Prepared in cooperation with U.S. Department of Agriculture, National Park Service,
U.S. Fish and Wildlife Service, and Wyoming Game and Fish Department

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Open-File Report 2023–1015
Version 2.0, November 2023

U.S. Department of the Interior
U.S. Geological Survey

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
yard (yd)	0.9144	meter (m)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	0.09290	square meter (m^2)
section (640 acres or 1 square mile)	259.0	square hectometer (hm^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)

Abbreviations

CF	continued feeding alternative
CWD	chronic wasting disease
EF	emergency feeding alternative
EIS	environmental impact statement
FS	U.S. Department of Agriculture Forest Service
FWS	U.S. Fish and Wildlife Service
HU	herd unit
NEPA	National Environmental Policy Act
NF	no feeding alternative
MDCR	mule deer critical winter range
MOCR	moose critical winter range
PO	phaseout alternative
PM	performance metric
PrP^{CWD}	misfolded prion protein that causes chronic wasting disease
RSF	resource selection function
SD	standard deviation
WGFC	Wyoming Game and Fish Commission
WGFD	Wyoming Game and Fish Department

Evaluating Management Alternatives for Wyoming Elk Feedgrounds in Consideration of Chronic Wasting Disease

By Jonathan D. Cook,[1] Paul C. Cross,[1] Emma M. Tomaszewski,[1] Eric K. Cole,[2] Evan H. Campbell Grant,[1]
James M. Wilder,[3] Michael C. Runge[1]

1. Executive Summary

The authors used decision and modeling analyses to evaluate management alternatives for a decision on whether to permit *Cervus canadensis* (elk) feeding on two sites on Bridger-Teton National Forest, Dell Creek and Forest Park. Supplemental feeding of elk could increase the transmission of chronic wasting disease (CWD) locally and disease spread regionally, potentially impacting elk populations over time with wider implications for *Odocoileus hemionus* (mule deer) and *Odocoileus virginianus* (white-tailed deer) populations and hunting, tourism, and regional revenue. Supplemental feeding is thought to improve overwinter elk survival and reduce the commingling of elk with cattle during months when brucellosis transmission risk is highest. We worked with the U.S. Department of Agriculture Forest Service to identify their fundamental objectives and associated performance metrics related to this feedground decision. We then developed disease and habitat selection models to quantify the effect of four management alternatives on select performance metrics. The four alternatives were to continue to permit feeding, phaseout permits to feed in three years, permit feeding on an emergency basis, or stop permitting feeding. In this report, we present methods and summarized results on disease and habitat selection models and summaries of other performance metrics analyzed by BIO-WEST, Inc. and Cirrus Ecological Solutions as part of an Environmental Impact Statement.

Data from Wyoming Game and Fish Department (WGFD) supported the assumption that supplemental elk feeding allows for larger elk populations in a region. We documented that herd units (HU) without feedgrounds had 23 percent lower densities of elk per area of winter range when compared against HUs with feedgrounds, after accounting for differences in sightability of elk during counts on and off feedgrounds. Thus, throughout our analyses, we assumed feedground closures would reduce elk carrying capacity resulting in an average decline of previously fed elk population segments by 23 percent (5th and 95th percentiles = [11 percent, 35 percent]) by year 20. Most of that decline occurred within the first few years after a feedground ceases to operate. We used a panel of CWD experts to help estimate CWD transmission in fed and unfed elk population segments. In aggregate, the expert panel estimated that median values of direct and indirect transmission of CWD are expected to be 1.9 and 4 times higher, respectively, in fed elk populations compared to unfed elk. We used these disease transmission estimates in combination with local elk demographic rates and carrying capacity estimates to project disease and population dynamics.

In year 20, we predicted CWD prevalence would increase to 42 percent (5th and 95th percentiles = [29 percent, 55 percent]), and 13 percent (5th and 95th percentiles = [4 percent, 26 percent]) on average for fed and unfed elk population segments, respectively, given a starting prevalence of 1.6 percent. The prevalence estimates for the unfed elk population segments are in the range of previous observations of CWD in elk in the western United States. The average CWD prevalence from 2016 to 2018 in the unfed elk population of Wind Cave National Park in South Dakota was 18 percent overall but up to 30 percent in some regions (Sargeant and others, 2021). Meanwhile, CWD prevalence in the Iron Mountain and Laramie Peak elk herds in Wyoming from 2016 to 2018 was 14 percent and 7 percent, respectively, despite being present since at least 2002 (Wyoming Game and Fish Department, 2020b).

From 2016 to 2020, elk that were fed at Dell Creek and Forest Park constituted on average 12–20 percent of the total elk on their respective HUs. As a result, the differences between management alternatives are modest when considering the closure of only one feedground on a HU. The no feeding alternative for Forest Park resulted in a CWD prevalence of 17 percent (SD = 7 percent) in the Afton HU compared to 20 percent (SD = 7 percent) with continued feeding by year 20. In the Upper Green River HU, no feeding on Dell Creek resulted in a CWD prevalence of 27 percent (SD = 6 percent) compared to 30 percent (SD = 5 percent) with continued feeding. In terms of disease-associated mortality, we predicted the closure of Forest Park and Dell Creek

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[1] U.S. Geological Survey.

[2] U.S. Fish and Wildlife Service.

[3] U.S. Department of Agriculture Forest Service.

feedgrounds would reduce the total number of CWD mortalities by 9 percent in the Upper Green River HU and 26 percent in the Afton HU during the 20-year timespan.

Our spatial analyses predicted that management alternative effects vary by HU as a function of private property and other wildlife winter ranges proximity relative to feedground location. The predicted number of elk abortions on private land, as a proxy for brucellosis risk to cattle, may increase by 8–21 percent in the absence of feeding at Dell Creek and Forest Park.

Eight feedgrounds are located on Bridger-Teton National Forest, all of which have permits that have expired or will expire prior to 2028. In addition, WGFD could change their management of feedgrounds given new information; therefore, we also assessed the cumulative effects of continued feeding, phaseout, and no feeding management alternatives across five HUs south of Jackson, Wyoming (Afton HU, Fall Creek HU, Piney HU, Pinedale HU, and Upper Green River HU). These five HUs ranged from about 41 to 85 percent of the elk herd using feedgrounds, which corresponded to a CWD prevalence at year 20 of 23–34 percent if all feedgrounds in those five HUs remained open relative to 12 to 14 percent if all feedgrounds were closed. We predicted feedground closures may result in immediate reductions in population size relative to alternatives that continue feeding (for example, continued feeding and emergency feeding alternatives); however, over longer periods of time, CWD-associated mortality leads to larger population reductions. The no feeding alternative resulted in higher elk population sizes compared to the continued feeding alternative after about 10 years of implementation. Delayed action under a phaseout alternative resulted in increasing the CWD prevalence to 20 percent relative to 12 to 14 percent, on average, without feeding on HUs with a large population of fed elk such as the Upper Green River HU.

Summarizing our cumulative results across all five of the analyzed HUs, we predicted continued feeding will lead to fewer elk by year 20 (mean = 8,300, standard deviation [SD] = 740) compared to no feeding at U.S. Department of Agriculture Forest Service sites (10,700, SD = 890). The closure of all feedgrounds was projected to result in the largest elk populations at year 20 (12,500, SD = 980). No feeding at all sites also resulted in the largest cumulative harvest of 57,700 (SD = 2,600) compared to 51,100 (SD = 3,800) for continued feeding at all current feedground sites on the five HUs. Continued feeding also resulted in the lowest brucellosis costs to producers ($194,600, SD = $11,500) compared to no feeding on all feedgrounds ($243,000, SD = $13,700). Assuming moderate reductions in hunter interest because of increasing CWD prevalence in elk, we predicted that no feeding resulted in regional revenues generated by hunting activities of $190 million (SD = $10 million) compared to $173 million (SD = $10 million) for continued feeding over the 20-year timeframe.

Recent CWD detections in mule deer and elk in Grand Teton National Park has elevated the importance of the current decision on whether, and how, to permit elk feeding on Dell Creek and Forest Park and the management of the other feedgrounds. Aggressive male harvest has slowed, but not stopped, the increasing prevalence of CWD in mule deer (Conner and others, 2021). It is unclear whether harvest management can be an effective tool to slow the spread of CWD in elk. There are also no effective treatments or vaccines for CWD, and it is unlikely that any will be developed that can be easily deployed in the near future. Thus, reducing artificial aggregations is one of the few management approaches suggested by the Western Association of Fish and Wildlife Agencies (Almberg and others, 2017).

Future surveillance and monitoring can be designed to resolve uncertainties that can improve future decision-making. If feedgrounds close, research could quantify elk population reductions in the absence of feeding, the redistribution of fed elk to other places, or the consequences of elk movement on private property. If feedgrounds remain open, research could assess how rapidly CWD spreads in artificial aggregations of elk; however, surveillance programs would need to be designed with sufficient power to detect initial changes of CWD prevalence. Delaying action on feedground management was projected to be costly. Results of the phaseout alternative relative to the no feeding alternative suggested a 3-year delay was enough for substantial long-term changes in CWD prevalence. The long-term persistence of infectious CWD prions in the environment suggests that feedground management decisions may have long-lasting consequences.

Our results indicated tradeoffs in the ability of a management agency to achieve all their objectives, and all management alternatives resulted in significant reductions in elk population size. This report contains the foundational elements for formal decision analysis methods, which can be implemented to help decision makers transparently evaluate the consequences of decision alternatives and identify the set of actions that best achieve agency and stakeholder priorities.

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2. Introduction

This report documents a structured decision-making process and supporting analyses developed to inform a National Environmental Policy Act (NEPA, 42 U.S.C. 4321-4347) Environmental Impact Statement (EIS). The assessment centered around a decision by the U.S. Department of Agriculture Forest Service (FS) on whether to permit the State of Wyoming to continue supplemental feeding of *Cervus canadensis* (elk) on two State-run feedgrounds, Dell Creek and Forest Park, located on Bridger-Teton National Forest (fig. 1, table 1). Although we framed the decision to evaluate the outcomes of management alternatives on these two feedgrounds, our analytical methods and approach are useful to evaluate feedground operations across western Wyoming.

Supplemental feeding of ungulates is a common practice and ranges in scale from agricultural mineral licks to State and federally operated feeding on an emergency or seasonal basis across several western States. Supplemental feeding of elk and *Bison bison* (bison) in Wyoming are some of the longest running programs, with feeding of elk beginning in the Jackson area around 1907. The National Elk Refuge, operated by the U.S. Fish and Wildlife Service (FWS), was established in 1912 and one of the first locations supplemental feeding of elk occurred (Smith, 2001). The State of Wyoming established 22 additional feedgrounds in western Wyoming from 1930 to 1980. Eight of those feedgrounds operated by the State of Wyoming are on FS property in the Bridger-Teton National Forest (table 1).

Feedgrounds in Wyoming usually operate from December to April depending on the location and severity of annual snowpack (Cross and others, 2007). Feedgrounds were created for a variety of reasons, including reducing wildlife damage, addressing public concerns about winter mortality of elk, supporting higher populations for increased hunting opportunities, and mitigating the loss of winter range to human development. Wyoming's wildlife damage law imposes liability on the Wyoming Game and Fish Commission (WGFC) to pay for damages to agriculture producers caused by big game animals (Wyo. Stat. § 23-1-901). When feedgrounds were established, wildlife managers found it easier and less expensive to feed elk in some areas during winter rather than maintain hazing operations or mitigate private property damage caused by elk (McWhirter and others, 2021).

Supplemental feedgrounds create denser aggregations of elk than native winter ranges (Cross and others, 2015; Janousek and others, 2021); thus, facilitating higher rates of disease transmission among elk (National Academies of Sciences, Engineering and Medicine, 2017). Brucellosis is a common, zoonotic disease globally (Pappas and others, 2006). In the early 1900s, it was widespread in the U.S. cattle population (Ragan, 2002) and probably spilled over to neighboring elk and bison populations. However, because of a long-term eradication program in cattle organized by the U.S. Department of Agriculture, the incidence of brucellosis cases in cattle and humans in the United States is now low (Ragan, 2002; Rhyan and others, 2013). The Greater Yellowstone Ecosystem is the last remaining wildlife reservoir of bovine brucellosis in the United States, where it is enzootic among elk and bison with occasional spillovers to cattle (Rhyan and others, 2013).

Historically, elk were not considered maintenance hosts for brucellosis in the absence of supplemental feeding; however, recent increases in brucellosis seroprevalence in elk populations that do not overwinter on feedgrounds suggests halting supplemental feeding is unlikely to eradicate the disease (Cross, Cole, and others, 2010; Cross, Heisey, and others, 2010; Brennan and others, 2017; National Academies of Sciences, 2017). Brucellosis seroprevalence and spatial extent in elk increased in the early 2000s, coincident with changes in elk density (Cross, Cole, and others, 2010; Cross, Heisey, and others, 2010; Proffitt and others, 2015). Earlier analyses of brucellosis seroprevalence suggested feedgrounds with longer feeding seasons had higher seroprevalence (Cross and others, 2007). Results of attempts to shorten the feeding seasons were less clear (Cotterill and others, 2020), potentially highlighting that even when feeding seasons are shortened, elk continue to remain at higher local densities in winter. Although feedgrounds serve as the primary management approach to limit brucellosis transmission from elk to cattle, this may have led to a cycle of increased aggregations and brucellosis transmission in fed elk.

