2021).

The effects of shifting prairie dog management objectives and sylvatic plague dynamics on livestock production and ranch economics are poorly quantified. Despite intense stakeholder interest in prairie dog–livestock competition, direct measures of how prairie dogs affect livestock weight gains are surprisingly rare (Detling 2006). To our knowledge, only three studies have compared weight gains of cattle grazing in pastures with or without prairie dogs (O'Meilia et al. 1982; Derner et al. 2006; Augustine and Derner 2021). Existing studies occurred in shortgrass rangelands of the southern Great Plains, where prairie dog effects on cattle may be mitigated by grazing resistance of the dominant grass species (Milchunas et al. 2008). Even less is known about the relationship between prairie dogs and livestock in the vast region of the northern mixed-grass prairie stretching across Wyoming, Montana, North Dakota, South Dakota, and Nebraska, where dominant grasses are less adapted to intense grazing pressure (Milchunas et al. 2008). Furthermore, most previous experimental studies of cattle–prairie dog competition only examined interactions during the growing season, when tradeoffs between forage quality and quantity could potentially mitigate negative effects of prairie dogs on cattle weight gain (Augustine and Springer 2013). Prairie dogs could have an even stronger effect on forage availability in the dormant season, when forage quantity is most limiting, with potentially important economic impacts on ranch operations.

Understanding the effects prairie dogs have on ranching operations in the Thunder Basin Ecoregion of northeastern Wyoming will assist decision makers in developing more strategic and adaptive management strategies for balancing prairie dog conservation and livestock production efforts in multiple use rangelands. In this study, we model a typical ranch operation in the Thunder Basin Ecoregion using a Multi-Period Linear Programming economic model. This model estimates long-term profitability and cow herd size impacts from a range of simulated prairie dog colony dynamics and management strategies. A simulation approach is valuable in this context because it can include a range of assumptions that reflect existing uncertainties about the strength and extent of prairie dog competition with livestock.

Using this framework, we seek to understand potential lower and upper bounds of BTPD boom-bust cycles on long-term ranch profitability given various assumptions about 1) the strength of livestock-BTPD competition, 2) how BTPD populations respond to weather variability, and 3) how BTPD populations are managed.

Methods

Representative ranch

Livestock classes, herd characteristics, seasonal use of forage resources, calendar of operations, and financial information about the ranch are essential in determining the financial implications prairie dog dynamics exhibit on a representative ranch. We used the typical land, livestock, and financial resources and production practices found in Thunder Basin Ecoregion of Wyoming ranch operations, gathered from the Northern Rolling High Plains Major Land Resource Area 58B enterprise budget (Dyer et al. 2018), the Thunder Basin Grasslands Prairie Ecosystem Association (D. Pellatz, personal communication, May 2019), and the Forest Service (USDA Forest Service 2020).

Linear programming model

A multiperiod linear programming model was used to model a representative ranch in the Thunder Basin Ecoregion. The model is a multiperiod profit maximizing model and is solved using the Generalized Algebraic Modeling System using the MINOS solver (Rosenthal 2008). The model was originally developed as part of a regional research project but has since been used for policy analysis (Torell et al. 2014), ranch planning (Torell et al. 2010), soil health improvement (Dyer et al. 2021), and the impact of precipitation variation as it relates to forage production (Hamilton et al. 2016), among many other applications. This study uses a variation of this model to include prairie dog effects on forage availability and various management strategies.

The model maximizes the net present value (NPV) of discounted net annual returns (gross margin) over a planning horizon, subject to linear constraints specifying the ranch's resource limitations. Livestock production in any year is constrained by the resource availability for that year and any resources transferred from previous production years. Ranch operations and income are heavily influenced by cattle prices. Over the planning horizon in the model, 100 different price iterations were used to determine optimal production for a variety of potential price cycles across the relevant cattle classes that impact optimal decisions based on the interaction of forage and price dynamics (Ritten 2008; Ritten et al. 2010). Here, a 40-yr planning horizon is used as this is a typical time frame of a ranch manager's control of ranch operations. Equations in the model are included to transfer livestock, land, and financial resources from one production period to the next. The general structure of the model is shown in Figure 1 (from Torell et al. 2014).

Objective function

The objective function of this study's model, similar to previous variations, is to maximize NPV over a planning/production period of T yr (Equation 1).

$$Max\ NPV = \sum_{t=1}^{T} (DF_t * ((Income_t - Variable\ costs_t - Fixed\ costs_t) + TERM_T) \quad (1)$$

All costs and returns are reported in 2018 values. The discount factor (DF_t) is used to calculate the present value of future net returns, and the discount rate used in this analysis is 7%. Income is generated from livestock sales from all animal classes and cull animals in yr *t*, where variable costs are the costs of livestock production, forage production, and feed expenses (including purchased hay) for the yr *t*. Variable costs of production change when the number of animals on the ranch changes given forage supply and the market environment, whereas fixed costs are constant across all years. The $TERM_T$ variable is a terminal value that accounts for

