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Original Research

PDOG MAPR: A Decision Support Tool to Inform Management of Prairie Dog Ecosystems

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ABSTRACT

Structured frameworks for Conservation Decision Making are increasingly used to guide complex land and wildlife management by fostering transparency, informed decision processes, and collaborative input. These tools are particularly valuable in working rangelands, where managers must balance ecological integrity with agricultural productivity amid mounting environmental pressures. In North America's Central Grasslands, black-tailed prairie dogs (*Cynomys ludovicianus*)—a keystone species often in conflict with livestock production—and the introduced pathogen, *Yersinia pestis*, create boom–bust colony dynamics that challenge management. We introduce PDOG MAPR, the first publicly accessible, web-based decision-support tool for prairie dog conservation and management. Users upload colony shapefiles, set management scenarios, and generate spatially explicit forecasts of colony-area trajectories and plague-outbreak risk. We demonstrate the tool with two case studies from the Central Grasslands, evaluating 1) plague mitigation and 2) lethal control along public–private boundaries. PDOG MAPR predicted that unmanaged colonies tend to expand and then collapse following plague, replicating patterns reported from plague-endemic regions, whereas plague mitigation prevented major population crashes and increased population stability. Our results show that management choices can meaningfully alter colony trajectories, underscoring the value of predictive tools for scenario-based, proactive planning. Although PDOG MAPR's predictions are not deterministic, the tool provides a flexible, data-driven platform to identify when and where to apply interventions to 1) meet site-specific objectives, 2) reduce the risk of large-scale colony collapse, and 3) support coexistence between prairie dog ecosystems and surrounding land uses. By translating complex dynamics into spatially explicit, manager-ready outputs, PDOG MAPR complements local expertise and facilitates dialogue among agencies, producers, and conservation practitioners. A public version is available for planning. More broadly, PDOG MAPR contributes to the growing suite of decision-support resources for multiuse grasslands and advances integrated planning that optimizes limited resources, supports biodiversity, and promotes coexistence on working lands.

Introduction

Structured frameworks for Conservation Decision Making are increasingly employed to guide natural resource management under conditions of complexity and uncertainty (Folk et al. 2005; Schwartz et al. 2018; Bower et al. 2018). These approaches promote transparency, accountability, and stakeholder participation—key elements in rangeland systems where land use decisions must balance ecological integrity with agricultural production (Sprague Jr. 1980; Schwartz et al. 2018). Nowhere is this balance more critical than in temperate grasslands, which are among the most extensively altered and threatened ecosystems globally due to widespread conversion for agriculture (Neke and Plessis 2004; Török et al. 2018; Squires et al. 2018; Augustine et al. 2021a;

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Douglas et al. 2023). In North America, over 80% of the Central Grasslands have been lost to land-use change, resulting in fragmented habitats and the decline of native species (Samson and Knopf 1994; Grand et al. 2019). Within working landscapes, decision-support tools can help managers integrate ecological data with land-management priorities, advancing biodiversity conservation while sustaining rangeland function and productivity.

One of the greatest challenges facing North America's Central Grasslands is the conservation and management of black-tailed prairie dogs (*Cynomys ludovicianus*; hereafter, prairie dogs), a keystone species and ecosystem engineer. Prairie dogs are a key food source for many predators, and they create unique open habitat and extensive burrow systems that provide refuge for numerous grassland animals (Davidson et al. 2007; Augustine et al. 2008a; Davidson et al. 2012; Eads et al. 2016; Parker et al. 2019; Duchardt et al. 2020). Historically, prairie dog colonies were expansive and abundant across their geographic range, extending from southern Canada to northern Mexico (Knowles et al. 2002). However, prairie dog populations have been drastically reduced (>95% loss) over the past century, due to habitat loss, the introduction of *Yersinia pestis* (the bacterium that causes sylvatic plague) from Asia, and widespread eradication campaigns meant to eliminate their competition with livestock for forage (Miller et al. 2007).

Prairie dog conservation and management are fraught with complex ecological and socioeconomic challenges, and strategies for prairie dog management vary starkly based on management goals (Knowles et al. 2002; Hoogland 2006). In areas where *Yersinia pestis* is present, prairie dog populations tend to follow "boom-and-bust" dynamics, with rapid, widespread declines during epizootics followed by periods of gradual recovery (Augustine et al. 2008b; Davidson et al. 2022a). These dramatic population fluctuations can negatively affect associated wildlife during population crashes, while colony expansion during recovery phases—especially in drought years—can lead to increased forage competition with livestock (Olson et al. 2016; Parker et al. 2019; Augustine and Derner 2021; Davidson et al. 2022a; Duchardt et al. 2022). From a conservation perspective, maintaining moderate to large prairie dog colony complexes is critical for sustaining biodiversity and supporting species of concern, such as the endangered black-footed ferret, which relies on prairie dogs for over 95% of its diet (Davidson et al. 2012; Miller and Reading 2012; USFWS 2013; Duchardt et al. 2020; Livieri et al. 2022). In response, conservation managers have implemented plague mitigation strategies—such as flea control with insecticides or vaccine delivery—to stabilize prairie dog populations and sustain large, intact colonies (Tripp et al. 2017; Eads and Biggins 2019). By contrast, livestock producers often seek to minimize colony size and prevent expansion to limit potential economic losses from forage competition (Crow et al. 2022; Augustine et al. 2025). These goals are often pursued through lethal control, including poisoning or shooting, applied across colonies or along their perimeters (hereafter, "boundary control") to prevent encroachment onto adjacent private lands (Knowles et al. 2002; Buehler et al. 2025).

Land management agencies face difficult decisions about how to most effectively deploy plague mitigation and boundary control strategies to enhance ecosystem services while minimizing negative impacts on surrounding private lands, ecosystem function, and limited agency budgets (Buehler et al. 2025). Both plague mitigation and lethal control are costly, labor-intensive interventions that vary in effectiveness (Collins et al. 1984; Bodenchuk et al. 2013; Eads and Biggins 2019; Roth 2019; Buehler et al. 2025). When applied independently or in a piecemeal fashion across the same landscape, these strategies may conflict with one another—potentially diminishing both economic efficiency and ecological outcomes. As such, there is a pressing need for decision-relevant information to guide the spatial and temporal application of these strategies in ways that reduce plague-driven population volatility, support biodiversity conservation, and promote coexistence with local ranching communities.

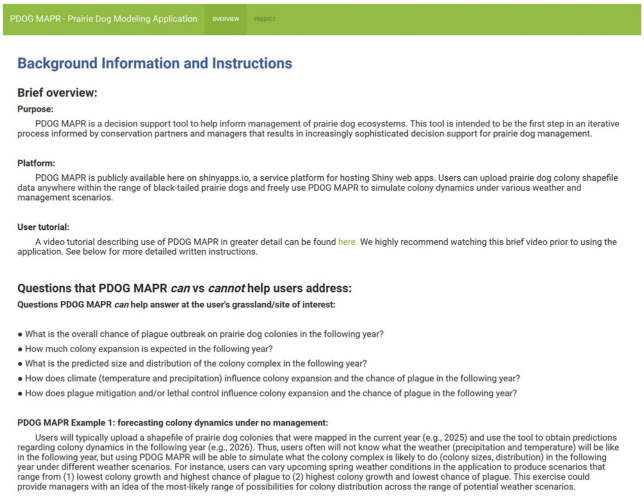
Herein, we introduce PDOG MAPR, an interactive, web-based tool to inform decision-making for prairie dog conservation and management. We first briefly describe a previous effort that developed a spatially-explicit model to reliably predict disease outbreaks and subsequent colony recovery in the prairie dog–plague system (Barrile et al. 2023). We then detail the integration of this predictive model into PDOG MAPR, an interactive Shiny Application that allows users to simulate various management scenarios. We incorporated plague mitigation and boundary control into PDOG MAPR because these are the primary strategies currently used to manage prairie dog populations, and we aimed to provide a flexible, spatially explicit decision-support tool that can inform conservation-oriented management tailored to diverse on-the-ground conditions and objectives. Finally, we demonstrate the utility of PDOG MAPR at two USDA Forest Service National Grasslands where prairie dogs experience sylvatic plague: Thunder Basin and Comanche National Grasslands in Wyoming and Colorado, USA, respectively. We chose these National Grasslands as case examples because they differ considerably in climatic regime, land ownership pattern, vegetation composition, management objectives, and the size, abundance, and connectivity of prairie dog colonies (Augustine et al. 2021a). Thus, management interventions may influence colonies differently at each grassland, a pattern that could manifest when users apply the tool to their specific study area. Ultimately, our application provides data-driven predictions that can assist with decision making in grassland ecosystems. Management remains a complex, multifaceted process, but decision support tools such as ours can offer evidence-based approaches for management and conservation partners with diverse interests (Folk et al. 2005; Schwartz et al. 2018).