Recent detections of chronic wasting disease (CWD) in mule deer and elk in Grand Teton National Park have raised additional concerns about disease impacts on elk populations if supplemental feeding continues. Chronic wasting disease affects members of the Cervidae family and is caused by a misfolded prion protein (PrP^{CWD}) that can persist in the environment for many years (Williams and Young, 1980; Williams and Miller, 2002; Miller and others, 2004). The disease is always fatal, but some elk genotypes are

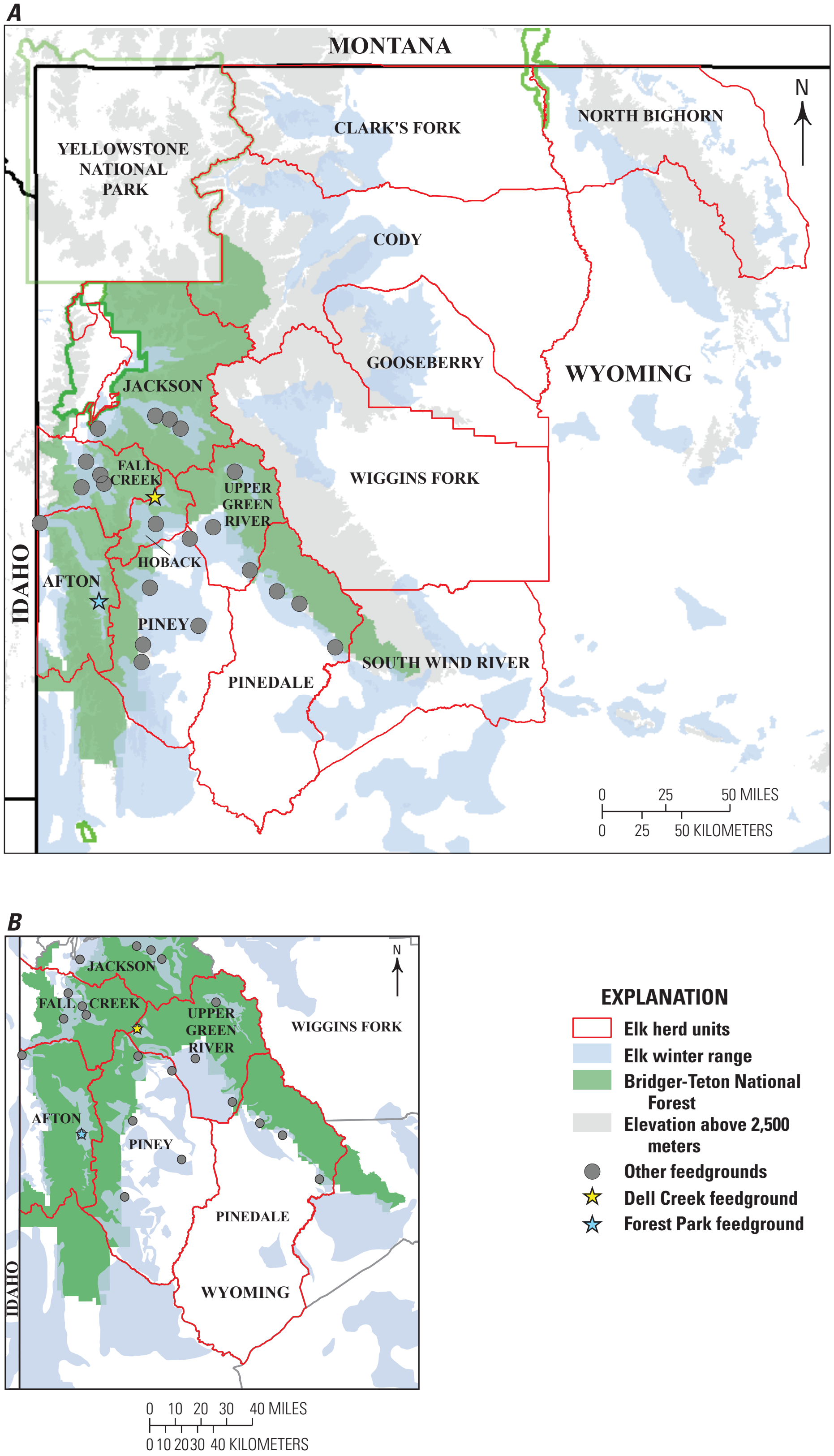

Figure 1. *A*, the supplemental elk feedgrounds in western Wyoming and associated elk herd units used to assess winter elk density in fed and unfed herd units; and *B*, the Hoback herd unit was incorporated into the Piney and Upper Green River herd units in 2020.

Table 1. Average counts of elk on Wyoming supplemental feedgrounds from 2016 through 2020, which feedgrounds are located on U.S. Department of Agriculture Forest Service (FS) property, and the year their supplemental feeding permit expires.

[SD, standard deviation; FWS, U.S. Fish and Wildlife Service; —, no data]

Feedground	Herd unit[1]	Herd unit[2]	FS	Expiration	Elk	SD
Greys River	Afton	Afton	FALSE	—	552	104
Forest Park	Afton	Afton	TRUE	[3]2016	550	161
Camp Creek	Fall Creek	Fall Creek	FALSE	—	791	277
Horse Creek	Fall Creek	Fall Creek	FALSE	—	1,297	290
South Park	Fall Creek	Fall Creek	FALSE	—	910	122
Dog Creek	Fall Creek	Fall Creek	TRUE	2028	374	151
National Elk Refuge	Jackson	Jackson	FWS	—	8,413	1,375
Patrol Cabin[4]	Jackson	Jackson	FALSE	—	—	—
Alkali[4]	Jackson	Jackson	TRUE	2024	—	—
Fish Creek[4]	Jackson	Jackson	TRUE	2028	—	—
Gros Ventre Total[4]	Jackson	Jackson	—	—	1,102	709
Scab Creek	Pinedale	Pinedale	FALSE	—	698	85
Fall Creek	Pinedale	Pinedale	TRUE	2028	558	323
Muddy Creek	Pinedale	Pinedale	TRUE	2028	516	73
McNeel	Piney	Hoback	FALSE	—	665	134
Bench Corral	Piney	Piney	FALSE	—	696	441
Finnegan	Piney	Piney	FALSE	—	436	41
Franz	Piney	Piney	FALSE	—	238	164
Jewett	Piney	Piney	FALSE	—	474	118
North Piney[5]	Piney	Piney	FALSE	—	—	—
Dell Creek	Upper Green River	Hoback	TRUE	[3]2016	409	94
Black Butte	Upper Green River	Upper Green River	FALSE	—	794	212
Soda Lake	Upper Green River	Upper Green River	FALSE	—	952	564
Green River Lakes	Upper Green River	Upper Green River	TRUE	2028	636	122

[1] Herd unit membership after 2020 without the Hoback unit.

[2] Herd unit membership before 2020 with the Hoback unit.

[3] Operating on a special-use permit.

[4] Historically elk frequently moved among the three Gros Ventre feedgrounds (Patrol Cabin, Alkali, Fish Creek), so the total for these three feedgrounds is shown as Gros Ventre Total.

[5] North Piney is a staging area where elk are fed for short periods of time before moving onwards to Bench Corral.

associated with a slower progression of disease (Robinson and others, 2012; Monello and others, 2017). Chronic wasting disease is transmitted through direct contact with an infectious individual and indirectly by contact with a PrP^{CWD} contaminated environment (Miller and others, 2004). In Wyoming, CWD-induced population declines have been observed in mule deer and white-tailed deer (Edmunds and others, 2016; DeVivo and others, 2017). Elk populations are predicted to decline when prevalence reaches 7–13 percent (Monello and others, 2014; Galloway and others, 2021). The impacts of CWD may be more severe in less productive, arid ecosystems with lower elk and deer densities and recruitment (Foley and others, 2015). As of 2023, there are no effective treatments for CWD at the individual, population, or landscape level.

Beyond disease issues, natural resource managers are balancing other ecological, social, and economic benefits associated with Greater Yellowstone Ecosystem elk and feedground programs. Elk are important prey for the predator guild of the Greater Yellowstone Ecosystem, including *Canis lupus* (wolves), *Ursus horribilus* (grizzly bears), and *Puma concolor* (mountain lions). For humans, elk are a valuable big game animal, which support local resource-associated economies and have valuable, non-consumptive uses associated with wildlife viewing and other forms of ecotourism. Local communities host elk festivals that draw in thousands of visitors, and shed antlers are collected for sale at the annual Jackson Hole Boy Scout elk antler auction.

To evaluate the environmental impact of a natural resource decision, NEPA requires an evaluation of environmental effects (in other words, objectives) in relation to the proposed alternatives. In practice, the evaluations are typically qualitative and narrative in structure, but require many, or all, of the same assumptions as the quantitative evaluations required by more formal decision analytical methods. A potential downside to qualitative assessments is the decision process is less transparent about assumptions made, how issues are weighed, and ultimately, how the lead agency arrived at the preferred alternative. We designed this report and analysis to support a quantitative assessment of effects, which can facilitate future decision analysis and transparent decision making.

This feedground permitting decision would benefit from a more rigorous evaluation of meeting agency objectives in relation to the selected alternatives. To guide such a process, the U.S. Geological Survey (USGS), in partnership with the U.S. Department of Agriculture Forest Service (FS) and Wyoming Game and Fish Department (WGFD), led a formal decision analysis process and developed quantitative models to evaluate the effects of alternatives on the objectives the lead agency, cooperating agencies, and stakeholders were interested in (and, in some cases, mandated to) achieving. This report captured the important technical elements of the decision context, the analytical methods, and is intended to inform the NEPA EIS process.

Overall, the report has three primary goals:

1. To describe the decision problem as defined by the FS with the support of cooperating agencies, stakeholders, and members of the public as part of the NEPA EIS process;
2. To develop and describe the modeling approaches used to project the effect of management alternatives on objectives; and
3. To provide results for use in agency deliberation, including a consequence table summarizing predicted performance of each alternative relative to objectives.

2.1. Report Structure

We organized the report into four primary sections (table 2). The first section focused on decision framing and included a description of the problem, fundamental and strategic objectives, performance metrics, and the management alternatives selected for evaluation. Following the description of the decision framing (Section 3), we presented two analytical sections used to estimate the effects of the alternatives on several of the fundamental objectives.

Section 4 used a sex- and age-structured population model to analyze the effects of alternatives on CWD prevalence and disease-induced mortality, elk population size, and elk harvest. Section 5 built on those results and used population sizes in a spatial model to project space use patterns of elk, human-elk conflict, and elk use of mule deer and moose ranges under the different alternatives. In total, the analytical sections provided effects estimates for 5 of 11 performance metrics associated with the six fundamental objectives. The fundamental objectives related to socioeconomic effects were evaluated by a separate team working on the NEPA EIS; thus, these methods and results will be presented therein.

The analytical sections on CWD, population size, and harvest projections (Section 4) and spatio-temporal analysis of elk distributions (Section 5) grappled with predictions about what would happen in the future under different management

Table 2. Fundamental objectives, associated performance metrics, and their sources in this report or the Environmental Impact Statement (U.S. Department of Agriculture Forest Service, in press).

[CWD, chronic wasting disease ; EIS, environmental impact statement]

Fundamental objectives	Performance metric(s)	Source
Minimize CWD in elk	CWD mortalities	Section 4
Maintain elk population numbers	Elk population size	Section 4
Maximize elk hunting opportunities	Number of harvested elk	Section 4
Maintain other big game populations	Elk use of mule deer range	Sections 4 and 5
	Elk use of moose range	Sections 4 and 5
Minimize conflict with agricultural and public stakeholders	Cost of brucellosis spillover	EIS
	Elk depredation costs	EIS
	Hay sales revenue (HAYS)	EIS
Maximize the prosperity of resource-supported economies	Revenue from harvest tag sales	EIS
	Regional economic inputs	EIS
	Revenue of outfitters	EIS

alternatives. These types of questions typically cannot be answered based upon empirical evidence alone. For example, we cannot compare what elk density would be in a herd unit (HU) with and without feeding because we only have comparable data from times when feeding occurred. We do not have data on how rapidly CWD spreads in comparable elk populations on supplemental feedgrounds. We constructed statistical and mechanistic mathematical models that incorporate prior knowledge and, in some cases, multiple hypotheses about future system dynamics to simulate scenarios that represent outcomes of management alternatives. These models required simplifying assumptions, which we attempted to make clear. The transparency of assumptions behind the models and use of decision analysis techniques are valuable because the alternative is a mental model of how the complex ecosystem interacts with unstated assumptions, biases, and weights.