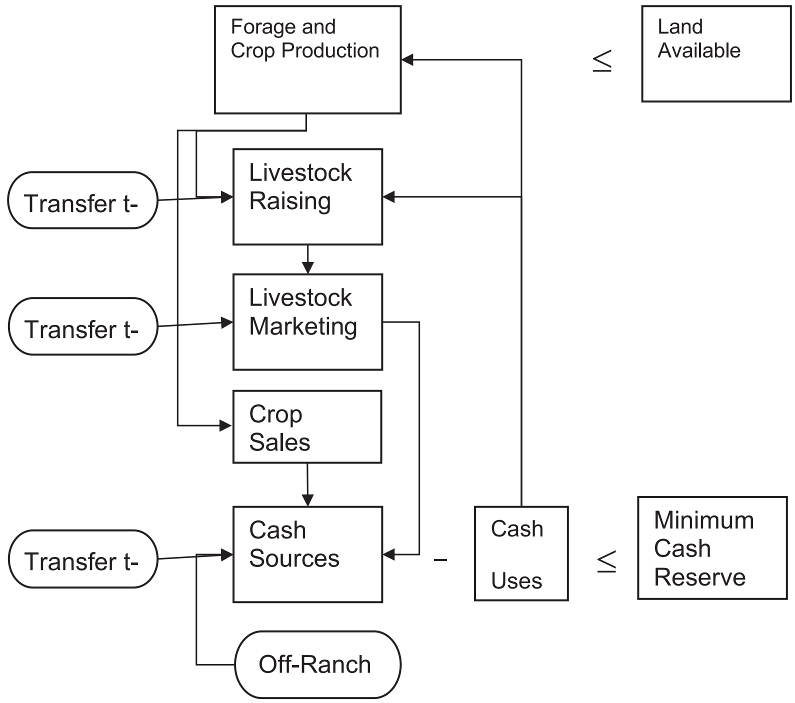

Figure 1. Linear programming conceptual model (Torell et al. 2014, fig. 1).

the value of brood cows, cull cows, replacement heifer yearlings, and replacement heifer calves after the 40-yr planning horizon. Given the objective is to maximize the NPV, if the terminal value is not included, the model would sell all breeding stock in the last year to maximize the NPV.

Livestock raising and marketing activities

The representative ranch accounts for three major livestock classes at various times of the year when accounting for forage demand, including calves, yearlings (replacement heifers), and mature animals such as brood cows and bulls. Brood cows, cull cows, and replacement heifer yearlings are typically co-mingled until sale. There is an annual variable cost of production per female of $105.67, which is in addition to all feed, grazing, and fixed costs of production. This variable cost includes protein tubs, salt and mineral, cake (15% protein), fuel, veterinary medicine, brand inspection, and beef check-off fees (Dyer et al. 2018).

Decision variables are the number of animals in each animal class on the ranch, which are optimally determined for profit maximization. The initial herd size is set at 800 cows, and in subsequent years the ranch model calculates the optimal number of brood cows subject to our forage constraints to maximize the net present value of profits over the 40-yr production period. Replacement heifer yearlings are retained from the previous calf crop. Herd productivity measures and required ratios between classes of livestock (bull/cow ratio, culling rate, calving success, death loss, and bull replacement rate, etc.) typical for the study area are used in the model. A minimum of 12% and a maximum of 80% of heifer calves are retained as replacement heifers. There is a minimum cow replacement rate of 15% while bulls have a 25% replacement rate. There is also a requirement of 1 bull to 25 cows or replacement heifers.

The ranch's calendar of operations is representative of operations in Thunder Basin, with calving from mid-March to mid-April with a 95% birth rate. Calves are weaned mid-October with a weaning rate of 88%. After weaning, all steer calves, some heifer calves, and replacement heifer yearlings not suitable as replacements are sold. Brood cows are pregnancy checked in October and, if determined not to be pregnant, are culled from the herd and sold. Animal sale weights are 249 kg steer calves, 227 kg heifer calves, 363 kg replacement heifer yearlings (those not suitable as replacements), 544 kg cull cows, and 816 kg bulls. Death losses for the animal classes are 2% for brood cows and replacement heifer yearlings, 1% for bulls, and 6% for replacement heifer yearlings not suitable as replacements. On the basis of the raising/selling activities and death loss in each production year, equations in the model transfer the remaining animals to the next year. Animal unit equivalencies are used to determine seasonal and annual forage requirements of the various livestock classes. An animal unit is a 454-kg cow and her calf, and linear adjustments (based on weight) are used for livestock classes in this model.

Land characteristics

Ranches in the Thunder Basin Ecoregion of Wyoming depend on three main land types/forage resources: deeded grazing lands, public grazing lands, and purchased supplemental hay. Hay production is not common in the region, but hay is readily available for purchase in seasons of low forage supply, particularly for feed in winter months. The public grazing lands used consist of both state-owned and federally owned land (US Forest Service). Public lands in the Thunder Basin are unique in allowing year-round grazing, but we assume hay is fed for at least one winter month each year. The representative ranch consists of 20 239 ha (10 182 AUMs on average) of Forest Service, 4 840 ha (2 512 AUMs on average) of deeded range, and 4 065 ha (2 110 AUMs on average) of state-owned land for a total 29 144 ha. The representative ranch's forage resources are based on the land types found within the ecoregion rather than a specific ranch. The total permit cost for State Trust grazing is $13 040 ($6.08/AUM; K. Schei, personal communication, October 2019), and the total permit cost for Federal Grazing is $13 746 ($1.35/AUM; Forest Service 2020 press release). The permit fees for State and Forest Service lands are in-