Methods

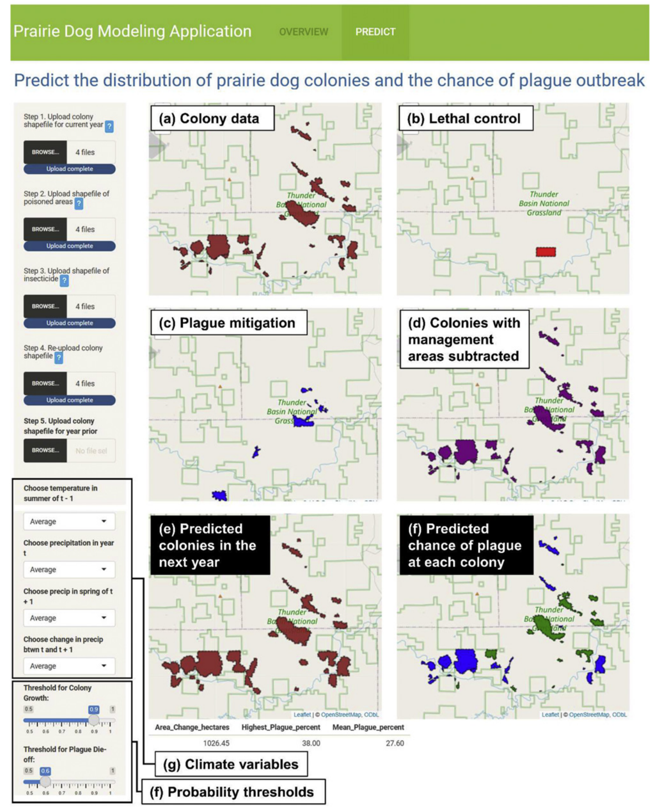
Development of a spatially explicit predictive model

Previously, our research team parameterized and validated a machine learning model to predict plague epizootics and subsequent colony recovery in the prairie dog–plague disease system (for full details, refer to Barrile et al. 2023). Briefly, we synthesized colony data between 2001 and 2020 from eight USDA Forest Service National Grasslands across the range of black-tailed prairie dogs in central North America. We then modeled spatiotemporal changes in prairie dog colonies in relation to complex interactions among climate, topoedaphic variables, colony characteristics, and disease history. Rigorous cross-validations and spatial predictions indicated that our final model predicted plague outbreaks and population recovery with high accuracy; overall accuracy from withholding randomly selected colonies achieved an area under the curve (AUC) of a receiver operator characteristic of 0.96 for colony recovery and a 0.87 for plague, whereas withholding all data from each National Grassland achieved an AUC of 0.91 for colony recovery and 0.78 for plague (Barrile et al. 2023). Overall, our model can be employed to produce spatially explicit predictions of colony distribution in areas where prairie dogs are challenged with sylvatic plague.

Specifically, for each grid cell (i.e., raster pixel) on a given landscape, our model predicts the probability of "colonization" (probability that prairie dogs will expand into an unoccupied cell between year t and $t+1$) and "extinction" (probability that prairie dogs will experience plague between t and $t+1$ at an occupied location). Probability thresholds are needed to reclassify colonization and extinction layers into binary rasters prior to merging and converting them into one shapefile of predicted colony distribution at



Box 1. Overview and Predict panels of PDOG MAPR application. The "Overview" tab provides information on the application as well as detailed instructions on its use. The "Predict" tab allows users to upload colony and management shapefiles and run the application to predict colony growth and probability of plague outbreaks. In the "Predict" tab of PDOG MAPR: (a) The user first uploads a shapefile of colony boundaries for black-tailed prairie dogs (i.e., colony data) in the current year or year of interest (i.e., year t). The application works across the entirety of the species range of black-tailed prairie dogs in the United States (see Figure 2). The user then uploads a shapefile for (b) lethal boundary control and/or (c) plague mitigation. If neither or one of these management actions are not relevant to the user's goals, the user can bypass each step accordingly. (d) Colony data with management areas masked are plotted for visual inspection by the user. In other words, subtracting management areas from the colony data in (d) allows the user to observe how management is expected to influence the connectedness of colonies. After these initial uploads (a–c), the server side of the application runs the machine learning model of Barrile et al. (2023) and produces (e) the predicted colony distribution in the following year and (f) the predicted probability of plague occurring at each existing colony that following year, with variation in color reflecting the probability of plague. For instance, green colonies in (f) have a higher predicted chance of plague then blue colonies, and users can click on each colony to observe the expected probability. A summary table appears below the outputs (e, f) displaying the total net change in colony area (in hectares) between the two years and the mean and maximum percent chance of plague across colonies. White boxes (a–d) denote inputs, whereas black boxes (e, f) denote outputs. Additional inputs that can be varied by users include (g) climate variables and (f) probability thresholds (see main text for an explanation of these inputs).



Box 1. Continued

time t + 1 (Barrile et al. 2023). For example, if the threshold is set at 0.80 for both colony growth and plague probabilities, grid cells with values above 0.80 are assumed to be colonized or to go extinct, respectively, when predicting colony distribution.

Integrating the predictive model into a decision support tool

We developed the model described above using RStudio, a free and open-source integrated development environment for Program R (R Core Team 2023). Our model therefore could only be used by those with some level of proficiency in the R programming language. To make the model more user-friendly, our objective herein was to deploy our model as an interactive web-based application. In addition to the spatially-explicit predictions of colony distribution produced by the original model, we aimed to allow users to simulate short-term effects of plague mitigation (i.e., insecticide/vaccine application) and lethal control (i.e., poisoning colonies) on disease dynamics and prairie dog distribution. Doing so would convert our model into a decision support tool where users could observe the predicted outcomes of real-world management applications, with the ultimate goal of informing decision making. We emphasize that we are not advocating for any specific management strategy in this study. Rather, we simulated the spatial outcomes of two management techniques commonly used to manage prairie dog colonies. Users of the tool are able to define spatial areas within which they assume a given treatment was effective at either removing or protecting prairie dogs for one year.

When integrating our model into a Shiny application using the Shiny package in Program R (Chang et al. 2021), our code consisted of three main components: 1) loading the fitted model and raster layers that correspond to model covariates, 2) the user interface, and 3) the server, an R session that runs code and returns results. The user interface (i.e., dashboard) of PDOG MAPR has two main panels. The first panel provides text on the overall project and utility of the application, while the second panel hosts all the functionality of the decision support tool (i.e., user inputs their data and obtains model predictions; Box 1). On the second panel, the user is first prompted to upload a shapefile (via clicking the browse button to locate all of the components of the shapefile on their local machine) of prairie dog colony boundaries. For more detailed instructions on the use of PDOG MAPR, please refer to Appendix S1.