The Bridger-Teton National Forest is currently faced with management decisions specific to the Dell Creek and Forest Park feedgrounds. The permits for six additional feedgrounds on the Bridger-Teton National Forest will expire in the next several years (table 1). Therefore, we also simulated the effects of management alternatives if they are implemented across all feedgrounds; however, State-run feedgrounds outside of FS lands are outside of the FS authority to manage. A 2021 Wyoming law House Bill 101 required an order of the governor to close an elk feedground and required WGFD to develop plans for alternative feedground sites (State of Wyoming, 2021). Therefore, we also analyzed the potential closure of all feedgrounds on FS-managed properties to inform this process. In these cumulative analyses, we included the Afton, Fall Creek, Piney, Pinedale, and Upper Green River HUs. We excluded the Jackson HU because the National Elk Refuge is developing their own feedground management plan that would likely have different alternatives than alternatives assessed here. Additionally, the proximity of the city to the National Elk Refuge and elk-proof fencing makes this HU a unique case.

3. Decision Framing

Structured decision making is a formal and transparent process by which decision makers break down complex problems into constituent parts (problem statement, objectives, alternatives, consequences, and tradeoffs) and then analyze using various methods, including decision analysis methodology and quantitative models. In the past, structured decision making has been successfully used to inform complex natural resource decisions that allow agencies to consider multiple management objectives and system uncertainties, which would otherwise challenge their ability to select the best course of action (Runge and others, 2013, 2015). The result is a transparent and deliberative process that leads to rational decisions, which can be effectively communicated to stakeholders and members of the public.

3.1. Problem Statement

The Bridger-Teton National Forest, located in western Wyoming, is part of the larger Greater Yellowstone Ecosystem. In total, the Bridger-Teton National Forest comprises more than 3.4 million acres of public lands, including 1.2 million acres that are designated wilderness. The cultural, biological, and physical resources on Bridger-Teton National Forest are managed and preserved to maximize their continued use and sustainability as guided by the 1990 Bridger-Teton Land and Resource Management Plan (hereafter Forest Plan) and based on the National Forest Management Act of 1976 (16 U.S.C. 1600) and Multiple-Use Sustained Yield Act of 1960 (16 U.S.C. 528-531). Decisions on Bridger-Teton National Forest resources and lands management are under the direct authority of the forest supervisor; however, the Bridger-Teton National Forest maintains close partnerships with many State and Federal agencies.

One of the premier biological resources in the Greater Yellowstone Ecosystem are Rocky Mountain elk. Elk are valued as a cultural resource for public viewing and tourism and a game animal that supports hunters, outfitters, and hunting guides. In recent years, CWD has emerged as an imminent threat to elk health on Bridger-Teton National Forest lands. The first detection of CWD in the feedground region occurred in the fall of 2020 when a cow elk tested positive in Grand Teton National Park. The migratory movements of elk within Bridger-Teton National Forest and among adjacent lands may serve as a direct route of CWD introduction onto Bridger-Teton National Forest. Chronic wasting disease has the potential to affect population productivity, hunting opportunities, and elk viewing opportunities for the public. Thus, recent CWD detection and potential spread onto the Bridger-Teton National Forest created concern about potential disease effects on elk populations, the Greater Yellowstone Ecosystem, public enjoyment, and local economies.

Many wildlife diseases are best managed in the early stages of an outbreak by implementing proactive measures that prevent introduction or limit the spread and growth (Langwig and others, 2015). Because of the diverse management responsibilities and objectives of the Bridger-Teton National Forest and the interests of stakeholders, a transparent and deliberative decision-making approach that considers system uncertainties is necessary to inform management of elk under threat of CWD. In the coming months, decisions that consider multiple potential benefits and risks of permitting elk feeding activities on Dell Creek and Forest Park sites are required. In the long-term, decisions on permitting other feedground sites on Bridger-Teton National Forest are also required and will consider multiple objectives of the Bridger-Teton National Forest by considering any tradeoffs in achieving Forest Plan objectives and diverse stakeholder interests.

Historically, FS issued special-use permits to WGFD to allow supplemental feeding of elk during winter at eight locations on Bridger-Teton National Forest. The permits include a use authorization and site-specific stipulations. Two of these locations, Dell Creek and Forest Park, have been in operation for at least 40 years. Both special-use permits expired in 2016, but the WGFD has been allowed to continue feeding using shorter, 1-year permits. To determine a 20-year long permit request for both feedgrounds, the Bridger-Teton National Forest is assessing the environmental impacts of elk feeding activities by producing an EIS and subsequent Record of Decision under NEPA. An EIS was determined necessary because of the uncertainty of management alternatives on elk populations, disease threats, and economic effects.

3.2. Fundamental Objectives and Performance Metrics

Fundamental objectives describe the set of system attributes a decision maker is motivated (or mandated) to achieve (Gregory and others, 2012). Under NEPA, the fundamental objectives are often referred to as “resource goals.” For a decision maker, the set of fundamental objectives is a comprehensive description of the full range of independent concerns related to a decision and should be sensitive enough to differentiate among the range of alternatives under consideration (Gregory and others, 2012; Runge and others, 2015). Bridger-Teton National Forest used U.S. Geological Survey-facilitated meetings, feedback from cooperating agencies and stakeholders, and public comments to identify six fundamental objectives and two strategic objectives that were important to consider when making permitting decisions on Dell Creek and Forest Park. Strategic objectives are higher level objectives that go beyond the scope of the immediate decision to help achieve or preserve other linked opportunities or relations (Keeney, 1996). Several objectives are drawn directly from an interpretation of the Bridger-Teton National Forest’s enabling legislation, the Forest Plan, the National Forest Management Act of 1976, and the Multiple-Use Sustained Yield Act of 1960. Other objectives were considered based on public and stakeholder concerns and evaluated as part of these fundamental objectives or as narratives described in the EIS. The FS completed the final selection of issues and concerns carried forward as fundamental objectives in this report.

Fundamental Objective 1.—Minimize Disease Prevalence in Elk. According to Land and Resource Management Objective 2.1(b) of the Forest Plan, Bridger-Teton National Forest is directed to provide suitable and adequate habitat to support game and fish populations established by the WGFD, as agreed to by the FS. The introduction and spread of diseases in elk that overwinter and are fed on feedgrounds could lead to faster disease spread and reductions in population size. Further, if elk aggregations occur repeatedly in the same geographic location, like at elk feeding sites, Bridger-Teton National Forest lands may be contaminated by pathogens, leading to locally elevated, indirect disease transmission. Thus, decisions on whether and how to permit elk feeding at Dell Creek and Forest Park could affect the suitability of Bridger-Teton National Forest habitats to support healthy elk populations (Objective 2.1[b]). The effect of alternatives on Fundamental Objective 1 will be measured by the cumulative number of elk mortalities attributed to CWD across the 20-year permitting period on the Afton (Forest Park) and Upper Green River (Dell Creek) HUs (performance metric 1, PM1).

Fundamental Objective 2.—Maintain Big Game Populations (Elk). According to Land and Resource Management Objective 2.1(b) of the Forest Plan, Bridger-Teton National Forest will provide suitable and adequate habitat to support game and fish populations established by the WGFD, as agreed to by the FS. Elk populations in the Greater Yellowstone Ecosystem may be limited in the amount of suitable and naturally occurring winter forage, particularly during harsh winter conditions and high snowpack. Supplemental feeding may help to improve overwinter elk body condition and survival. Conversely, the continuation of feedground operations may increase elk mortality by increasing CWD prevalence in elk that overwinter on feedgrounds. A decrease in the health and size of elk herds would negatively affect hunting and wildlife viewing opportunities. The effect of alternatives on Fundamental Objective 2 will be measured by elk population size on the Afton (Forest Park) and Upper Green River (Dell Creek) HUs in the last year of the 20-year permitting period (performance metric 2, PM2).

Fundamental Objective 3.—Maximize Elk Hunting Opportunities. Several goals as described in the Forest Plan support maximizing elk hunting opportunities and hunter satisfaction. Of relevance is Forest Challenge Goal 2.1, which aims to ensure adequate supplies of products and experiences related to wildlife, fish, and edible vegetation to meet human food needs. Forest Challenge Goal 2.1 is supported by Objectives 2.1(b) and 2.1(c), which requires suitable and adequate habitat to support game populations and the maintenance of forest-user opportunity (including recreational, enjoyment, play, and subsistence uses). Further, maintaining disease free elk populations is an important consideration. According to a 2019 Wyoming Hunter Perspective survey, a majority of hunters were concerned about the potential for CWD to reduce deer hunting opportunity and future generations’ ability to enjoy deer hunting (Wyoming Game and Fish Department, 2020b). Needham and others (2006) documented similar opinions in Wyoming elk hunters. The effect of alternatives on Fundamental Objective 3 will be measured by the number of elk available for harvest on the Afton (Forest Park) and Upper Green River (Dell Creek) HUs across the 20-year permitting period (performance metric 3, PM3).

Fundamental Objective 4.—Maintain Other Big Game Populations (Mule Deer and Moose). Similar to Fundamental Objective 2, the Bridger-Teton National Forest aims to provide suitable and adequate habitat to support mule deer and moose populations. Permitting decisions on the use of Dell Creek and Forest Park sites for supplemental feeding activities may affect the space use patterns and behavior of elk overwintering on Bridger-Teton National Forest lands; thus, changes in feeding may affect competitive interactions among mule deer, moose, and elk on critical summer, transitional, or winter ranges for these species. The effect of alternatives on Fundamental Objective 4 will be measured by the total number of elk-use days of mule deer critical winter range (MDCR) and moose critical winter range (MOCR) within the Afton (Forest Park) and Upper Green River (Dell Creek) HUs over 20 years (performance metrics 4a and 4b, respectively, PM4a and PM4b).

Fundamental Objective 5.—Minimize Conflict with Agricultural and Public Stakeholders. Elk feeding on Bridger-Teton National Forest and other feedgrounds in the Greater Yellowstone Ecosystem have been maintained, in part, to reduce human-elk conflicts. Feedgrounds help mitigate potential conflicts including the spillover of brucellosis to cattle, elk depredation on private agricultural products (for example, stored hay), and elk overwintering in suburban areas leading to wildlife-vehicle collisions and destruction of developed areas. The effect of alternatives on Fundamental Objective 5 will be measured by the cost of elk depredation on privately owned hay stackyards (performance metric 5a, PM5a), the number of elk abortions on private lands during the high-risk brucellosis transmission period, and projected costs to livestock producers within the Afton (Forest Park) and Upper Green River (Dell Creek) HUs (performance metric 5b, PM5b).

Fundamental Objective 6.—Maximize the Prosperity of Resource-Supported Economies. Elk hunting and viewing opportunities in the Greater Yellowstone Ecosystem rely on healthy and abundant populations. In combination, hunting and wildlife viewing supports many economic and social benefits in and around the Bridger-Teton National Forest. Many business owners and clientele (outfitters, guides, lodges, restaurants, and others) may suffer without healthy game populations to harvest, view, and enjoy. The effect of alternatives on Fundamental Objective 6 will be measured by the loss of potential hay sales revenue (performance metric 6a, PM6a), revenue generated by elk harvest tag sales to residents and nonresidents (performance metric 6b, PM 6b), regional revenues generated by hunting activities (performance metric 6c, PM6c), and revenue of elk outfitters and guides (performance metric 6d, PM6d). We calculated all performance metrics for Fundamental Objective 6 as cumulative costs or revenues across the 20-year permitting period. BIO-WEST, Inc. and Cirrus Ecological Services developed the methods to calculate costs and revenues and the methods are described in the EIS.

Beyond the set of fundamental objectives, the Bridger-Teton National Forest was motivated to minimize administrative and legal costs and maintain close partnerships with agencies located in the Greater Yellowstone Ecosystem (in other words, strategic objectives). Dell Creek and Forest Park feedgrounds cost a total of $1,392 or 45 h/yr per feedground to administer. For NEPA litigation, the past two lawsuits have cost the FS an average of $174,500 each [(1) Alkali cost $145,000 in plaintiff attorney fees and $22,000 in FS salary costs, and (2) Alkali, Dell Creek, and Forest Park cost $160,000 in plaintiff attorney fees and $22,000 in FS salary costs]. For partnerships, managing the cultural, biological, and physical resources of the Greater Yellowstone Ecosystem requires close collaborations and joint decision making across State and Federal jurisdictions. Bridger-Teton National Forest has long maintained productive and healthy relations with the State of Wyoming (for example, WGFD and Wyoming Department of Agriculture) and Federal land managers (for example, FWS and National Park Service).

3.3. Management Alternatives

Based on a series of meetings among the Bridger-Teton National Forest, the FWS, National Park Service, and the WGFD, and comments during the NEPA EIS scoping period, the Bridger-Teton National Forest developed four management alternatives. The alternatives evaluated whether to continue permitting the WGFD to feed on Bridger-Teton National Forest at Dell Creek and Forest Park and consider changes in feeding frequency and duration according to feedground specific triggers or a phaseout period.

In detail, the four management alternatives are:

1. Provide special use authorization (hereafter referred to as continued feeding or CF): The WGFC proposal is to continue long-term use (20 years) of the Dell Creek feedground (35 acres), Forest Park feedground (100 acres), and existing facilities for their winter elk management program.