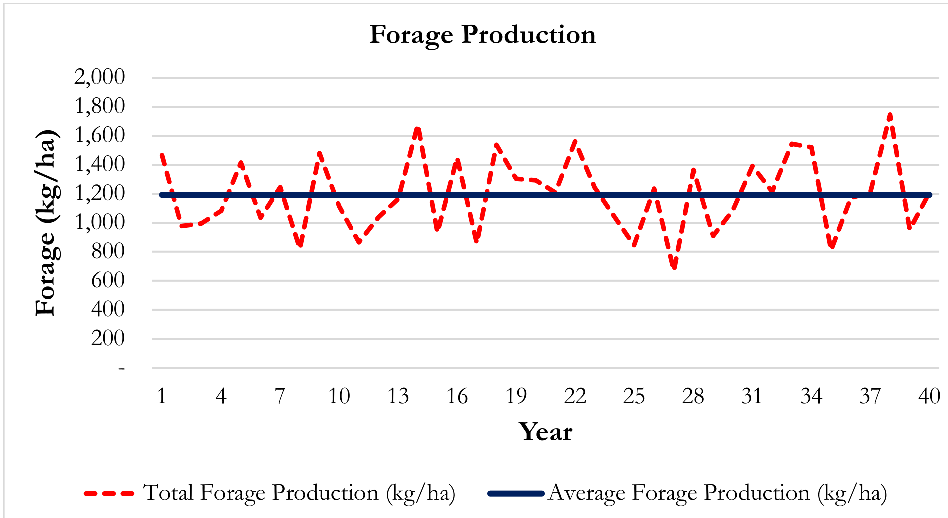

Figure 2. Total forage produced and average forage produced from 1978 to 2017 based on historical precipitation data from Cheyenne and Niobrara climate division.

cluded in the fixed ranch expenses, as ranchers pay this fee regardless of whether their cattle graze these lands in a particular year. All lands (including deeded lands) incur a $3.25/AUM nongrazing fee, or use cost, which represents the cost to the ranch when cattle graze this land (including the costs of range improvements, herding, checking, moving, and tending to cattle). Purchased meadow hay and purchased alfalfa hay are $164/ton and $172/ton, respectively (USDA-NASS 2018).

Annual forage production

In the Thunder Basin Ecoregion, growing season precipitation occurs from April to June, and precipitation received during this time has the largest effect on annual forage production. Following Hamilton et al. (2016), we estimate annual forage available for grazing (Fig. 2) using precipitation data from 1978 to 2017 (Water Resources Data System & Wyoming State Climate Office 2020). We assume 35% of total forage produced is allowed for livestock consumption.

Assumptions for prairie dog impacts on cattle

The effects prairie dogs have on forage are widely debated (Vermiere et al. 2004; Miller et al. 2007). Controversy arises in part from the high degree of variability in plant growth rates within and among years. During some portions of the growing season, plant growth rates outpace prairie dog consumption, such that standing forage availability on prairie dog colonies can be substantial (Augustine and Springer 2013; Brennan et al. 2021). Furthermore, dominant grasses in the western Great Plains can regrow rapidly after defoliation, and frequent cropping by prairie dogs can maintain them in a vegetative state with enhanced protein content and high digestibility (Jamarillo and Detling 1988; Whicker and Detling 1988; Augustine and Springer 2013; Connell et al. 2019). As a result, cattle often forage on colonies in proportion to their availability during the growing season (Guenther et al. 2003; Brennan et al. 2021; Augustine and Derner 2021). At the same time, during low-precipitation years and periods of plant senescence, standing biomass on colonies can be limited (e.g., Johnson-Nistler et al. 2004; Augustine and Springer 2013) and cattle intake rates on colonies decline (Brennan et al. 2021). Additionally, prairie dogs can alter plant species composition on some portions of their colonies, to the point that forage grasses become rare, annual forbs and subshrubs increase, and cattle intake rates are low (Archer et al. 1987; Brennan et al. 2021; Duchardt et al. 2021).

Given the existing uncertainties in the literature, we simulate cattle herd dynamics for two different sets of assumptions representing two extreme possible interactions between prairie dogs and livestock. The first likely underestimates the true impact, and the latter likely overestimates the true impact. In our first set of model scenarios based on *Forage Consumption,* we make the simple assumption that the positive and negative effects that prairie dogs can have on forage quality and quantity during the growing season effectively cancel one another over a 40-yr period and that the net direct effect of prairie dogs is equivalent to the amount of forage they consume. Given the high degree of dietary overlap between cattle and prairie dogs (Miller et al. 2007), the *Forage Consumption* scenarios assume that 335 prairie dogs equal an animal unit equivalency, meaning that 335 prairie dogs consume the same amount of forage as one 454-kg cow over any given time period. Prairie dog density estimates per hectare vary greatly, ranging from 12 to 86 prairie dogs per hectare (May 2004), and we assume a density of 42 prairie dogs per hectare. We acknowledge this scenario may underestimate total impact of prairie dogs on forage availability to cattle because it does not account for the fact that in addition to consuming vegetation, black-tailed prairie dogs also clip unconsumed vegetation to enhance visibility of their surroundings (Tileston and Lechleitner 1966; Gabrielson 2009). Further, Stoltenberg (2004) and Duchardt et al. (2021) show that prairie dog colonization can alter species composition, further impacting forage available for livestock.