At a minimum, PDOG MAPR can be used with simply a shapefile of colony data for a given year, describing expected colony dynamics under no management in the following year (year t + 1); however, PDOG MAPR can also incorporate management in the forms of plague mitigation or lethal control by uploading separate shapefiles for areas within which the desired management strategy is assumed to be effective for one year. Preset management strategies were not incorporated into the application as management differs greatly between grasslands and for the most realistic outcomes, managers should upload scenarios relevant to their particular regions. PDOG MAPR also can be used to explore the influence of climate on prairie dog dynamics, as informed by relationships identified in Barrile et al. (2023). Users have the option to vary temperature and precipitation data to examine how these covariates alter predicted colony distribution in year t + 1.

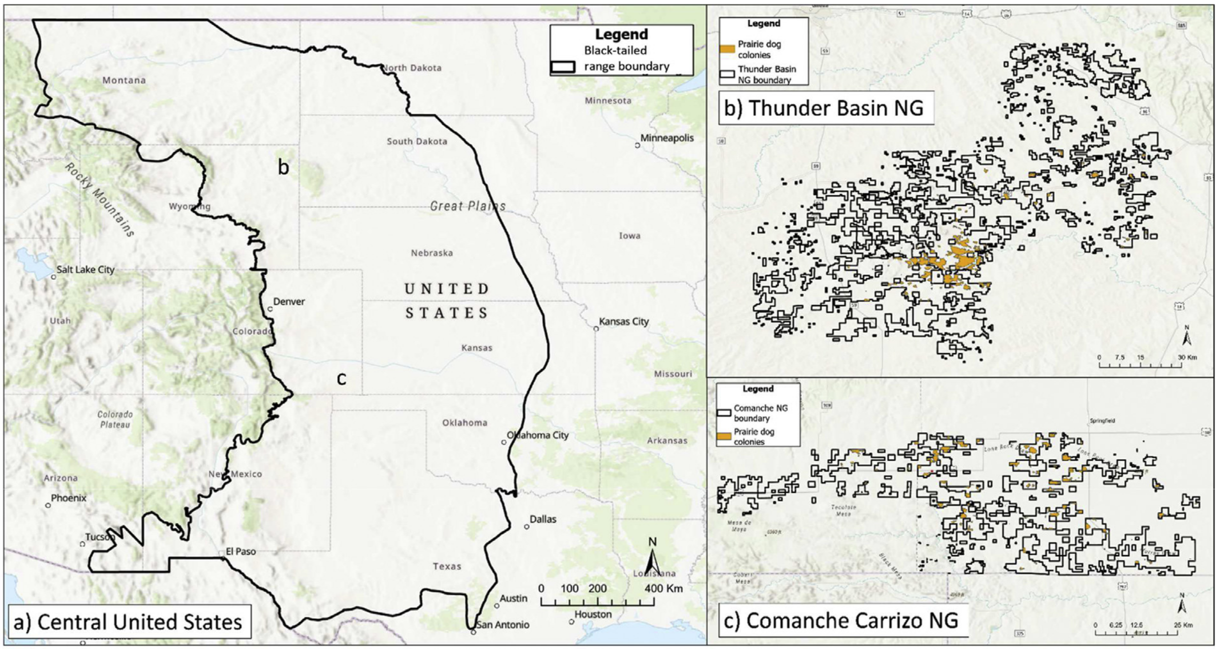


Figure 1. Study area for two case studies demonstrating the use of a decision support tool to manage prairie dog populations. Panel a) shows the range of prairie dogs, across the entirety of which PDOG MAPR is functional, as well as the locations of the two grasslands within the broader United States, panel b) shows Thunder Basin National Grassland, WY, and panel c) shows the Carrizo unit of Comanche National Grassland, CO. Prairie dog colonies are represented in orange; black lines denote grassland boundaries.

Specifically, users can choose to simulate average, warm, or cool temperatures and average, wet, or dry precipitation. Here, climate variables represent the long-term average, minimum, and maximum during 2000–2020, which mirror the model covariates used in Barrile et al. (2023). Users can also vary the probability thresholds for colony growth and plague die-offs to examine how these user-defined thresholds affect colony and plague dynamics.

PDOG MAPR applications and case studies

To evaluate the utility of PDOG MAPR, we used the Shiny application to simulate prairie dog colony growth and plague outbreaks during historical years of rapid expansion (“booms”) and plague-induced collapse (“busts”) at two contrasting National Grasslands in the central United States—Thunder Basin National Grassland (TBNG) in northeastern Wyoming and Comanche National Grassland (CNG) in southeastern Colorado (Fig. 1). Because landowner conflicts often arise from fluctuations in colony size and location, these two case studies were designed to demonstrate how PDOG MAPR can project colony responses under varying management strategies, supporting both conservation and conflict-mitigation objectives.

TBNG lies at approximately 1 300 m elevation, with dominant vegetation including big sagebrush (*Artemisia tridentata*), perennial C3 and C4 grasses (e.g., *Pascopyrum smithii*, *Bouteloua gracilis*), and annual forbs and grasses such as *Alyssum desertorum*, *Lepidium densiflorum*, and *Bromus tectorum* (Davidson et al. 2022). The semi-arid climate averages 319 mm annual precipitation (range 250–350 mm) with temperatures from −5°C to 22°C (Porensky et al. 2018). TBNG supports large, well-connected prairie dog complexes that are periodically reduced by plague, often at intervals of 5–10 years (Davidson et al. 2022). Colony area in the central study region increased from roughly 2 000 ha in 2005 to over 10 000 ha in 2016–2017, exceeding 30 000 ha across public and private lands, before a near-total collapse in 2018 with substantial consequences for associated wildlife (Duchardt et al. 2022). Management of prairie dogs on TBNG has been occurring for over two decades, with focuses on increasing colony size and reducing plague outbreaks in certain areas and controlling colony expansion in other areas. Plague mitigation has been implemented for the past two decades, initially using Deltamethrin dust and more recently Fipronil grain baits, with treatment areas ranging from 0 to 1 200 ha annually since 2010 (USFS 2020) typically covering between 4% and 38% of total colony area (Davidson et al. 2022). Lethal control of prairie dogs has also occurred intermittently on TBNG over the past two decades, typically through applications of rodenticide or hunting by the public.

In contrast, CNG was composed of smaller, disconnected portions of public land interspersed within private land and supported smaller, more isolated colonies as a result. Dominant vegetation included blue grama (*B. gracilis*), purple threeawn (*Aristida purpurea*), buffalograss (*B. dactyloides*), and sideoats grama (*B. curtipendula*) (Augustine et al. 2008b). The region received an average of 403 mm annual precipitation. Our analysis focused on the Carrizo subunit, where colony extent ranged from approximately 2 500 ha in 2003 to 8 000 ha in 2014 before collapsing in 2016. Due to the smaller and more fragmented nature of prairie dog colonies on CNG, management of prairie dogs did not involved applications of plague mitigation or lethal control.