2. No special use authorization (hereafter referred to as no feeding or NF): Use of National Forest System lands for the WGFC's winter elk management activities would not be permitted at Dell Creek and Forest Park feedgrounds.

3. Phaseout alternative (PO): Use of National Forest System lands for the WGFC's winter elk management activities would be permitted at Dell Creek and Forest Park feedgrounds for three feeding seasons.

4. Emergency feeding only (EF): Use of National Forest system lands for the WGFC's winter elk management activities would be permitted at Dell Creek and Forest Park feedgrounds or the designated trailing route for emergency use over a 20-year period. Dell Creek and Forest Park would have different emergency triggers. For Dell Creek, most of the concern surrounding a feedground closure relates to the physical location's proximity to private land and the high likelihood elk would seek out alternative sources of food on those private lands. Increased use of private lands would lead to increased depredation of agricultural products and close contact with cattle during the high-risk brucellosis transmission period (January 15–April 30). Thus, for the Dell Creek emergency trigger, there would be no feeding in early winter months; however, feeding could occur from January 15 to April 15 if elk were on private lands. For Forest Park, the primary concern is overwinter

reductions in calf survival from a lack of naturally occurring winter range in areas on and adjacent to the feeding location. As a result, emergency feeding could occur on Forest Park when the natural winter mortality rate in calves exceeded 5 percent of the previous year's calf population estimate in Hunt Area 90 (includes Forest Park feedground). If either criterion were met, feeding would occur immediately. As part of this alternative, a 200-m wide trailing route to alternative winter forage areas would also be included to allow the WGFC to feed elk at other sites outside of the established feedground location (see map in Section 2 of the draft EIS).

3.4. Performance Metric Scaling

We analyzed the fundamental objectives and associated performance metrics (five total in this report and additional socioeconomic indicators are described in the draft EIS) primarily at the elk HU level, which is a spatial scale that defines the area most elk management decisions are made (fig. 1). The HUs are designated with consideration of the natural distribution and movement patterns of elk, their seasonal ranges, and human developments (fig. 1). The Dell Creek and Forest Park feedgrounds occur in the Upper Green River and Afton HUs, respectively; therefore, performance metrics are primarily summarized at the herd-unit spatial scale. However, it is important to recognize that although summaries at the Upper Green River and Afton HU level aligns best with regional management decisions, the alternatives under consideration in this EIS (specifically, whether and how to permit Dell Creek and Forest Park feedgrounds) would act on a much smaller and localized population around the feedgrounds. For Dell Creek (Upper Green River HU), the management alternatives would directly affect only about 12 percent of elk in the HU based on feedground counts from 2016 to 2020 and our reported projections. For Forest Park (Afton HU), the estimated affected elk would be 20 percent. Thus, wherever possible, we also presented metrics at the feedground level to provide important context to the reader and decision maker.

4. Chronic Wasting Disease, Population Size, and Harvest Projections

4.1. Overview

We combined empirical data and expert knowledge in a model to project elk population size, CWD prevalence and mortality, and hunter harvest in the Afton and Upper Green River HUs under the four management alternatives and across the 20-year permitting period. We expanded on an existing sex- and age-structured disease model and included density-dependent calf survival and reductions in harvest at low populations. Density-dependent calf survival is included to model projected declines in elk populations without continued feeding. For parameter values, we used existing empirical data from regional elk populations and a formal process of expert judgment.

4.2. Methods

We modified a sex- and age-structured stochastic simulation model previously developed by Cross and Almberg (2019) and later expanded by Rogers and others (2022) to project the effects of CWD and management alternatives (Cross and others, 2023). Each simulation begins in May and iterates on a monthly timestep, with transitions accounting for aging; reproduction; natural, harvest, and disease associated mortality; and disease transmission. The model structure included male and female sex classes and 12 age classes where harvest and vital rates are structured according to i categories: calves (0–1 years, i = 1), yearling males (1–2 years, i = 2), yearling females (1–2 years, i = 3), adult males (>2 years, i = 4), and adult females (>2 years, i = 5). Individuals transition between stages according to sex- and age-specific survival, ϕ_i reproductive, γ_i , and harvest, h_i, probabilities. Individuals older than age 12 remain in the 12th age class until they die.

We modeled CWD dynamics at the HU scale. Each HU consisted of feedground and native winter range elk that intermix during summer months but separate during winter months. The fed elk population segment may be further subdivided during winter to include the target feedground, such as Dell Creek or Forest Park, versus any other feedground(s) in the HU. We constructed two different models for our hypotheses about how CWD may transmit among fed and unfed elk population segments (eqs. 1 and 2). Our first hypothesis was that CWD transmission occurs during winter when elk tend to be the most concentrated, and feedground and native winter range elk do not intermingle during summer. For this hypothesis, we assume that fed and native winter range elk are independent, and the monthly probability of infection for a susceptible individual can be written as:

$$\lambda_{jtk} = 1 - exp\left(-\frac{\beta_k I_{jtk}}{N_{jtk}{}^{\theta_k}}\right), \tag{1}$$

where

k is an indicator variable for fed (k =1), unfed (k = 2), and target feedground (k = 3) elk;
t represents the year;
j represents the month of the year;
β_k is the CWD transmission coefficient for fed (k = 1 or 3) and unfed (k = 2) elk;
I_{jtk} is the number of CWD infectious elk;
N_{jtk} is the population size; and
θ_k describes the density-dependent transmission.

In the formulation of equation 1, the exponent to population size, θ, controls the strength of the density dependence in disease transmission. When θ is zero, the risk of infection per susceptible individual depends only on the number of infectious individuals, so-called density dependent transmission, whereas when θ is equal to one, the per-susceptible risk is proportional to I/N, so-called frequency dependent transmission (Getz and Pickering, 1983).

Our second hypothesis was that feedground and native winter range elk intermix for the nonfeeding months of May–November and that disease transmission is not highly seasonal. We model this possibility by assuming individuals from all populations can contribute toward the probability of CWD infection during the summer months but at a different transmission coefficient β' a density-dependence θ' given as:

$$\lambda_{tk}(j) = \begin{cases} j \in \{1,2,3,4,12\}, 1 - exp\left(-\dfrac{\beta_k I_{jtk}}{N_{jtk}^{\theta_k}}\right) \\ j \in \{5,6,7,8,9,10,11\}, 1 - exp\left(-\dfrac{\beta' \sum_k I_{jt}}{\sum_k N_{jt}^{\theta'}}\right) \end{cases}, \quad (2)$$

where the transmission coefficient β' and strength of density dependence θ' for May–November in equation 2 are estimated from mixture distributions defined by the fed and unfed parameters. We used the R package distr version 2.8 to calculate the mixture distribution and draw random deviates (R Core Team, 2022; Ruckdeschel and others, 2006). The mixture distribution was weighted according to the proportion of the population at the start of the simulation that was fed or unfed.

We considered direct and indirect CWD transmission pathways. We defined direct transmission as direct contact between an infectious individual and a susceptible individual that results in CWD infection. We defined indirect transmission as infections that result from contact with a contaminated environment. The PrP^{CWD} are stable outside of hosts and may remain infectious in the environment for months to years following external shedding (Miller and others, 2004). The stability of PrP^{CWD} in the environment suggests indirect transmission through a contaminated environment may become more important to disease dynamics over time (Almberg and others, 2011). However, it remains difficult to quantify the dynamics and importance of environmental contamination and indirect transmission because of limitations in diagnostic techniques. Thus, we modeled probability of infection from the environment as a simple linear relationship that increases over time, starting at zero in the first-time step and ending at some maximum in year 20. Using expert judgment, we obtained the final probability of becoming infected from the environment at year 20 as described below.

For post-infection CWD survival, we transitioned elk through 10 infectious stages, which produced a stochastic, bell-shaped time-to-death Gamma distribution. We set the probability of progressing through infectious stages at 0.28, which results in a median time-to-death of 34 months (fig. 2, Brandell and others, 2022). Thus, the performance metric of CWD mortalities included only elk that progressed to the last infectious stage and did not include individuals that may be CWD infected but died from hunting or natural mortality. We assumed no difference in CWD transmission between sexes or ages of individuals.

The simulation model included two additional processes specific to the feedground CWD situation: density-dependent calf survival and harvest reductions in declining populations. Previous work by Singer and others (1997) indicated calf survival on winter range declines as density increases, which is similar to the broader literature which found calf survival more variable than adult survival (Gaillard and others, 1998; Lubow and others, 2002). Density-dependent calf survival follows from an assumption that halting feedgrounds will reduce elk carrying capacity as mediated through calf survival. Thus, the annual calf survival rate, ϕ_1, varied between a minimum (0.1) and maximum annual survival rate (0.8) according to a density-dependent response to the previous year's annual population size on each HU (fig. 1.4), given by

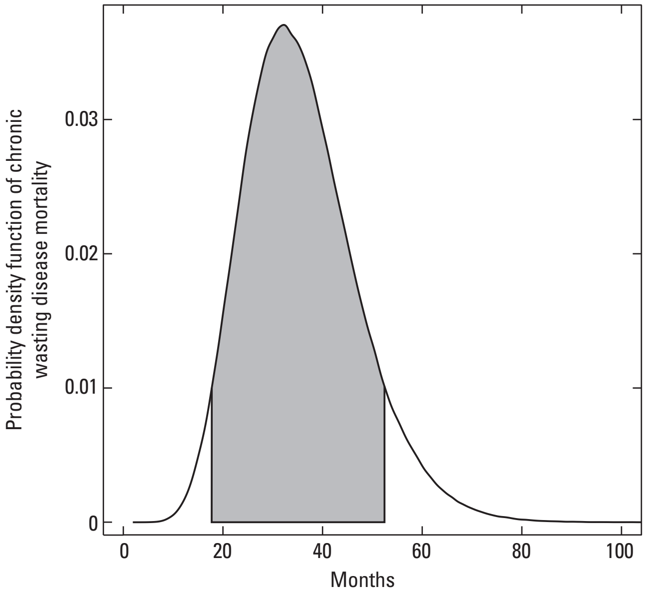

Figure 2. Probability density function of the time-to-death because of chronic wasting disease in the absence of other mortality hazards (for example, harvest and natural mortality). The gray area represents the highest density interval containing 90 percent of the distribution.

$$\phi_{1,t,k} = max\left(\phi_{\max}\left(1-c\left(\frac{N_{j-1,k}}{K_{HU,k}}\right)^{\delta}\right),\phi_{\min}\right), \tag{3}$$

where

$N_{j-1,k}$ is the January population size from the previous year for fed or unfed elk;

k is an indicator variable as in equation 1;

$K_{HU,k}$ is a parameter related to the carrying capacity of fed and native winter range elk in each HU;

c is the proportion reduction when population was at carrying capacity;

δ controls the shape of the density-dependence;

$\phi_{\max}$ is the maximum calf survival rate; and

$\phi_{\min}$ is the minimum calf survival rate.

We based our estimates of K on the starting population sizes such that

$$K_{HU,k} = N_{0,k} \times \upsilon, \tag{4}$$

where

$N_{0,k}$ is the starting population size of fed or native winter range elk; and

υ is a calibration constant used to stabilize the population at carrying capacity.

We calibrated density dependence parameters $K_{HU,k}$, and υ for equations 3 and 4 such that elk populations remained stable given current harvest rate estimates and no CWD transmission. This stability occurred when υ =3.0. We assumed fed elk segments and unfed segments could be supported at their current densities; however, when a feedground was subject to closure, we assumed the fed elk population associated with that feedground would be reduced to densities measured on other HUs without feedgrounds in the Greater Yellowstone Ecosystem. Thus, we calculated the average elk density on fed and unfed units and based on those estimates reduced $K_{HU,3}$ according to the percent decline in average elk density on fed and unfed units.

Based on previous management of other big game populations in Wyoming, we assumed a reduction in female elk harvest rates as a function of herd-unit specific population objectives. When populations fell to below half of the population objective (in other words, $\sum_{j-3}^{j} \sum_{k=1}^{3} N_{t,k}/3 < 0.5 \times P_{HU}$), we eliminated adult female harvest. The WGFD has made similar adjustments in western mule deer regions in response to CWD-driven population declines.

4.2.1. Parameter Estimation

For vital and harvest rate estimates (table 3), we used a combination of Galloway and others (2021), Raithel and others (2007), Cotterill and others (2018), and WGFD data (Wyoming Game and Fish Department, 2020a), and references therein; unpublished data are available from Wyoming Game and Fish Department; contact Wyoming Game and Fish Department for further information). Adult elk have the highest annual survival rates whereas juvenile and calf survival is lower. Annual reproduction rates are higher in adult females when compared against juvenile females. The probability of harvest per year per sex and age class was set in rough agreement with proportions harvested in the Jackson HU from 1993 to 2021. Harvest rates were higher in males than females with adults harvested at higher rates than juveniles and calves. We assumed feedground and native winter range elk have the same vital rates when populations are at stable equilibria (in other words, growth rate equal to one).