Studies discussed earlier focused mainly on effects during the growing season. However, prairie dogs are typically active year-round, and consumption of forage during fall and winter can severely reduce standing biomass, to the point that little or none is effectively available for cattle. Managers may also choose to exclude cattle from colonies, for objectives related to either vegetation outcomes or cattle performance. We therefore conducted a second set of simulations, referred to as the *No Forage on Colonies* scenarios, based on the assumption that cattle are unable to acquire any forage from prairie dog colonies at any time of the year. This scenario assumes a more extreme effect of prairie dogs on vegetation than even what is expected from the combination of consumption and nonconsumptive clipping. It is important to note that this scenario does not include any potential costs associated with purposefully excluding cattle from prairie dog colonies. Although the exact effects prairie dogs have on forage can vary substantially in time and space, we assume the actual effects are likely between these two scenarios.

Table 1
Prairie dog livestock interaction assumptions.

Forage consumption	No forage on colonies
• Prairie dog density of 42/ha. • 335 prairie dogs consume as much forage as 1 cow. • As the colony expands, more forage is consumed. • # of prairie dogs/335 = AUM decrease	• Cattle do not forage on established colonies. • As the colony expands, less land is available for grazing. • Total ranch size (29 144 ha)—colony size = land available to graze

Assumptions for prairie dog population dynamics

We first estimate a base ranch model assuming no prairie dogs so that economic comparisons can be made to our various prairie dog-livestock interaction scenarios. We then estimate the model for each of the two sets of prairie dog–livestock interaction assumptions, assuming three different prairie dog population dynamic scenarios (Table 1). In the first scenario, we assume colonies grow at a constant rate of 20% annually between plague epizootics, and in the second, we assume they grow at 20% in normal or wet years, but at 40% annually in drought years. For comparison, Collins et al. (1984) found that the most reasonable prairie dog expansion rate was 30% annually in the Conata Basin of South Dakota. In our third scenario, we assume prairie dogs grow at 20% annually as in the first scenario but managed to maintain them at or below a target colony size (described later).

Epizootic outbreaks of plague, caused by the bacterium *Yersinia pestis* and transmitted via fleas, commonly affect prairie dog colonies in the western Great Plains and are a major reason for population decline in the Thunder Basin Ecoregion in recent years. Plague was introduced to the west coast of North America from Asia in the early 1900s and began to affect prairie dog populations in the Great Plains in the 1940s. Epizootic outbreaks of plague often result in > 95% mortality in infected colonies. Epizootics are density dependent, typically occurring when colonies are large and interconnected, at intervals of 5–15 yr (Augustine et al. 2008; Hartley et al. 2009; Johnson et al. 2011; Davidson et al. 2022). The relationship between weather patterns and epizootic outbreaks of plague is complex, and outbreak timing and location are currently difficult to predict (e.g., Cully et al. 2010; Eads and Biggins 2017; Davidson et al. 2022). In our model, we assume colony die-offs occur at approximately 8- to 12-yr intervals to mimic die-offs that have been observed and recorded in the TBNG (Davidson et al. 2022). Our model assumes rapid recovery of forage biomass to noncolony levels following removal of prairie dogs via plague or poisoning, such that forage is available to cattle the year after prairie dogs are removed. Actual recovery rates may vary in real systems (Augustine et al. 2014; Connell et al. 2019).

Unmanaged prairie dogs. The first scenario analyzed in our model is a ranch with *unmanaged prairie dogs*. In the first yr, colonies occupy 809 ha and then expand at 20% annually in all years without plague epizootics. The model assumes that three plague epizootics occur in yr 10, 20, and 28, which mimics the frequency of plague events recorded by the Forest Service personnel and Thunder Basin Grasslands Prairie Ecosystem Association in the Thunder Basin (Davidson et al. 2022), and on other National Grasslands in the western Great Plains (Augustine et al. 2008; Johnson et al. 2011). Over the 40-yr planning horizon, peak colony size is assumed to occur in yr 10 (4 176 ha and population of 176 162 prairie dogs), followed by a postplague area of 437 ha. Plague events in yr 20 and 28 reduce the size to 269 and 154 ha, respectively. At the peak colony size, 14.3% of the 29 144-ha ranch is occupied by prairie dogs (Fig. 3**A**).