There are many tools that can be implemented for both prairie dog control and plague mitigation. Control in Thunder Basin and Comanche typically consisted of application of prebaiting with nontoxic grain followed by application zinc phosphide grain baits in fall and winter. This temporal window 1) targets a timeframe where food is limiting, increasing the probability of bait uptake and 2) reduces potential nontarget species consumption of grains, as most breeding birds have migrated at this time, and species with highest probability of conflict (e.g., burrowing owl *Athene cunicularia*) are rare or absent. In Thunder Basin specifically, zinc phosphide application is limited to Oct 1–Jan 31 each year (U.S. Forest Service 2020). Plague mitigation efforts in recent years have shifted from application of Deltadust to Fipronil grain baits, but efficacy for both treatments is comparable (Eads et al. 2019); while timing application is not as restricted as control methods, application typically occurs in summer or fall. PDOG MAPR does not ex-

Table 1
Full list of management scenarios applied to prairie dog colonies at Comanche National Grassland, CO, USA (CNG) and Thunder Basin National Grassland, WY, USA (TBNG) applied as either plague mitigation designed to protect prairie dogs from plague, applied as either large polygons (Encourage zones) or circular treatments at the center of each colony of differing radius (100 m, 250 m or 500 m) or as lethal boundary control (BC) designed to remove prairie dogs along public-private landownership boundaries or as.

Treatment	Potential effect	Grassland
No management	No treatment	CNG, TBNG
0.40 km BC	Reduce colony growth at edges	CNG, TBNG
0.40 km BC + private land control	Reduce colony growth at edges + eliminate colonies on private land	CNG, TBNG
100 m insecticide core	Protect SMALL portion of inner colony	CNG, TBNG
250 m insecticide core	Protect intermediate portion of inner colony	CNG, TBNG
500 m insecticide core	Protect large portion of inner colony	CNG, TBNG
Encourage zones	Protect large swaths of colony	TBNG
0.40 km BC + 100 m insecticide core	Reduce colony growth at edges + protect small portion of inner colony	CNG, TBNG
0.40 km BC + 250 m insecticide core	Reduce colony growth at edges + protect intermediate portion of inner colony	CNG, TBNG
0.40 km BC + Encourage zones	Reduce colony growth at edges + protect large swaths of colony	TBNG
0.40 km BC + private land control + 100 m insecticide core	Reduce colony growth at edges + eliminate colonies on private land + protect small portion of inner colony	CNG, TBNG
0.40 km BC + private land control + 250 m insecticide core	Reduce colony growth at edges + eliminate colonies on private land + protect intermediate portion of inner colony	CNG, TBNG
0.40 km BC+ private land control + Encourage zones	Reduce colony growth at edges + eliminate colonies on private land + protect large swaths of colony	TBNG
0.80 km BC	Reduce colony growth at edges to a larger extent	TBNG
0.80 km BC + private land control	Reduce colony growth at edges to a larger extent + eliminate colonies on private land	TBNG
0.80 km BC + 100 m insecticide core	Reduce colony growth at edges to a larger extent + protect small portion of inner colony	TBNG
0.80 km BC + 250 m insecticide core	Reduce colony growth at edges to a larger extent + protect intermediate portion of inner colony	TBNG
0.80 km BC + Encourage zones	Reduce colony growth at edges to a larger extent + protect large swaths of colony	TBNG
0.80 km BC + private land control + 100 m insecticide core	Reduce colony growth at edges to a larger extent + eliminate colonies on private land + protect small portion of inner colony	TBNG
0.80 km BC + private land control + 250 m insecticide core	Reduce colony growth at edges to a larger extent + eliminate colonies on private land + protect intermediate portion of inner colony	TBNG
0.80 km BC+ private land control + Encourage zones	Reduce colony growth at edges to a larger extent + eliminate colonies on private land + protect large swaths of colony	TBNG
0.20 km BC	Reduce colony growth at edges to a smaller extent	CNG

Boundary control was applied at two different buffer widths (402 m (1/4 mile) boundary control or 804 m (1/2 mile) boundary control), and for each of these, we also explored the effect of presence or absence of lethal control on the private land side of the boundary. In the event that plague mitigation overlapped with lethal control zones, we cropped the plague mitigation zones so as not to apply both forms of management. These management strategies were selected to mimic the current application of management strategies across North American grasslands, not to advocate for one strategy over another. Middle column provides the hypothetical effect of each treatment and the final column denotes at which grassland each treatment was applied.

plicitly model management efficacy. Input polygons therefore represent the assumed net area of effective control or plague mitigation, not necessarily the full area treated. Where efficacy is uncertain or expected to be less than complete, users may specify a smaller polygon extent (or experiment with several extents of different sizes) to reflect that uncertainty.

We calibrated plague and growth probability thresholds in PDOG MAPR to match observed annual colony mapping at each site, finding that thresholds of 0.60 for plague mortality and 0.90 for colony growth provided the closest correspondence. These thresholds can be adjusted to reflect user familiarity with the system and tolerance for risk; for example, increasing the growth threshold to 0.95 would model more conservative expansion potential.

Simulations at TBNG included a boom period (2011–2012) characterized by rapid annual growth and a bust period (2016–2018) marked by widespread plague-induced declines. We first modeled each period without management intervention, then repeated simulations using management strategies that included lethal boundary control, plague mitigation or combinations of both strategies, reflecting practices commonly used throughout the Central Grasslands (Table 1). Lethal control was applied as boundary control surrounding private land as either a 402 m buffer (1/4 mile) or an 804 m buffer (1/2 mile). Plague mitigation was applied either as circular treatments at the center of each colony polygon or applied as large polygons that were referred to as “Encourage Zones” (areas where mitigation was applied to encourage the growth of prairie dog colonies). To examine plague mitigation alone, we re-ran the TBNG bust period without lethal control, starting with a minimum plague mitigation treatment size of a 100 m radius circle and progressively increasing the radius to 250, 500, 750, 1 000, 1 500, and 2 000 m. The goal of this exercise was to examine whether plague mitigation on its own could have similar effects in controlling population fluctuations as did the combination of boundary control and plague mitigation. For CNG, we focused on two bust periods (2005–2006 and 2014–2015) when colonies experienced plague. Given the smaller, less connected colony structure, we excluded scenarios with 804 m buffers and “Encourage Zone” polygons, which are not implemented at CNG. We compared 11 scenarios combining plague mitigation and boundary control, including a no-management baseline (Table 1).

Climate covariates for the simulations were obtained from NOAA Climate at a Glance (NOAA 2000) using 20-year (2000–2020) means for annual and spring precipitation and summer temperature. Years and seasons were classified as average, above, or below average based on mean ± 1 SD, with precipitation categories of dry, average, or wet, and temperature categories of cold, average, or warm. Users assign these categories for each year in PDOG MAPR. Covariate definitions and derivations are provided in Barrile et al. (2023) (Appendix S1: Tables S1 and S2).

Results—Case Studies

Deployment of PDOG MAPR

PDOG MAPR is publicly available on shinyapps.io, a service platform for hosting Shiny web apps. Researchers, managers, and practitioners with colony data anywhere within the range of black-tailed prairie dogs (Box 1) can freely use PDOG MAPR to simulate colony dynamics under various management scenarios by visiting https://nccasc.shinyapps.io/PDOGMAPR/. In addition, a video tutorial describing use of PDOG MAPR in greater detail can be found at https://youtu.be/jnRZ6dRA6mg.

Case study 1—Thunder Basin National Grassland

During the 2011–2012 boom period at TBNG, PDOG MAPR projected substantial colony expansion under no management, with area increasing by more than 70% (~2 300 ha; Fig. 2, Fig. S1). Management reduced predicted growth, with 402 m boundary control decreasing expansion by ~375 ha (without private land poisoning) and ~500 ha (with private land poisoning). The 804 m boundary control caused net declines of 18% (−570 ha) and 15% (−470 ha), and all 804 m scenarios resulted in overall losses. Plague mitigation alone produced growth similar to unmanaged colonies but prevented plague-induced collapse. Combining plague mitigation with boundary control yielded the smallest increases in colony area and lowered plague probability. For example, a scenario combining 402 m boundary control, private-land control, and plague mitigation in 250 m radius circles at colony centers limited growth to 12%. (~375 ha; Fig. 2).