There are no data to estimate CWD transmission dynamics in fed and unfed elk. Therefore, we used a process of formal expert elicitation to parameterize the rates and modes (in other words, frequency- or density-dependent) of CWD transmission. We invited a panel of eight experts with diverse professional expertise, training, and backgrounds in disease ecology, ungulate ecology, population management, and epidemiological modeling to use their expert judgment and provide estimates of necessary parameters and associated uncertainty (table 1.1 in appendix 1). We used a modified Delphi process (Hanea and others, 2017) and four-point Speirs-Bridge elicitation protocol to develop estimates for fed and unfed disease transmission dynamics (Speirs-Bridge and others, 2010). The four-point estimates are described by an expert's low, high, and best estimate of a parameter and confidence the true value falls within their low and high values. The quantiles of each expert (based on their four-point responses) were first used to fit a probability distribution by finding the parameters for a beta or log-normal distribution, which minimized the sum of square differences between the elicited and fitted quantiles. The choice of beta or log-normal distributions reflected the range of values appropriate for each parameter of interest. We aggregated individual distributions into a single probability distribution for each parameter using an unweighted Vincent average. Our Vincent average was calculated by averaging the 2.5 and 97.5 quantiles from each fitted individual distribution to develop a single aggregate distribution of the same family (for example, beta or log-normal; Conroy and Peterson, 2013).

Most of the empirical and theoretical modeling work on CWD in deer suggested frequency-dependent transmission best explains trends in prevalence (Jennelle and others, 2014). However, these studies were evaluated at regional spatial scales where changes in population size may not reflect changes in local group sizes. We expect changes in local group sizes to be heterogeneous, particularly for elk populations in which some portion of the population aggregate on feedgrounds. Therefore, we asked experts to estimate CWD transmission modes (θ, eq. 1) in elk on native winter range and feedgrounds separately. To inform their estimates of density- or frequency-dependent transmission strength, we provided experts with an interactive version of the simulation model and asked them to provide four-point estimates based on simulated CWD prevalence trends and population sizes. Individual distributions can be found in appendix 1 figs. 1.1, 1.2, 1.3. The aggregate estimate for CWD transmission mode on feedgrounds was more density-dependent (fig. 3, aggregate median estimate, $\theta_{k=1} = 0.57 \pm 0.12$) than unfed elk that overwinter on native winter range (aggregate median estimate, $\theta_{k=2} = 0.72 \pm 0.1$). Similarly, we elicited four-point estimates for direct and indirect transmission for fed and unfed elk population segments (figs. 4, 5). Scaling of the transmission coefficient, β, is not intuitive even for experts. Meanwhile, R_0, the average number of infections that result from a single infectious individual in a fully susceptible population, depends on the transmission coefficient, infectious period, and survival rates. Therefore, we elicited an annual R_0—the average number of infections an initially infected individual would cause given they survive and remain infectious for a year. We then calculated monthly transmission coefficients for fed and

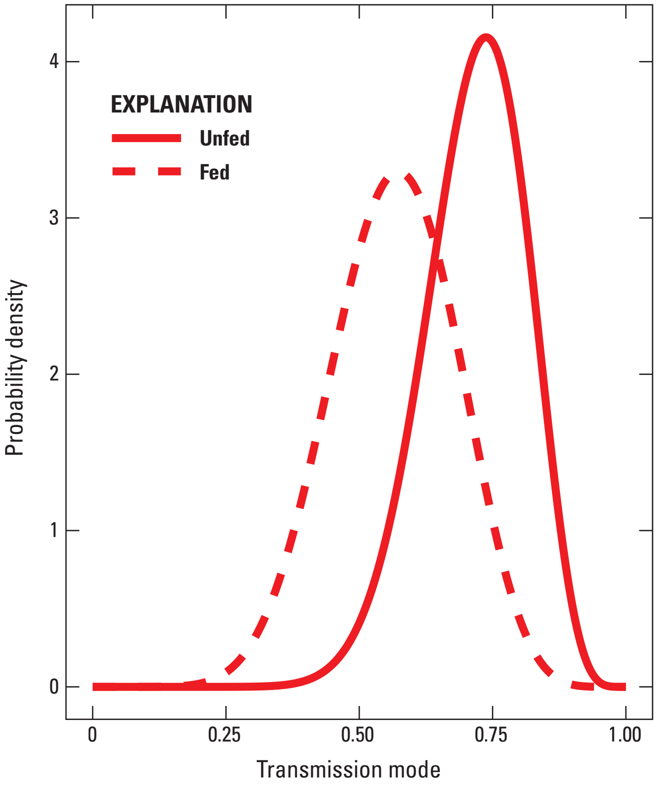

Figure 3. Aggregate distributions of the mode of chronic wasting disease transmission for fed and unfed elk population segments. Transmission is density dependent when the mode, θ equals zero, frequency dependent when the mode is equal to one, or some intermediate form when $0< \theta >1$.

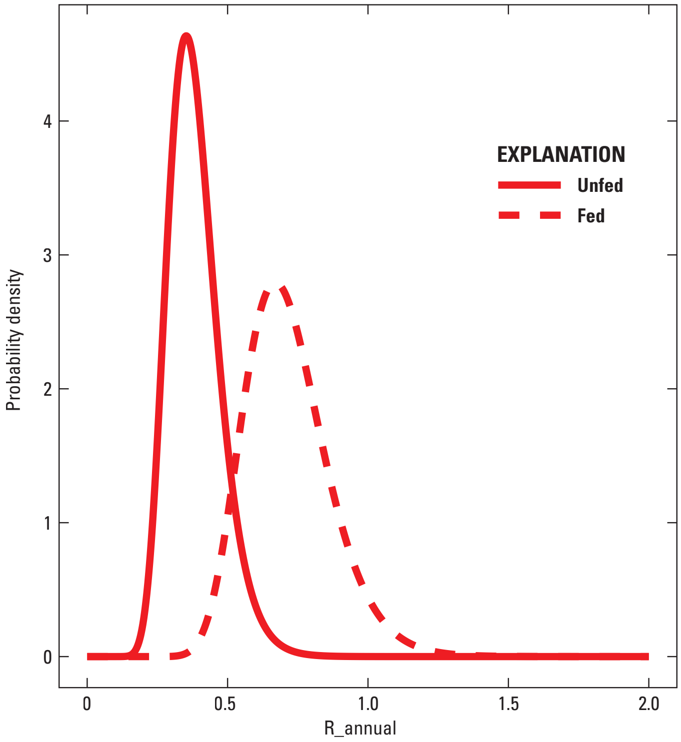

Figure 4. Aggregate distributions of the number of chronic wasting disease infections that result from a single infectious individual, R_annual, under fed and unfed scenarios.

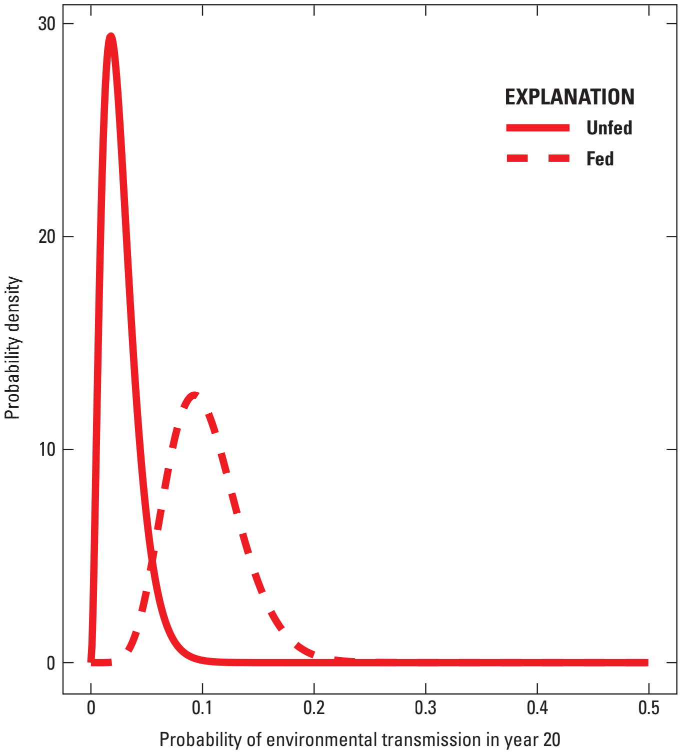

Figure 5. Aggregate distributions of the probability of environmental transmission in year 20 in a completely susceptible population on native winter range and feedgrounds under fed and unfed scenarios.

unfed population segments assuming $\beta_k = R_{k,0\_annual} N_{0,k}^{\theta_k - 1}/12$, where $N_{0,k}$ was the starting population size. For direct transmission, the aggregated expert estimates for the mean number of annual infections from a single infectious individual were 0.39 (standard deviation [SD] = 0.09) and 0.71 (SD = 0.14) for native winter range elk and fed elk, respectively (fig. 4). For indirect transmission, the aggregate estimates for the expected annual probability of infection following 20 years of spread in a completely susceptible elk population were 0.03 (SD = 0.02) and 0.10 (SD = 0.03) on native winter range and feedgrounds, respectively (fig. 5).

According to trend counts for fed and unfed elk population segments and estimates of available winter range on each HU, we estimated HUs with feedgrounds supported an average density of 6.21 elk/km^2 on available winter range, whereas unfed HUs supported an average of 4.79 elk/km^2 on available winter range (Wyoming Game and Fish Department, 2020a). Based on these averages, we assumed previously fed elk population segments would decline by approximately 23 percent in the absence of feeding (table 4).

At the beginning of each simulation, we drew each vital rate from a stochastic distribution based on the reported average and parametric uncertainty. This random value served as the mean of a beta distribution representing temporal variation in the vital rate from year to year, with process variance reported in table 3; the resulting annual values ranged between zero and one. We also incorporated parametric uncertainty in the expert elicited CWD transmission modes and rates but did not allow for the parameter to vary within simulations (in other words, no temporal or process variance).

4.2.2. Initial Conditions

To initialize each of our model projections, we required a starting population size and an estimate of CWD prevalence in each HU. To estimate initial conditions, we made four important assumptions. First, we assumed elk that occur on native winter range during winter counts are undercounted and thus, should be corrected by a sightability factor (Lubow and Smith, 2004). Second, we further adjusted the starting population sizes so that the resulting number of harvested elk approximates the number harvested in WGFD reports for that HU. This accounted for potential immigration and emigration of elk among HUs between the hunting season and winter counts and how sightability may vary by region. Third, we treated the initial elk population size as a random variable estimated by the average adjusted elk population counts from 2016 to 2020 and the coefficient of variation in these annual counts. We assumed that the fed and unfed populations counts for each projection were completely correlated so the percentage of fed elk in a HU was held constant. Finally, we assumed initial CWD prevalence matches WGFD reports (McWhirter and others, 2021), and there are no initial CWD prevalence differences between feedground and winter range elk.

Table 3. Elk vital and harvest rate estimates used in the sex- and age-structured stochastic simulation model.

[SD, standard deviation]

Vital rate	Notation	Mean	Parametric SD[1]	Process SD[2]
Maximum calf survival[3,4]	ϕ_1	0.8	0.103	0.0385
Juvenile survival[3,4]	ϕ_{2-3}	0.88	0.0085	0.0042
Adult male survival[3,4]	$\phi_{m,4}$	0.95	0.017	0.0034
Adult female survival[3,4]	$\phi_{f,5}$	0.93	0.0085	0.0034
Calf reproduction[3,4]	γ_1	0	0	0
Yearling female reproduction[5]	γ_3	0.25	0.033	0.035
Adult female reproduction[5]	γ_5	0.93	0.033	0.035
Harvest mortality calf[6]	h_1	0.09	0.007	0.005
Harvest mortality yearling male[6]	$h_{m,2}$	0.18	0.007	0.005
Harvest mortality yearling female[6]	$h_{f,3}$	0.10	0.007	0.005
Harvest mortality adult female[6]	$h_{f,5}$	0.10	0.007	0.005
Harvest mortality adult male[6]	$h_{m,4}$	0.46	0.007	0.005

[1] Parameteric variation created different mean values across simulations.

[2] Process variation resulted in parameter variation between years within a simulation.

[3] Approximated from Galloway and others, 2021.

[4] Approximated from Raithel and others, 2007.

[5] Approximated from Cotterill and others, 2018.

[6] Approximated from the Jackson herd unit from 1993 to 2020 (Wyoming Game and Fish Department, 2020a, and references therein).

Table 4. Average elk population sizes from 2011 to 2020 in 13 Wyoming herd units around the Greater Yellowstone Ecosystem.