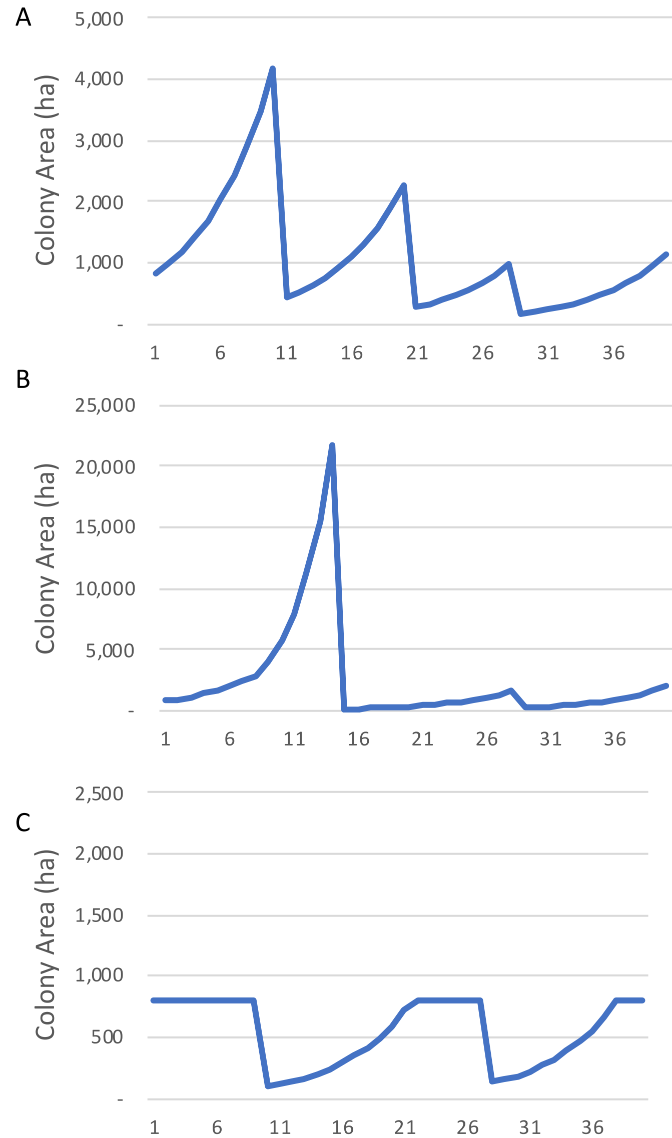

Figure 3. Modeled prairie dog colony acreage. A, Unmanaged prairie dogs. B, Unmanaged prairie dogs with increased expansion during drought. C, Managed prairie dogs for 809-ha colony target through 40-yr production period.

Unmanaged prairie dogs with increased expansion during drought. The second scenario is also a ranch with unmanaged prairie dogs where colonies begin at 809 ha and expand at a typical rate of 20% annually. However, in this scenario the prairie dog boom-cycle coincides with a 5-yr drought period of below-average forage production. During this boom-cycle, we assume that colonies expand at a rate of 40% annually. This scenario includes two plague events at yr 14 and 28. Peak colony area occurs in the last year of the drought, reaching 21 836 ha and population of 921 080 prairie dogs. At peak colony size, 74.9% of the 29 144-ha ranch is occupied by prairie dogs. Large colony expansions during drought periods could compound drought-induced forage limitations. This magnitude of colony expansion mimics colony expansion patterns documented during 2009–2017 in the Thunder Basin Ecoregion (Davidson et al. 2022), which was followed by major plague-induced colony contraction between 2017 and 2018. In this scenario, we assume that colony area declines to 154 ha in yr 14 and 269 ha in yr 28 (see Fig. 3B).

Managed prairie dogs for 809-ha colony target. The final scenario assumes prairie dogs are controlled using zinc phosphide applied via bait. Under this scenario, management of prairie dog populations is only implemented when colonies reach a total of 809 ha (equivalent to 34 140 prairie dogs), which corresponds to 2.8% of the ranch area occupied by prairie dogs. Here, we assume that the representative ranch seeks to contribute to 20% of a potential total objective of 4 047 ha of prairie dog colonies to sustain populations of wildlife species associated with prairie dogs across the Thunder Basin National Grassland. This scenario assumes 809 ha of colonies in the first year, which remains constant until a plague epizootic reduces colony size to 96 ha in yr 10 and 129 ha in yr 28. After these declines, the colonies expand at a 20% rate annually until they return to the target size of 809 ha (see Fig. 3C).

Many Wyoming counties offer a cost-share program to the county's producers for prairie dog management. Using the 50% cost-share program from Weston County Weed & Pest District, this scenario assumes that zinc phosphide is used to control colony size in 17 of the 40 production yr, or every 2.35 yr. Compared with a Collins et al. (1984) study in the Conata Basin of South Dakota, Schenbeck (1981) stated that most prairie dog colonies will need retreatment at least every 3 yr. Here, the retreatment of colonies occurs slightly more often because management is not used to reduce the colony below the target of 809 ha. In years when colonies are at 809 ha, we assume 162 ha of prairie dog colonies are treated annually, until a plague event reduces colony area below the 809-ha target. Zinc phosphide applications cost $26.77/ha, including a $28 cost per bag (assumed coverage area of 13.5 ha per bag; USDA Forest Service 2020) and labor cost of $24.71/ha (D. Gordon, personal communication, January 2020). Our economic model therefore assumes a cost to the ranch of $4 336 using zinc phosphide each year treatment occurs.

Ranch financial characteristics

The ranch model's financial situation includes fixed incomes, expenses, and an initial endowment of wealth acquired at the beginning of the planning period. The model uses an initial cash position of $100 000 and fixed ranch expenses are $64 036 including facility maintenance, machinery maintenance, depreciation, insurance, taxes, professional services, and the cost of public grazing fees (Eisele et al. 2011).