During the 2016/2017–2018 bust period at TBNG, PDOG MAPR projected a severe population collapse under no management, with colony area declining by 89% (~23 500 ha; Fig. 4, Fig. S2). Management reduced both plague probability and the extent of decline. Scenarios involving a 402 m boundary control buffer were successful in spatially separating the colonies, thereby reducing colony connectivity and reducing the probability of plague. Applying a 402 m boundary-control scenario together with plague mitigation in the “Encourage Zones” led to the largest reductions in the probability of plague and decreased the loss in colony area from 89% to 9.5% (~23 500 ha to ~2 500 ha; Fig. 3). Despite reducing the probability of plague, all scenarios involving control on private land and 804 m boundary control resulted in significant declines in colony area due to the significant amount of area being poisoned.

Without lethal control during the 2016/2017–2018 plague outbreak at TBNG, PDOG MAPR predicted that plague mitigation in 100 m and 250 m radius circles at colony centers was insufficient to lower plague probability or prevent collapse. Increasing treatment to a 500 m radius reduced mean plague probability from 72.5% (no management) to 50.6%, below the 60% threshold, thereby preventing collapse and producing 12% growth (~3 200 ha; Fig. S3). All treatments ≥500 m were predicted to reduce plague probability below the threshold and avert population collapse. Population growth remained consistent after treatments of 500 m.

Case study 2—Comanche National Grassland

In the second case study, PDOG MAPR predicted severe plague-induced declines on CNG in the absence of management, with colony area decreasing by 36% (~2 100 ha) between 2005 and 2006 and by 94% (~7 400 ha) between 2014 and 2015. During 2005–2006, all management scenarios except 500 m radius plague mitigation at colony centers resulted in net losses. The 500 m mitigation increased colony area by 69% (~4 000 ha; Fig. 4). Although 402 m boundary control reduced plague probability and prevented collapse, the large amount of lethal control applied still produced a 43% decline (~2 500 ha). During 2014–2015, all scenarios produced net declines. Ten of eleven scenarios resulted in losses of 59–97% (~4 700–7 700 ha), whereas the 500 m plague mitigation substantially reduced the decline to 23% (~1 800 ha) compared with 94% (~7 400 ha) without mitigation (Fig. 5).

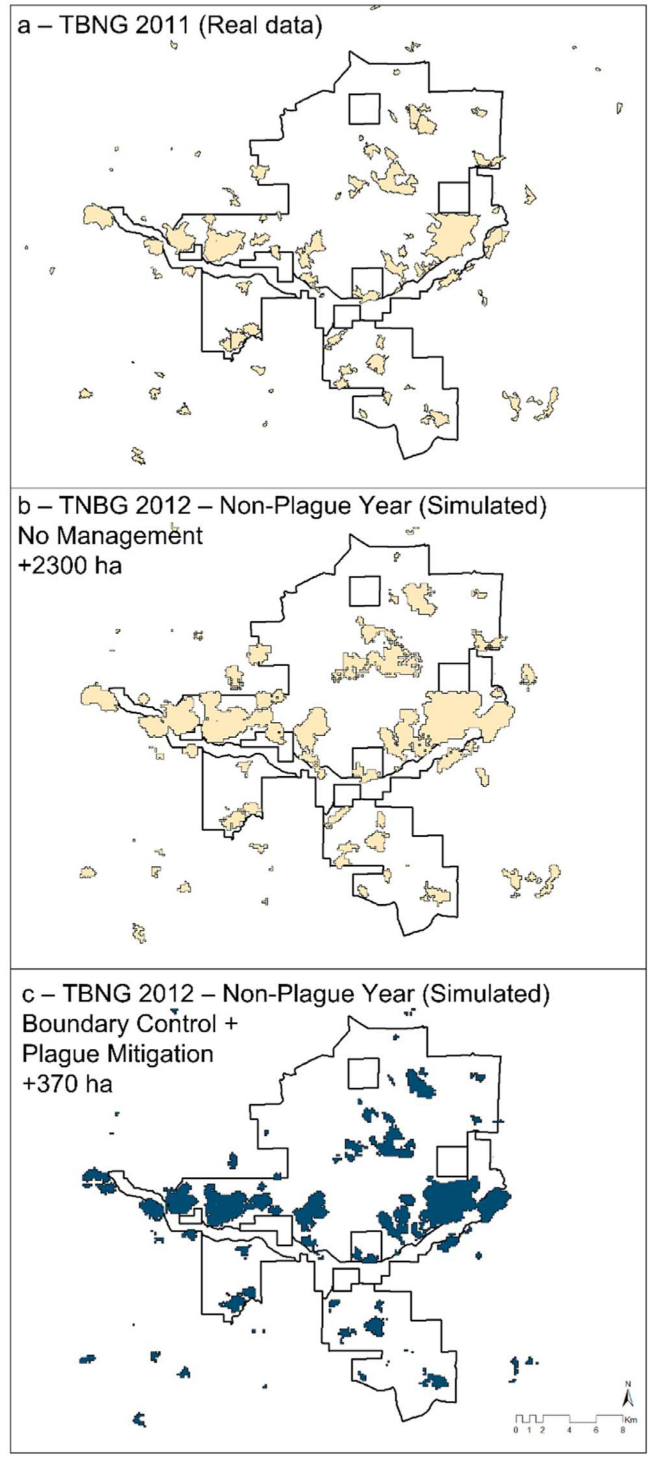


Figure 2. Maps show impact of different management scenarios on colony dynamics: a) Map of real prairie dog colonies on Thunder Basin National Grassland, WY, USA, in 2011. b) Projected colonies in 2012 under no management. c) Projected colonies in 2012 under the most stabile management scenario (least change in colony area) out of 21 scenarios examined. Colored polygons in each figure denote prairie dog colonies.

Discussion

We developed PDOG MAPR, an interactive web-based decision support tool that allows users to upload prairie dog colony data and simulate the effects of management strategies—specifically, lethal boundary control and/or plague mitigation—on colony distribution and disease risk. PDOG MAPR is intended to support adap-