[Population estimate, accounts for the 67.3-percent sightability of unfed elk in the herd unit; winter range, critical elk winter range defined by Wyoming Game and Fish Department in square kilometers; elk density, estimated by the population estimate divided by the critical winter range; km2, square kilometers; —, no data]

Herd unit	Feedgrounds	Fed elk	Trend count	Hunted elk	Population estimate	Winter range km^2	Elk density
North Bighorn	FALSE	—	5,649	1,481	8,394	1,073	7.82
Clark's Fork	FALSE	—	3,130	452	4,652	1,305	3.56
Cody	FALSE	—	5,421	1,394	8,055	1,805	4.46
Gooseberry	FALSE	—	2,553	728	3,793	1,416	2.68
Wiggins Fork	FALSE	—	6,012	1,012	8,934	1,110	8.05
South Wind River	FALSE	—	2,907	633	4,319	1,991	2.17
Jackson	TRUE	9,536	10,828	1,275	12,748	837	15.23
Fall Creek	TRUE	3,425	4,154	603	5,236	499	10.49
Upper Green River	TRUE	2,466	2,734	420	3,132	666	4.70
Hoback	TRUE	989	1,063	216	1,172	355	3.30
Afton	TRUE	1,276	2,106	811	3,338	667	5.00
Piney	TRUE	2,174	2,466	908	2,934	1,998	1.47
Pinedale	TRUE	1,869	2,094	480	2,428	739	3.28

Based on these assumptions, we used the trend counts for each HU and count data from WGFD feedground surveys (Wyoming Game and Fish Department, 2020a, and references therein) and adjusted them using a sightability constant and adjustment factor. Thus, initial populations for the Afton and Upper Green River HUs are given by $y_t^{\text{count}} = (y_t^{fed} + \frac{y_t^{\text{unfed}}}{\psi})\,\omega$, where ψ is a sightability constant (0.673 estimated from Lubow and Smith, 2004) and ω is the HU-specific adjustment factor. The adjustment factor is 1.73 for the Afton HU and 0.81 for the Upper Green River HU (table 5).

The Hoback HU was dissolved in 2020–21 (fig. 1). Based on WGFD estimates, we assumed 36 percent of the previous Hoback HU elk were associated with the redrawn Upper Green River HU, and 64 percent were associated with Piney HU elk. We accounted for these HU changes in our calculations of the 2016–20 counts, which we used as initial conditions for the model. For the Afton HU, the average total initial population size estimate was 2,729 (SD = 568) elk, with an average of 1,101 elk overwintering on two feedgrounds: Forest Park and Greys River. Between 2016 and 2020, Forest Park had 550 (SD = 161) individuals, and Greys River had 552 (SD = 104) individuals on average. Our total initial population size for the Upper Green River HU was 3,332 (SD = 346) after accounting for elk from the Hoback unit and those counted on feedgrounds (Black Butte, Dell Creek, Green River Lakes, and Soda Lake).

Wyoming Game and Fish Department (McWhirter and others, 2021) estimated CWD prevalence in 2020 was 1.6 percent (95 percent Bayesian credible interval = 0.2–5.8 percent) for the Afton elk population and 2.4 percent (95 percent Bayesian credible interval = 0.4–6.4 percent) for the Hoback/Upper Green River HU elk population. Based on these data, we set initial CWD prevalence for juveniles and adults as the median of the Afton and Upper Green River HU estimates (2 percent) and half of that value for calves (1 percent).

4.2.3. Implementation of Management Alternatives

The purpose of the disease model is to forecast effects of the different alternatives on three fundamental objectives (performance metrics 1, 2, and 3). To better understand the effects the management alternatives have on long-term CWD trends and hunting opportunities, our models tracked the total number of CWD mortalities (performance metric 1), elk population size in year 20 (performance metric 2), and the cumulative harvest (performance metric 3) across the 20-year permitting period. Each alternative (defined in Section 3.3) required a corresponding set of changes under the four alternatives and across the 20-year permitting period.

For simulation under the continued feeding alternative, the distribution of elk on feedgrounds and native winter range is maintained as it was from 2016 to 2020. For the simulation under the no feeding alternative, elk are redistributed from Forest Park and Dell Creek to native winter range population segments. For the phaseout alternative, the first three simulated years maintained feedground and native winter range distributions after which, Forest Park and Dell Creek feedgrounds are redistributed to native winter ranges and simulated for the remaining 17 years of the permitted period. Figure 6 illustrates the phaseout of the Dell Creek feedground and subsequent elk decline because of a lack of feeding in a model without CWD. For the emergency feeding alternative, all elk are maintained on feedgrounds and winter ranges with no reduction in the carrying capacity (fig. 6). However, elk on Forest Park and Dell Creek are treated as distinct from other elk on feedgrounds because of the emergency triggers considered under this alternative. On Forest Park, the emergency feeding criteria required overwinter elk calf mortality to exceed five percent of the previous year's calf population estimate in Hunt Area 90 before feeding activities can occur (for an example of model behavior without disease, see fig. 6). We estimated that this trigger was likely to result in emergency feeding in around 70 percent of years based on Singer and others (1997), which documented calf winter mortality in excess of 5 percent in 13 out of 19 studied years. Thus, we considered the frequency of not feeding on Forest Park to operate according to a stochastic process defined by a beta distribution with shape equal to 7 and scale equal to 14.

On Dell Creek, the EF alternative was designed to reduce elk-to-cattle brucellosis transmission during the high-risk period of February–May. Because of the proximity of Dell Creek to adjacent private rangelands, we assumed elk would commingle with cattle annually during winter months unless provided supplemental feed. Therefore, there were no

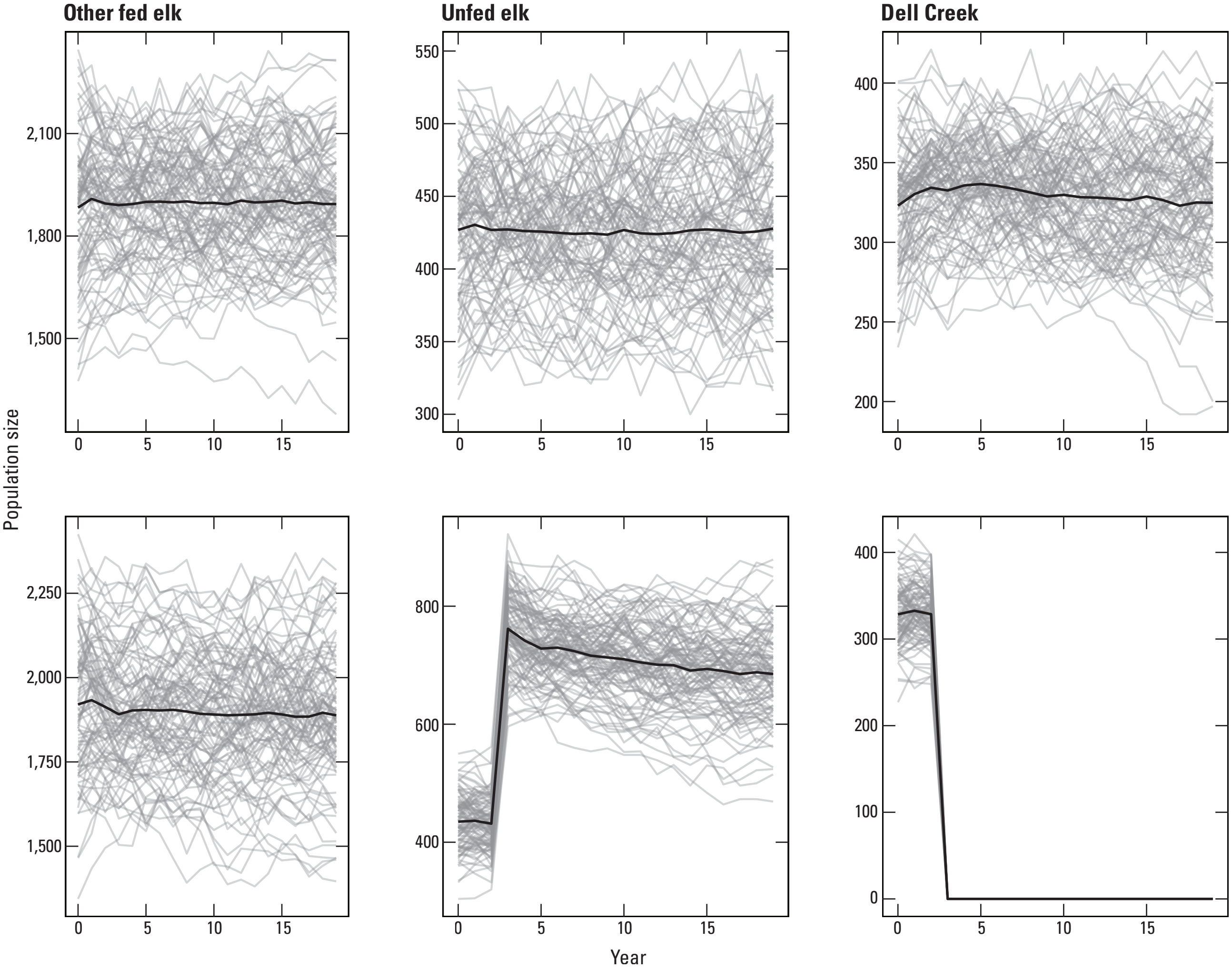

Figure 6. One hundred simulations (gray lines) and the average population size (black lines) of the Upper Green River herd unit in the absence of any chronic wasting disease effects for the emergency feeding (top row) and phaseout alternative (bottom row) alternatives. For the phaseout alternative, the target feedground Dell Creek, is added into the unfed population in year 3 and then assumed to have a 23-percent reduction in carrying capacity.

Table 5. Average elk counts from 2016 to 2020 for the six modeled herd units in Wyoming. Hoback was combined with Upper Green River and the Piney herd units.

[Average hunt, the average number of elk hunted from 2016 to 2020; Simulated hunt, the average number hunted per year in the chronic wasting disease model prior to corrections when disease is excluded; Correction factor, the average 2016–20 hunt divided by the simulated hunt. The Upper Green River and Piney herd unit corrections account for the incorporation of the Hoback unit; est., estimate; SD, standard deviation; —, no data]

Herd unit	Trend count	Hunted elk	Fed elk	Unfed elk	Population est.	SD	Percent fed	Simulated hunt	Correction factor
Afton	2,197	870	1,101	1,628	2,729	568	0.41	503	1.73
Fall Creek	4,241	523	3,372	1,291	4,663	389	0.72	858	0.61
Jackson	10,598	1,240	9,515	1,610	11,124	465	0.85	—	—
Pinedale	2,036	452	1,772	393	2,165	208	0.83	407	1.11
Piney	2,976	957	2,508	696	3,204	608	0.78	604	1.58
Upper Green River	3,155	501	2,791	541	3,332	346	0.85	617	0.81

differences considered in the frequency of feeding. However, we assumed the seasonal duration of feeding would be reduced by one month, and this reduction would reduce CWD transmission. We assumed that the feeding started on February 1 under emergency conditions rather than January 1, since both the CWD and habitat models operate on a monthly basis. As a result, for the EF alternative on Dell Creek, we used $\beta_{k=2}$ for January.

In addition to the unique conditions for each of the four alternatives, we incorporated our two hypotheses about CWD transmission occurring among and between fed and unfed population segments. We considered each hypothesis as equally likely to occur (in other words, 50 percent of the weight placed on each) based on the considerable uncertainty in elk space use patterns, social behaviors, relatedness, and other factors that might affect CWD spread within populations. Thus, for each simulation, the CWD transmission mode and rate estimates for elk outside of winter months (May–November) were estimated as a group-weighted mixture distribution of the fed and unfed parameter estimates, where groups were defined as the proportion of elk in fed and unfed segments at the beginning of each simulation.

4.2.4. Cumulative Effects

In addition to analyzing the alternative actions for Dell Creek and Forest Park, we ran simulations where the CF, PO, and NF alternatives were implemented across all feedgrounds in a HU or all feedgrounds located on FS property. We did not model an EF alternative because we were unable to identify feedground-specific triggers (for example, brucellosis risk and calf mortality) that could be used for each location. We further assumed the management action would occur simultaneously across all feedgrounds. In practice, however, management actions (for example, closures) are expected to occur over time, perhaps in accordance with the expiration of permits for feedgrounds on FS property. We used the same vital rate parameters as in Section 5, which are the same for each HU.

4.3. Results

4.3.1. Dell Creek and Forest Park

Population sizes were projected to decline and CWD prevalence was projected to increase on the Afton and Upper Green River HUs across the four alternatives (figs. 6–11; table 6). Figures 6–11 illustrate fed and unfed elk population and CWD prevalence trajectories over time for the CF, PO, and NF alternatives. Population size estimates after 20 years indicated projected declines on average of 25–35 percent of average population sizes from 2016 to 2020 on the Afton HU and 53–57 percent on the Upper Green River HU. Corresponding to the population size, we predicted declines in available harvest on average between 12 and 14 percent in the Afton HU and 23–25 percent in the Upper Green River HU. We predicted CWD prevalence increases across the same 20-year period from an initial mean of 1.6 percent to 17–20 percent on average in the Afton HU and 27–30 percent on the Upper Green River HU.

For both HUs, the no feeding alternative had higher projected population sizes after 20 years compared to phaseout, emergency feeding, and continued feeding alternatives (figs. 10 and 11, table 6). In both HUs, the no feeding alternative had the lowest projected CWD prevalence estimates in year 20 (figs. 10 and 11, table 6). Emergency feeding and continued feeding resulted in the highest CWD prevalence and the phaseout alternative was intermediate. Finally, the no feeding alternative had the highest projected cumulative harvest in the Afton HU, and phaseout had the lowest cumulative harvest. On the Upper Green HU, emergency feeding had the highest cumulative harvest, and phaseout had the lowest. The average differences in CWD prevalence, population size, and cumulative harvest were smaller than the projected standard deviations (table 6).