In years when revenue from livestock operations does not cover the production expenses, short-term borrowing is allowed. When the ranch requires a short-term operating loan, a 9% borrowing rate is applied and the loan is paid off within 1 yr for every production year except the last. In years when revenues exceed costs and profit is made, cash is rolled over to the next production year or placed in a savings account with a 3% return on interest. A minimum cash reserve of $500 must be maintained to cover any variable production expenses, fixed ranch expenses, and loan obligations (Torell et al. 2002).

Results

Cow herd size

Given the parameters we used to represent a ranching enterprise in the Thunder Basin Ecoregion, the model predicts that in the absence of prairie dogs, the ranch supports an average of 692 brood cows over the 40-yr production period, which fluctuates to a low of 409 cows due to forage limitations in dry years (Table 2). Under the assumptions of *Forage Consumption*, all three

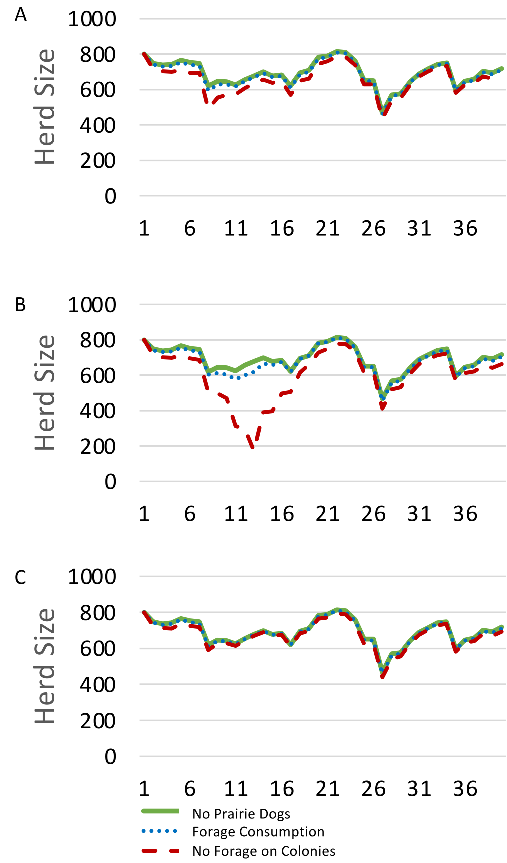

Figure 4. Simulated optimal cow herd dynamics for a ranch with **A,** unmanaged prairie dogs, **B,** unmanaged prairie dogs with increased expansion during drought, and **C,** managed prairie dogs for 809-ha colony target through 40-yr production period.

of the population scenarios result in reduced-average cow herd size. For the *unmanaged prairie dogs* scenario, the model predicts that average brood cow herd size is reduced to 684 cows, fluctuating to as low as 402 cows (see Table 2, Fig. 4**A**). Assuming *increased expansion of prairie dogs during drought,* average herd size declines to 679 brood cows and fluctuates more widely, reaching a low of 398 cows during a 5-yr drought (see Table 2, Fig. 4B). If prairie dogs are *managed to maintain an 809-ha colony target,* predicted average herd size is reduced to 687 brood cows and fluctuates to a minimum of 403 cows over the 40-yr production period (see Table 2, Fig. 4C).

For the *No Forage on Colonies* scenarios, the baseline scenario of a ranch with *no prairie dogs* remains unchanged, with an average 692 brood. For the *unmanaged prairie dogs* scenario, average cow herd size declines to 655 cows, with a minimum cow herd of 380 (see Table 2, Fig. 4A). The *unmanaged prairie dogs with increased expansion during drought* scenario predicts an average of 599 cows (see Table 2, Fig. 4B). When the prairie dog colonies reach a peak of 21 836 ha, only 22.6% of the ranch's forage is available and the herd declines to 167 cows, which is 72% lower than the 599 cow average. This extreme level of herd liquidation occurred during yr 8–13. After a plague epizootic in yr 14 reduces colonies to 154 ha, the ranch requires nearly a decade to recover its cow herd (see Fig. 4B). This decade-long recovery period reveals the severity of impacts if prairie dog expansion coincides with drought and illustrates what could be a worst-case scenario for a cow-calf producer. Under the *managed prairie dogs for an 809-ha colony target* scenario, the ranch supported an average of 673 cows and minimum cow herd size declined to 385 (see Table 2, Fig. 4C).

Table 2
Brood cow herd statistics from Forage Consumption and No Forage on Colonies scenarios.

		No Prairie Dogs	*Unmanaged Prairie Dogs*	*Unmanaged Prairie Dogs with Increased Expansion During Drought*	*Managed Prairie Dogs for 809-hectare Colony Target*
Forage consumption	Average	692	684	679	687
	Minimum	409	402	398	403
	Maximum	1 040	1 034	1 034	1 034
	Standard Deviation	100	101	104	100
No forage on colonies	Average	692	655	599	673
	Minimum	409	380	167	385
	Maximum	1 040	1 018	999	1 016
	Standard Deviation	100	108	165	101

Table 3
Proportion of annual net returns less than zero for all scenarios.