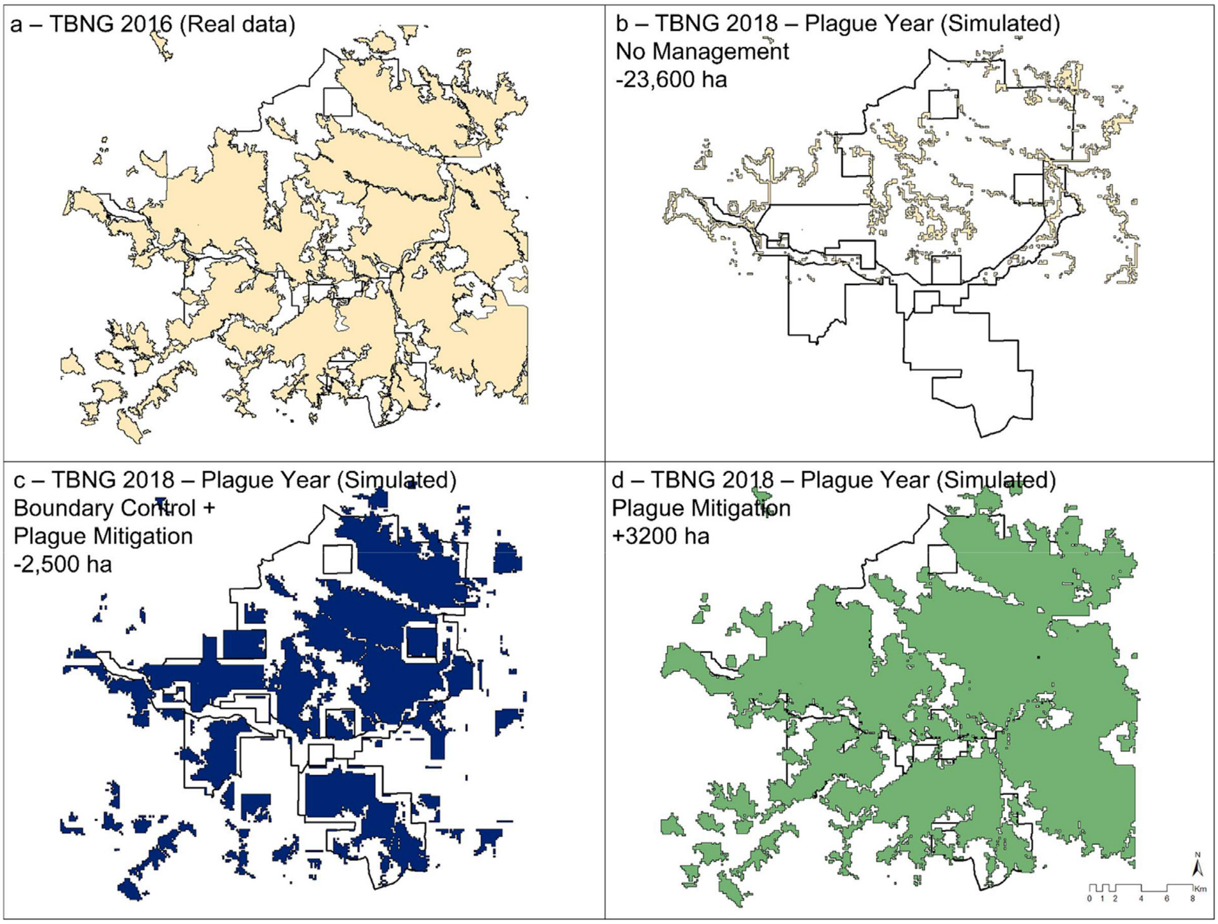


Figure 3. Maps show impact of different management scenarios on colony dynamics: a) Map of real prairie dog colonies on Thunder Basin National Grassland, WY, USA, in 2016. b) Projected colonies in 2018 under no management. c) Projected colonies in 2018 under the most stable management scenario (least change in colony area) out of 21 scenarios examined. d) Projected colonies in 2018 using plague mitigation to prevent a plague collapse. Colored polygons in each figure denote prairie dog colonies.

tive management by helping users explore how different actions may influence spatial outcomes of prairie dog colonies and associated plague dynamics. The tool can aid managers and conservation partners in identifying when and where to apply available interventions to 1) meet site-specific management objectives, 2) reduce risk of large-scale colony collapse, and 3) support coexistence between prairie dog ecosystems and surrounding land uses. Results from our two case studies demonstrate that management strategies can meaningfully alter colony trajectories, underscoring the value of predictive tools in informing rangeland decision making. Regardless of whether the goal is to conserve biodiversity, limit conflict with livestock, or achieve both, PDOG MAPR provides a flexible, data-driven platform to evaluate management tradeoffs. As such, it contributes to a growing suite of decision support tools designed to inform grassland conservation and multiuse land management (Brown et al. 2005; He et al. 2005; Hanrahan et al. 2017; Neal et al. 2019; Djeumen et al. 2021; Neyret et al. 2021).

In both National Grasslands, simulated scenarios without management resulted in dramatic colony collapses during plague epizootics—consistent with long-term observations in plague-endemic systems (Augustine et al. 2008b; Johnson et al. 2011; Eads and Biggins 2017; Keuler et al. 2020; Davidson et al. 2022). Yet, PDOG MAPR simulations predicted that plague mitigation, when applied at sufficient spatial extent, may lower plague probability and prevent collapse (Tripp et al. 2017; Eads and Biggins 2019; Eads et al. 2023; Matchett et al. 2023). While PDOG MAPR predictions are not deterministic, they provide a flexible framework for exploring how different management strategies may influence plague risk and colony dynamics, thereby supporting proactive, scenario-based planning.

Our case studies also suggest that prairie dog colonies respond differently to management depending on their size and spatial configuration. At TBNG, where colonies are large and well connected and public lands are relatively contiguous, simulations showed that combining boundary control with plague mitigation reduced colony expansion during nonplague years and helped prevent large-scale collapses during plague years. These findings align with known vulnerabilities of large, contiguous colonies to plague outbreaks (Snäll et al. 2008; Davidson et al. 2022). However, lethal control is not always appropriate as a tool to reduce plague outbreaks. Lethal control via shooting may actually increase the potential for plague outbreaks by increasing flea:host ratios that can act as a trigger for epizootic plague (Biggins and Eads 2019). Further, lethal control via poisoning is costly, often incomplete, and rapid recolonization of treated areas is common (Buehler et al. 2025), often necessitating repeated applications to maintain spatial discontinuities, especially in suitable habitat. In addition, toxicants can pose threats to nontarget species through direct exposure or indirect exposure via predation of poisoned prairie dogs (Witmer et al. 2023).

In contrast, at CNG—where prairie dog colonies were smaller and more spatially dispersed—simulations suggested that boundary control caused significant colony declines, even in the absence of plague due to the smaller and less connected nature of the colony

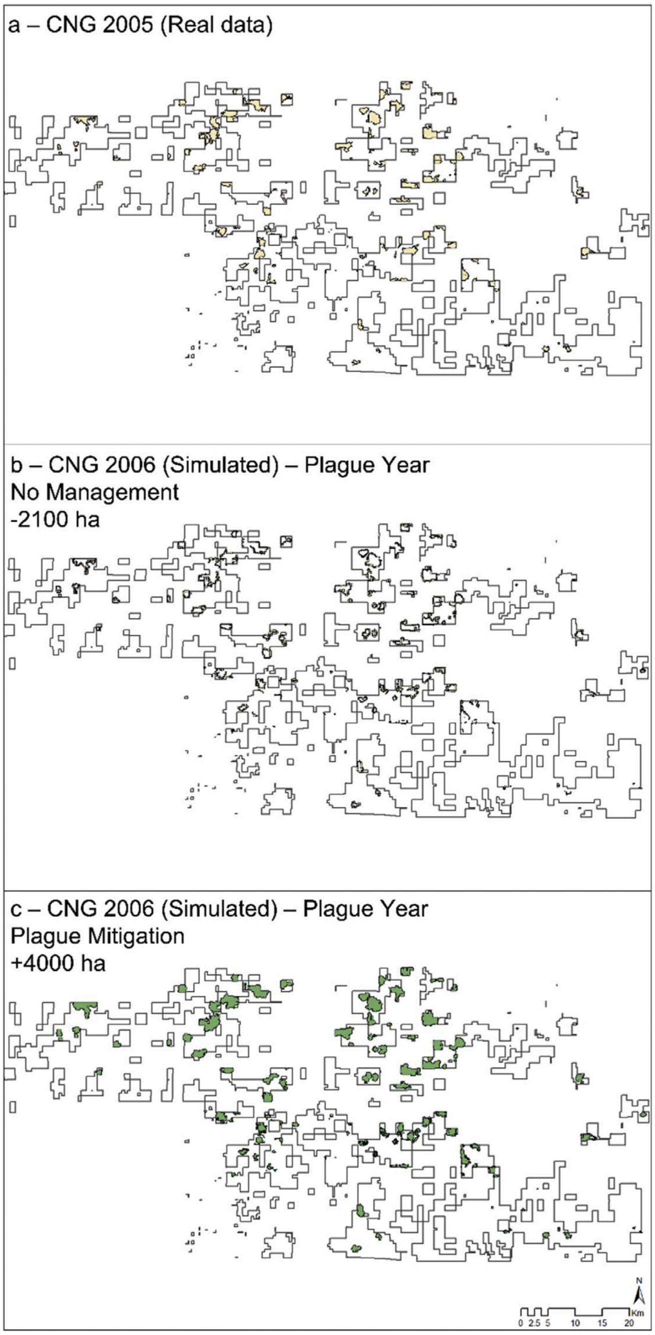


Figure 4. Maps show impact of different management scenarios on colony dynamics during a plague year (2006): a) Map of real prairie dog colonies on Comanche National Grassland, CO, USA in 2005. b) Projected colonies in 2006 under no management. c) Project colonies in 2006 under the most stabile management scenario (least change in colony area) out of 11 scenarios examined. Colored polygons in each figure denote prairie dog colonies.