The no feeding alternative was projected to have lower CWD mortalities and higher population sizes at year 20, but there is significant overlap among simulations when we account for uncertainty (figs. 12, 13). Interestingly,

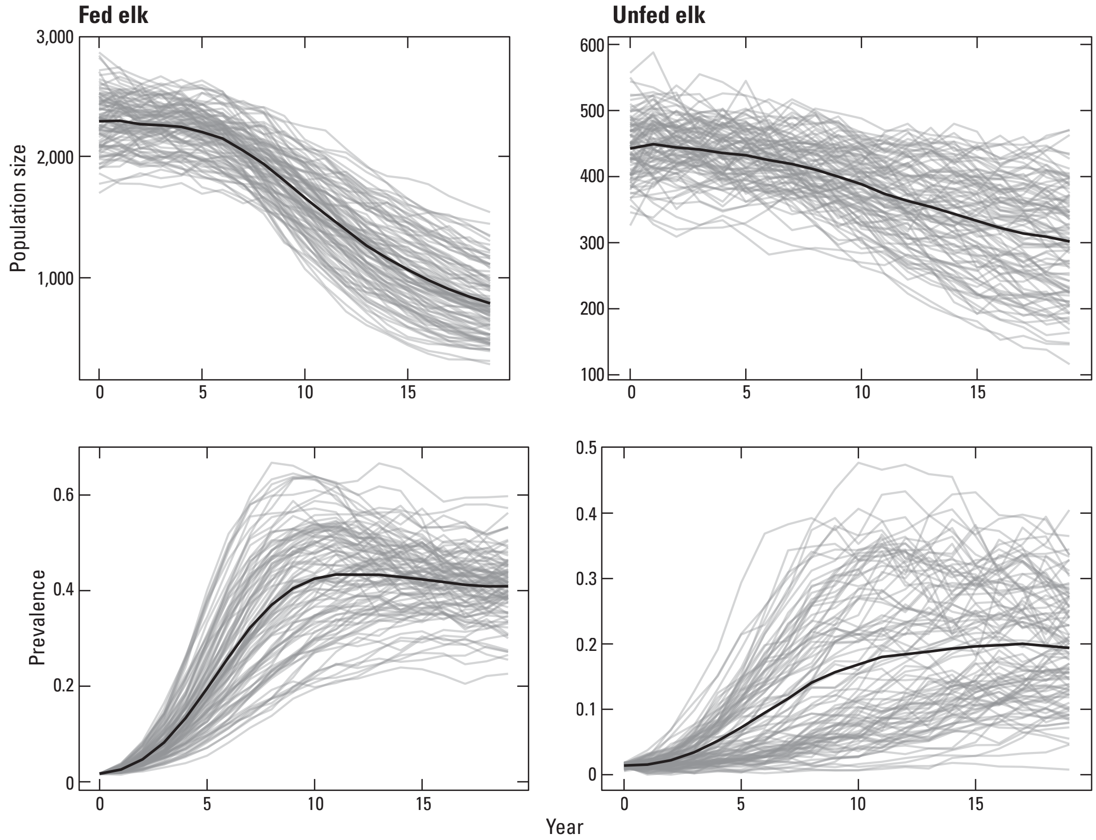

Figure 7. Elk counts and chronic wasting disease prevalence for fed elk and unfed elk in the Upper Green River herd unit for the continued feeding alternative.

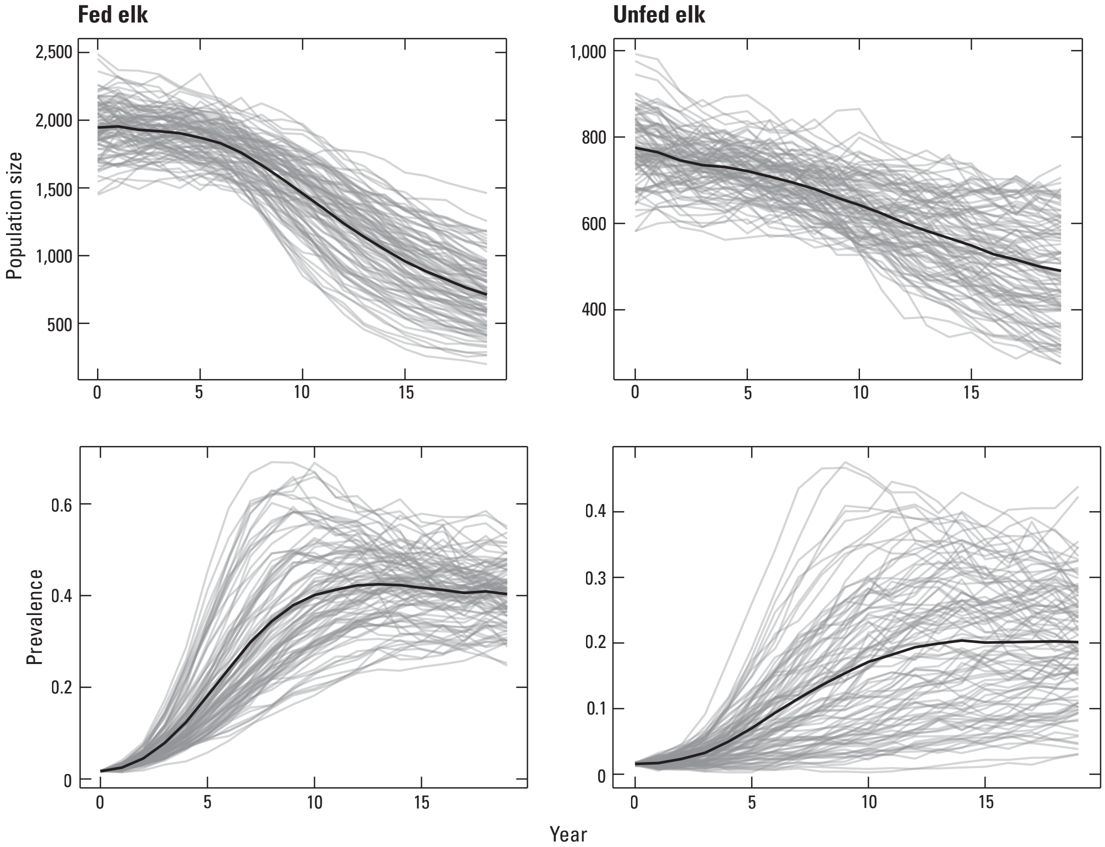

Figure 8. Elk counts and chronic wasting disease prevalence for fed elk and unfed elk in the Upper Green River herd unit for the no feeding alternative.

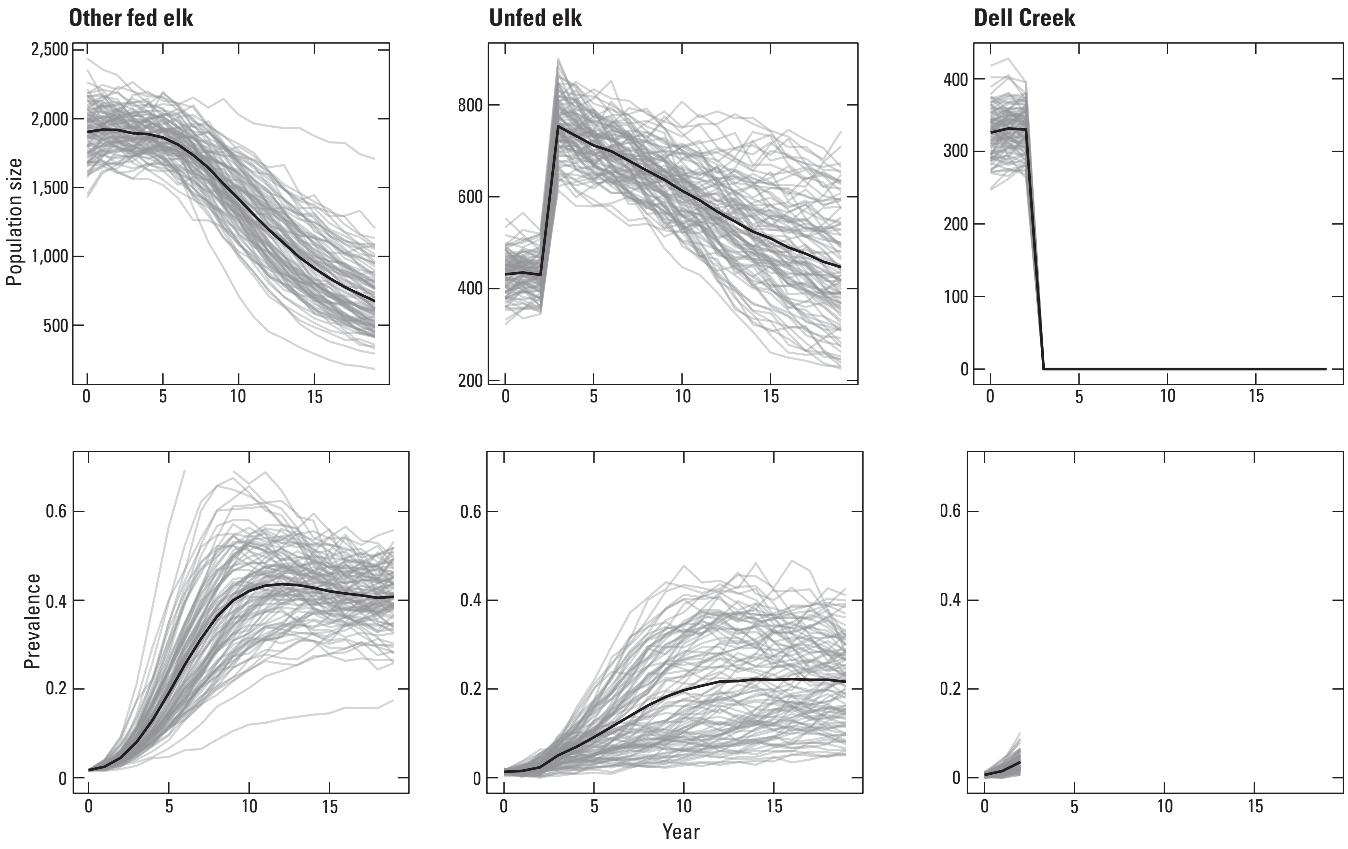

Figure 9. Elk counts and chronic wasting disease prevalence for other fed elk, unfed elk, and the target feedground of Dell Creek in the Upper Green River herd unit for the phaseout alternative. Elk on the Dell Creek feedground are added to the unfed elk population in year 3.

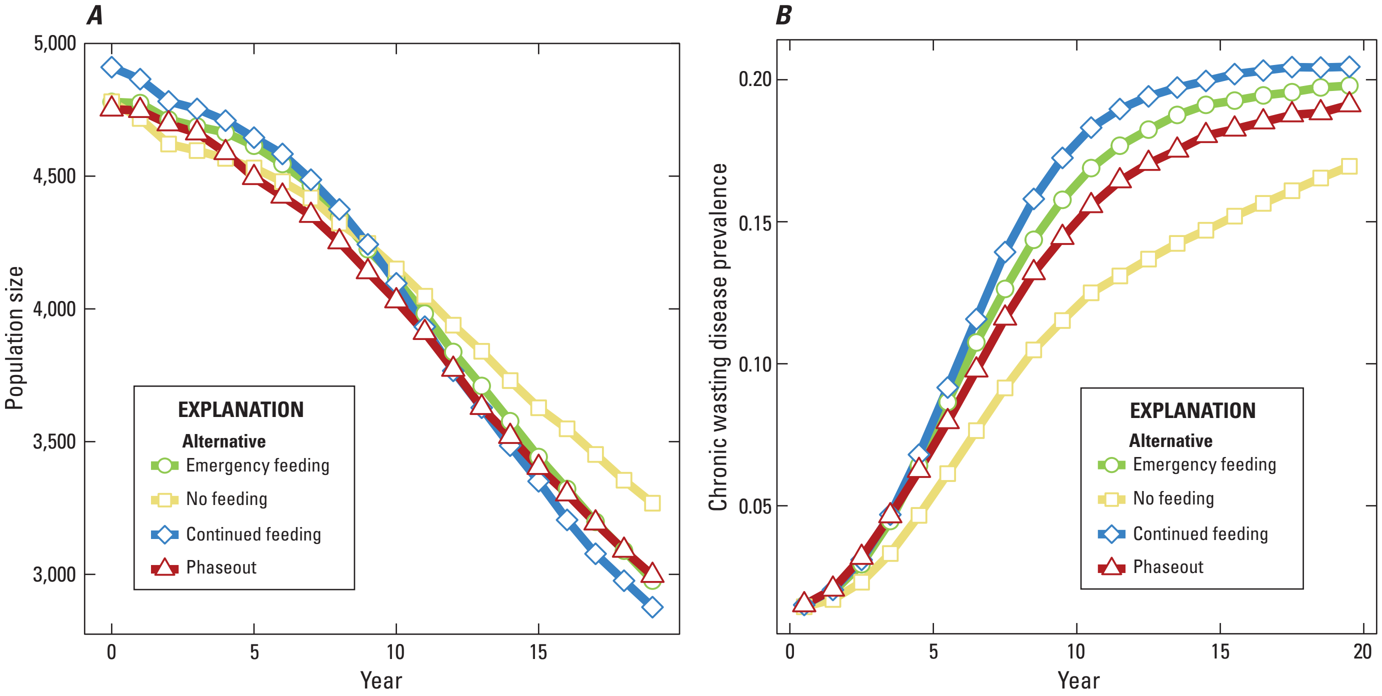

Figure 10. *A,* Average population size and *B*, chronic wasting disease prevalence over time for the four alternatives in the Afton herd unit.