	Forage consumption	No forage on colonies
No prairie dogs	10.6%	10.6%
Unmanaged prairie dogs	10.9%	12.3%
Unmanaged prairie dogs with increased expansion during drought	10.9%	16.5%
Managed prairie dogs for 809-ha colony target	10.9%	11.5%

Annual returns

Stability in revenue from year to year can be an important consideration for ranching enterprises, particularly for those that are already highly leveraged. We therefore examined the frequency of years that the simulated ranch would experience negative annual net returns. In the absence of prairie dogs, the simulated weather and market conditions resulted in a 10.6% chance of negative returns (Table 3). Under the assumptions of *Forage Consumption,* this increases slightly to 10.9% for all three population scenarios. In contrast, under the *No Forage on Colonies* the chance of negative annual returns increases by 1.4%, 5.6%, and 0.6% for ranches with *unmanaged prairie dogs, unmanaged prairie dogs with increased expansion during drought,* and *managed prairie dogs for an 809-ha colony target,* respectively. In the assumed worst-case scenario where a prairie dog boom-cycle expansion is coupled with a multiyear drought, not only do annual returns decrease substantially as compared with a ranch with no prairie dogs, but the likelihood that the operation will not have the funds to pay expenses in any given year increases notably.

Net present value of returns

For each of the scenarios, we calculated the NPV as the summed discounted net returns over a 40-yr production year, simulated for 100 different price iterations (Table 4), all reported in 2018 dollars. Under the assumptions for *Forage Consumption,* the NPV declines by 1.5% with the *unmanaged prairie dogs* scenario and by 2.5% for both the *unmanaged prairie dogs with increased expansion during drought* and the *managed prairie dogs for a 809-ha colony target* scenarios. If the only impact of prairie dogs is direct consumption of forage, management of prairie dogs does not pay, even if prairie dogs expand rapidly during a drought period.

Under the assumptions for *No Forage on Colonies,* we found larger decreases in NPV of 7.7% with unmanaged prairie dogs and 22% for *unmanaged prairie dogs with increased expansion during drought*. In contrast, NPV for the *managed prairie dogs for an 809-ha colony target* scenario declined by only 4.8% (Table 4).

Discussion

We used a multiperiod linear programming model to examine potential impacts of various prairie dog dynamics on a cow-calf operation in the Thunder Basin Ecoregion of Wyoming. Because epizootic outbreaks of plague periodically decimate prairie dog populations throughout the western Great Plains even in the absence of any management actions, the degree to which prairie dog control is an economically viable strategy remains uncertain. Because prairie dog effects on forage and livestock production could potentially vary widely in time and space, we examined scenarios designed to represent relatively extreme assumptions about these effects. On one hand, our *Forage Consumption* scenarios assume forage consumed by prairie dogs is unavailable for livestock but that the colony is still grazed and provides useable forage for cattle. Under these conditions, we found that even if prairie dogs are unmanaged and expand rapidly during a multiyear drought period, the decline in a ranch's NPV is relatively minor. Furthermore, the costs of managing the prairie dogs to maintain them at or below an 809-ha target are not outweighed by the increase in revenue generated by cattle production. This result arises in part because plague outbreaks maintain the prairie dog population at low acreages in a majority of the years. The assumptions of the *Forage Consumption* scenarios may be most applicable to situations where cattle graze primarily or exclusively on prairie dog colonies during the growing season, when prairie dogs often enhance forage quality (e.g., Connell et al. 2019) and standing biomass of palatable plant species is often high enough to maintain cattle intake rates (Brennan et al. 2021). Indeed, the magnitude of the decline in NPV simulated by the *Forage Consumption* model was similar to that measured in experimental studies of yearling cattle in northeastern Colorado, where cattle weight gains declined by only 4−8% when prairie dogs occupied 30−60% of a pasture and long-term average weight gains declined by only 2% over a 12-yr period where prairie dog population fluctuated in response to plague (Augustine and Derner 2021). In the Colorado study, the limited effect of prairie dogs could be attributed to yearlings only being studied during the growing season (May–October), thus alleviating effects of prairie dogs on dormant season forage reserves.

In contrast, under the *No Forage on Colonies* assumption when prairie dog colony expansion occurs in conjunction with a multiyear drought, the impacts can be catastrophic. This heightens the risk for a cow-calf operation in an area managed for prairie dog colony expansion. The assumptions of our *No Forage on Colonies* model scenarios may be more applicable to situations where cattle rely on pastures occupied by prairie dogs during the dormant season, when plant growth is not offsetting consumption and clipping by prairie dogs and standing forage biomass can become so low that it is effectively unavailable to cattle. This can also occur during the growing season on portions of colonies where long-term prairie dog occupancy shifts species composition to annual forbs and subshrubs that are typically uneaten by cattle, although such

Table 4
Average net present value of Forage Consumption and No Forage on Colonies scenarios over 100 different price cycle iterations.