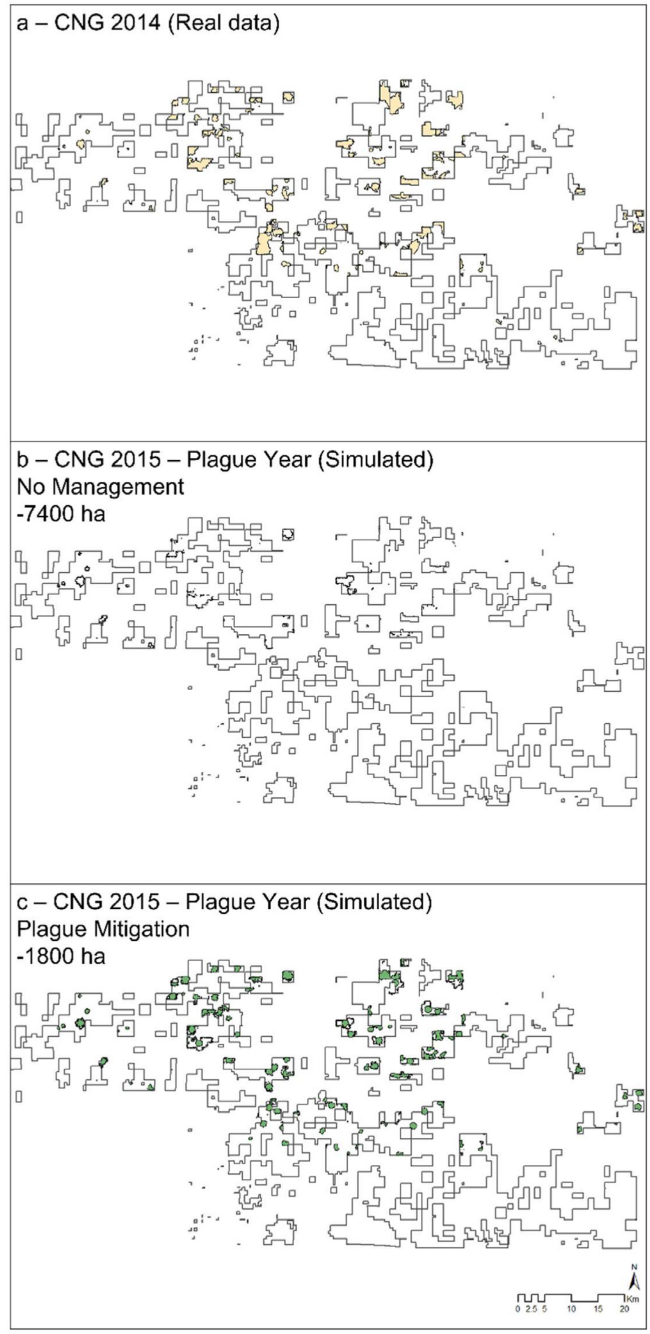


Figure 5. Maps show impact of different management scenarios on colony dynamics during a plague year (2014): a) Map of real prairie dog colonies on Comanche National Grassland, CO, USA in 2014. b) Projected colonies in 2015 under no management. c) Projected colonies in 2015 under the most stabile management scenario (least change in colony area) out of 11 scenarios examined. Colored polygons in each figure denote prairie dog colonies.

complexes. While smaller colonies are less likely to trigger conflict with adjacent landowners or interfere with livestock operations (Derner et al. 2006), they are less able to support the broader suite of species that rely on large, stable prairie dog colony complexes (Davidson et al. 2012; Duchardt et al. 2019; Livieri et al. 2022). Our results suggest that for complexes composed of relatively small to medium sized colonies (colony complexes of ca. 10 000 ha or less), lethal control can be counterproductive, whereas plague mitigation is essential for achieving prairie dog ecosystem conservation.

Overall, our finding that colony size, spatial configuration, and land-use context may influence how prairie dogs respond to management suggests that strategies aimed at conservation outcomes—such as maintaining colony stability or promoting growth—must be tailored to site-specific conditions. PDOG MAPR provides a valuable platform for exploring these tradeoffs in a spatially explicit, scenario-based framework, helping managers identify approaches that support ecological goals while minimizing conflict. To maximize its utility, the tool should be used in conjunction with expert knowledge of local systems, recognizing that the conservation value and management implications of prairie dog colonies vary widely across landscapes.

Plague mitigation is a well-established strategy for reducing the risk of large-scale colony collapse in prairie dog populations (Eads et al. 2022), and our model similarly predicted that plague mitigation substantially reduced collapse risk at both National Grasslands in simulated scenarios. This finding reinforces the critical role of plague mitigation in supporting conservation goals, particularly for black-footed ferret recovery. Ferrets require extensive prairie dog colony complexes (>2 023 ha) with high prey densities to sustain viable populations (USFWS 2013; Livieri et al. 2022), yet such colonies have become increasingly rare due to habitat fragmentation and recurring plague outbreaks (Livieri et al. 2022). Although effective, plague mitigation is often resource-intensive—costly and laborious (depending on method)—and thus typically limited to high-priority conservation areas (Eads et al. 2022, 2023). For instance, across five black-footed ferret recovery sites, approximately 18 140 hectares were treated for plague in 2025 (USFWS, personal communication, January 2026). In this context, PDOG MAPR offers a valuable planning resource to help managers prioritize where and when to apply plague mitigation to achieve conservation outcomes within budgetary and logistical constraints.

Caveats

Our case studies illustrate the utility of PDOG MAPR for informing real-world management and supporting scenario-based evaluation of local management options, rather than providing prescriptive or guaranteed solutions. PDOG MAPR does not explicitly model management efficacy in the current version; instead, it evaluates how prairie dog colony distribution and associated plague risk would respond if colony configurations were altered in a specified way. In practice, users should upload polygons representing the assumed net area of effective management, rather than necessarily the full treated area, so that incomplete efficacy can be approximated through conservative inputs. Management effects apply only within the immediate time step; treated areas are not assumed to remain permanently free of prairie dogs or plague, as recolonization can occur in subsequent time steps through natural expansion processes (Buehler et al. 2025). Model outputs therefore represent short-term projections of colony dynamics under specified spatial changes intended to inform management planning, rather than serve as literal forecasts of realized outcomes.

We did not impose fixed efficacy assumptions because the effects of lethal control and plague mitigation vary substantially among systems depending on method, timing, treatment coverage, colony configuration, environmental conditions, and local flea communities (Witmer et al. 2003; Rocke et al. 2017; Tripp et al. 2017; Russell et al. 2018; Augustine et al. 2023). Accordingly, plague-mitigation scenarios should be interpreted as short-term reductions in plague risk under the specified spatial configuration, not as evidence of lasting protection from future epizootics, and control scenarios should not be interpreted as permanent removal. Managers should interpret outputs alongside local knowledge of treatment performance and ecological conditions when evaluating management tradeoffs.

Further, PDOG MAPR is designed to model plague large-scale plague epizootics that significantly alter the spatiotemporal configuration of prairie dog colonies, rather than enzootic dynamics. Although plague may persist at low levels in some systems and contribute to individual mortality, our focus was on predicting major die-offs that drive population collapse. Because our goal was to explore the potential influence of different management strategies without logistical constraints, we applied management consistently and uniformly within the defined polygons in our simulations. In real-world settings, however, management is rarely uniform and is influenced by a range of factors, including cost, labor availability, terrain, and site-specific management objectives (Bodenchuk et al. 2013).

Another important caveat is the influence of user-defined probability thresholds for colony growth and plague-induced die-offs on scenario outputs. In our modeling exercise, we calibrated these thresholds to best match observed patterns of colony expansion and collapse, based on empirical data (Barrile et al. 2023). Although we recommend using these thresholds, PDOG MAPR allows users to adjust them based on local knowledge and management priorities (e.g., lowering the colony growth threshold in systems where prairie dogs expand rapidly). Overall, PDOG MAPR is not designed for precise, fine-scale prediction; rather it is intended to serve as a strategic, spatially explicit planning tool that complements expert knowledge, helping users explore large-scale patterns in colony dynamics and evaluate the potential effects of different management strategies across space and time. In fact, PDOG MAPR is already being used in this capacity: during the winter of 2024–2025, the Thunder Basin Working Group used the tool to evaluate a range of possible outcomes under different spring weather scenarios, from lowest colony growth and highest plague risk to highest growth and lowest risk. This exercise provided insight into the range of potential colony distributions under varying conditions and informed seasonal management planning.

Implications

We introduce PDOG MAPR as the first publicly available decision support tool designed to inform conservation and management of prairie dog ecosystems across North America's grasslands. By simulating prairie dog colony dynamics and plague risk under user-defined management scenarios, PDOG MAPR forecasts the potential outcomes of plague mitigation and boundary control in spatially explicit terms. By making such predictive modeling accessible to managers, PDOG MAPR helps translate complex ecological dynamics into actionable insights. Importantly, the tool is designed to complement local expertise and facilitate discussions among land managers, conservation practitioners, and livestock producers. This collaboration is especially relevant in working rangelands, where coexistence between prairie dogs and human land use is central to sustaining both ecological function and agricultural viability.

PDOG MAPR represents a foundational step toward building more integrated, science-informed planning tools for grassland systems. Future iterations could incorporate management efficacy, implementation costs, and interactions with climate extremes—providing a stronger foundation for optimizing limited resources and minimizing conflict (Bodenchuk et al. 2013; Sturm et al. 2018; Roth 2019). As prairie dog conservation continues to intersect with livestock production, tools that support transparent, scenario-based decision making will be critical to identifying strategies that reduce risk while supporting long-term ecosystem resilience (Crow et al. 2022). Ultimately, PDOG MAPR contributes to ongoing efforts to foster coexistence between humans and wildlife and offers a model for integrating decision support into rangeland ecosystem management.

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.

CRediT authorship contribution statement

Maksim Sergeyev: Writing – original draft, Methodology, Formal analysis, Data curation. **Gabriel M. Barrile:** Writing – re-

view & editing, Methodology, Formal analysis, Data curation, Conceptualization. **David J. Augustine:** Writing – review & editing, Project administration, Funding acquisition, Data curation, Conceptualization. **Lauren M. Porensky:** Writing – review & editing, Project administration, Funding acquisition, Data curation, Conceptualization. **Courtney J. Duchardt:** Writing – review & editing, Project administration, Methodology, Conceptualization. **Kevin T. Shoemaker:** Writing – review & editing, Project administration, Methodology, Conceptualization. **Cynthia R. Hartway:** Writing – review & editing, Project administration, Methodology, Conceptualization. **Ana D. Davidson:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rama.2026.04.010.

Appendix S1. – Additional details and instructions on PDOG MAPR

PDOG MAPR first loads the predictive model (as an .rds file), then loads raster layers (.tif files) that correspond to covariates in the model. Raster layers used for climate inputs cover the entire extent of the black-tailed prairie dog range, such that users can apply the app to any study area with colony data. Geospatial layers associated with temperature and precipitation covariates were derived from the Daymet data product (Sadoti et al. 2020; Thornton et al. 1997) and a habitat suitability raster was included from a study that modeled black-tailed prairie dog occurrence as a function of soil, climate, topography, and land-cover data across the entire species' range in the United States (Davidson et al. 2023). Finally, we loaded a raster layer that contained latitude values in each pixel, as latitude was an important control covariate when forecasting plague outbreaks and colony growth (Barrile et al. 2023). All remaining model covariates (e.g., mean nearest-neighbor distance between colonies, distance to previously plagued colonies) are calculated based on user inputs and derived on the server side of the app, prior to model prediction (see below). For a detailed description of all covariate layers (definition and derivation), please refer to the Methods section and Appendix S1: Tables S1 and S2 in Barrile et al. (2023).

Upon loading colony data for the site and year of interest (year t), PDOG MAPR plots a map of the data for users to inspect (Box 1). Users are then prompted to upload two optional additional shapefiles related to on-the-ground management: one shapefile of areas where prairie dogs were lethally controlled in year t, and/or another shapefile of areas treated with plague mitigation in year t (Rocke et al. 2017; Eads and Biggins 2019; Eads et al. 2023). If users do not have these shapefiles, they can simply re-upload the colony shapefile from step 1 to proceed with the application. A fourth map is also plotted such that users can visualize how management influenced colony distribution (e.g., lethally controlled areas are subtracted from the original colony data). From this new spatial configuration of prairie dog colonies, the server side of PDOG MAPR recalculates colony connectedness variables (e.g., mean nearest neighbor, dispersion) that were important covariates in our predictive model.

Next, users are prompted to upload colony data from the same site but for the year prior (year t - 1). The server side of PDOG MAPR uses colony data from year t - 1 to calculate model covariates related to changes in colony distribution between years. For instance, colonies that suffered greater than 50% loss in area between years are assumed to have experienced a plague outbreak. We were confident that such large-scale declines were primarily attributable to plague because plague is the only disease known to cause extensive die-offs among BTPDs over short time periods (Barnes 1993), and no other mechanism (e.g., predation, drought) is likely to cause the extreme population reductions that could be confused with the effects of plague (e.g., Cully et al. 2010; Johnson et al. 2011; Matchett et al. 2021). If users do not have colony data from year t - 1, they can simply reupload their colony data from year t, in which case the model assumes there were no plague outbreaks between years. The server side of PDOG MAPR then runs the machine learning model and produces a predictive map of colony distribution in year $t+1$.

The decision support tool was presented to the Thunder Basin National Grassland Working Group (a diverse group of partners working together to advise the US Forest Service on prairie dog management issues in the TBNG region, https://sites.google.com/view/tbngworkinggroup/) in an iterative process in which we received feedback from managers, scientists, landowners, and other interested parties and incorporated these suggestions with each new version of the tool. Feedback revealed that a simple map of the percent chance of plague at each colony would be useful. Thus, the final step in PDOG MAPR prompts the user to again upload colony data from year t - 1 (or reupload year t). The server side of the app then runs the model for a second time and calculates the average probability of plague outbreak (based on model predictions) for each colony on the landscape. Users can alter climate covariates in this step, as described above. Finally, PDOG MAPR presents a summary table displaying the total net change in colony area (in hectares) between the actual colonies in year t and the predicted colonies during $t+1$, as well as the mean and maximum percent chance of plague outbreak across prairie dog colonies as predicted by the model.

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