		No prairie dogs	Unmanaged prairie dogs	Unmanaged prairie dogs with increased expansion during drought	Managed prairie dogs for 809-ha colony target
Forage consumption	Average	$1 834 052[1]	$1 806 458	$1 788 147	$1 788 045
	Standard deviation	131 982	132 432	131 417	131 500
No forage on colonies	Average	$1 834 052	$1 692 503	$1 431 554	$1 745 580
	Standard deviation	131 982	135 037	102 102	129 688

[1] All figures are reported in 2018 dollars.

areas often occupy only a minor portion of the total colony (e.g., Archer et al. 1987; Brennan et al. 2021; Duchardt et al. 2021). One of the primary limiting factors in a cow-calf operation, where year-round grazing is required, is the forage quantity available during the dormant season. Unlike stocker operations where yearling cattle's forage intake directly translates to weight gains and the cattle are typically sold before the dormant season, cow-calf operations require forage throughout the year to produce a marketable calf. Thus, the increased forage quality during the growing season is less important for cow-calf pairs grazing year-round and to begin cycling post-calving within 30 d to maximize productivity of the cow herd. As a result, the impacts of prairie dogs on a cow-calf operation may depend on the extent of colonies occurring on growing-season versus dormant-season pastures. To the extent that all colonies occur on dormant-season pastures, the effect of prairie dogs could be nearly equivalent to our assumptions for the *No Forage on Colonies* scenarios. Conversely, economic impacts of prairie dogs could be minimized by a mixed strategy where prairie dogs are allowed to occur on growing-season pastures up to a target size threshold, but populations are controlled in a spatial configuration that ensures they do not expand into dormant-season pastures.

Under the *No Forage on Colonies* assumptions, we found that managing prairie dogs for an 809-ha target was economically better than allowing prairie dogs to fluctuate without management and was especially important in mitigating the risk of extreme herd liquidation if prairie dogs expand rapidly during a multiyear drought. These findings differ from those of Collins et al. (1984), who found that managing prairie dogs with zinc phosphide was not economically feasible in the Conata Basin of South Dakota. However, the South Dakota analyses were conducted in a region and time period when plague was not affecting prairie dog populations and in more productive grassland where prairie dog colonies do not expand as rapidly. Given high uncertainty in the timing and length of droughts in eastern Wyoming, as well as uncertainty in the timing of plague epizootics, management to control prairie dog populations when they reach a threshold appears to be an effective strategy to mitigate the risk associated with a herd liquidation followed by slow herd regrowth.

Additional uncertainty in the value of prairie dog population control arises from uncertainty in the effectiveness of control measures. The cost-effectiveness of managing prairie dogs is highly dependent on the situation, but using a threshold approach can reduce the need to control prairie dogs in all years while also accounting for the facts that ranchers have different risk tolerances, prairie dog densities and colony expansions are highly variable, and timing of the next drought is unknown. If prairie dogs were not managed, a rancher would be taking an inherent risk assuming that a drought or prairie dog boom-cycle expansion will not occur, but the rancher also incurs no extra cost of managing the prairie dogs. If a rancher chose to manage prairie dogs, they are ensuring that their cattle will have forage to graze, but the rancher will incur the cost of managing the prairie dogs. In this situation, if the management of prairie dogs lasts more than 1 yr, meaning that further treatment is not needed for several more years, the management of prairie dogs is more likely to be economically feasible. But, if managing prairie dogs involves multiple consecutive years of treatment, it is less likely that the value of forage gained from treatment of colonies will outweigh the cost of treatment through consecutive years.

Another strategy to increase ranch enterprise flexibility and minimize operational risk is the addition of a yearling stocker enterprise, which could increase profitability by up to 35% given increased variability in growing season precipitation while also stabilizing the cow herd across years and sustaining herd genetics (Bastian et al. 2018). The addition of a stocker enterprise would decrease the size of the cow herd but increase flexibility for which herds graze pastures containing prairie dog colonies at which time of year, potentially reducing the magnitude of negative effects on stocker weight gain compared with the assumptions made in our model scenarios. Thus, a mixed cow-calf and stocker approach could represent a useful risk mitigation strategy for ranchers operating in the context of coexistence with temporally dynamic prairie dog colonies. Indeed, herd diversification is a strategy used worldwide by dryland livestock producers to reduce risk in the face of climate variability (Espeland et al. 2020).

Implications

Our modeling results evaluated two extreme scenarios for how black-tailed prairie dogs may affect economic viability of a cow-calf operation in the Thunder Basin Ecoregion of Wyoming. Under the assumption that prairie dogs only compete with cattle via direct consumption of forage (minimal competition scenario), prairie dogs had only a minor effect on average net present value of the enterprise and management to maintain prairie dogs on the ranch at a maximum colony extent of 809 ha was less economically viable than leaving prairie dogs unmanaged. However, under the assumption that prairie dogs eliminate all available forage on occupied colony areas (maximum competition scenario), management to maintain prairie dogs on the ranch at the 809-ha maximum extent was more profitable than leaving prairie dogs unmanaged. The former scenario may more closely represent prairie dog effects on growing-season pastures, while the latter may more closely represent effects on dormant-season pastures. As a result, we suggest spatially explicit management plans for prairie dogs that account for seasonal use of different pastures by cattle may help mitigate economic effects of prairie dogs. Further research efforts that could improve understanding of economic impacts of prairie dogs on livestock operations include 1) empirical measures of prairie dog effects on livestock use of dormant season pastures and 2) understanding costs of spatially targeted prairie dog control to prevent colony expansion into portions of the ranch where they have the greatest economic impact.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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