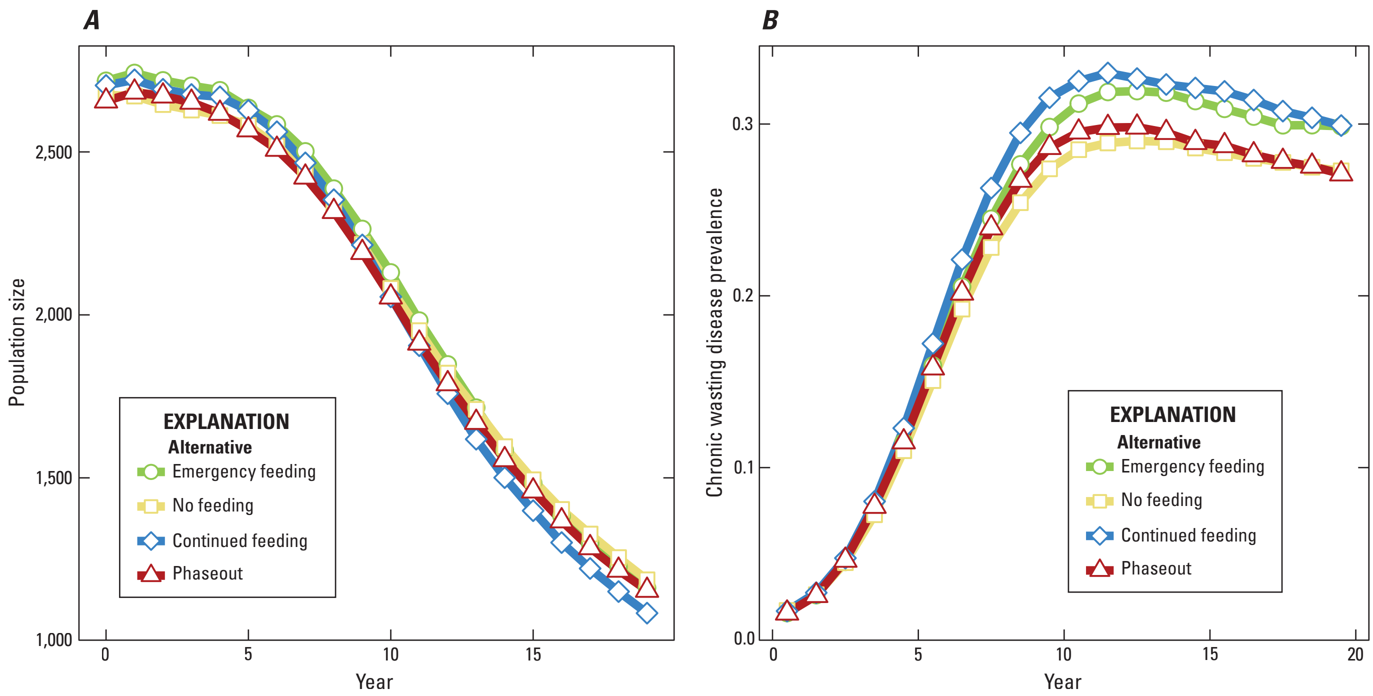

Figure 11. *A*, Average population size and *B*, chronic wasting disease prevalence over time for the four alternatives in the Upper Green River herd unit.

Table 6. Chronic wasting disease prevalence in year 20, cumulative chronic wasting disease mortalities, population size, and cumulative harvest of elk under the four alternatives and two herd units (Afton and Upper Green River).

[CWD, chronic wasting disease; SD, standard deviation]

Alternatives	Herd unit	CWD prevalence	SD	CWD mortalities	SD	Population size	SD	Harvest	SD
Continued feeding	Afton	0.20	0.07	2,598	702	3,091	659	14,959	1,826
Emergency feeding	Afton	0.20	0.06	2,490	607	3,221	568	14,938	1,637
Phaseout	Afton	0.19	0.08	2,251	820	3,251	749	14,923	1,824
No feeding	Afton	0.17	0.07	1,930	687	3,551	668	15,249	1,665
Continued feeding	Upper Green River	0.30	0.05	2,106	407	1,158	288	7,562	970
Emergency feeding	Upper Green River	0.30	0.05	2,100	336	1,241	289	7,765	845
Phaseout	Upper Green River	0.27	0.06	1,942	391	1,234	316	7,598	835
No feeding	Upper Green River	0.27	0.06	1,910	367	1,267	337	7,679	1,005

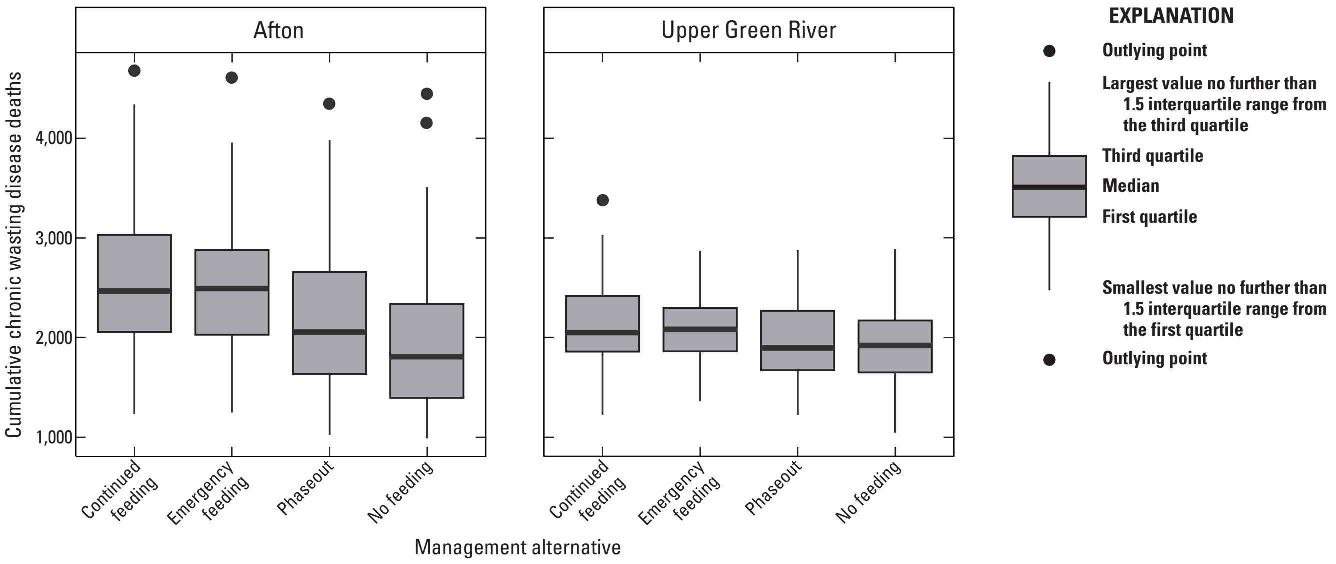

Figure 12. Boxplots of the cumulative number of chronic wasting disease mortalities for the four management alternatives in the Afton and Upper Green River herd units. Chronic wasting disease mortalities include only terminal cases and did not include other forms of mortality.

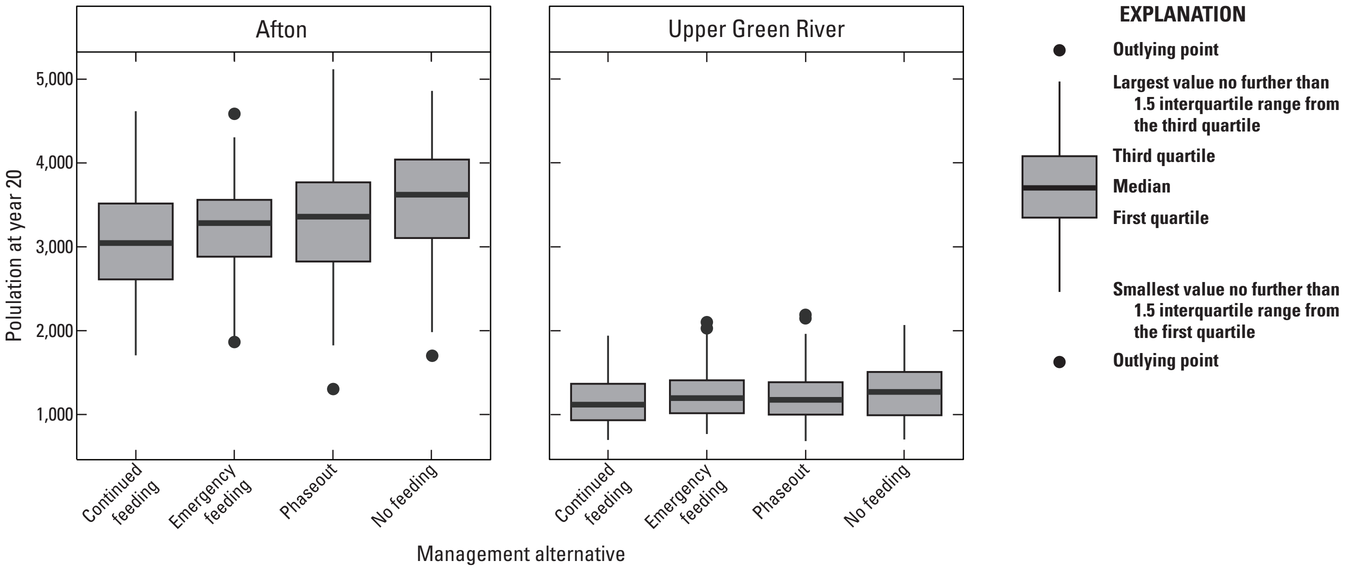

Figure 13. Boxplots of elk population size at year 20 for the four management alternatives in the Afton and Upper Green River herd units.

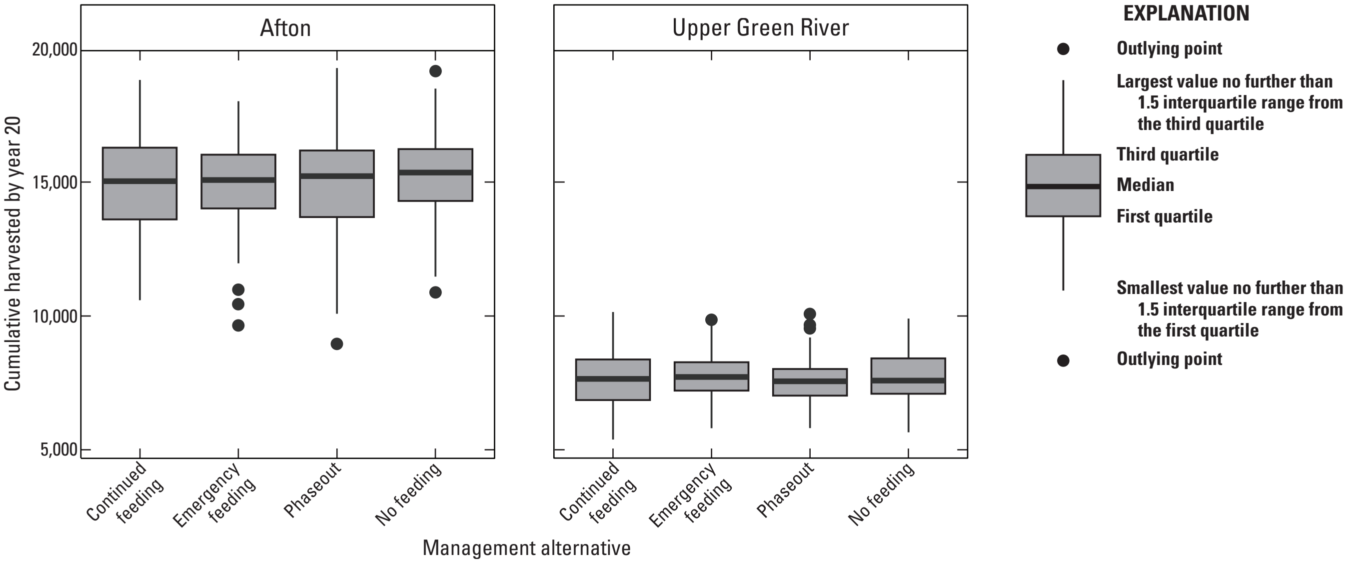

Figure 14. Boxplots of the cumulative number of harvested elk for the four different management alternatives in the Afton and Upper Green River herd units.

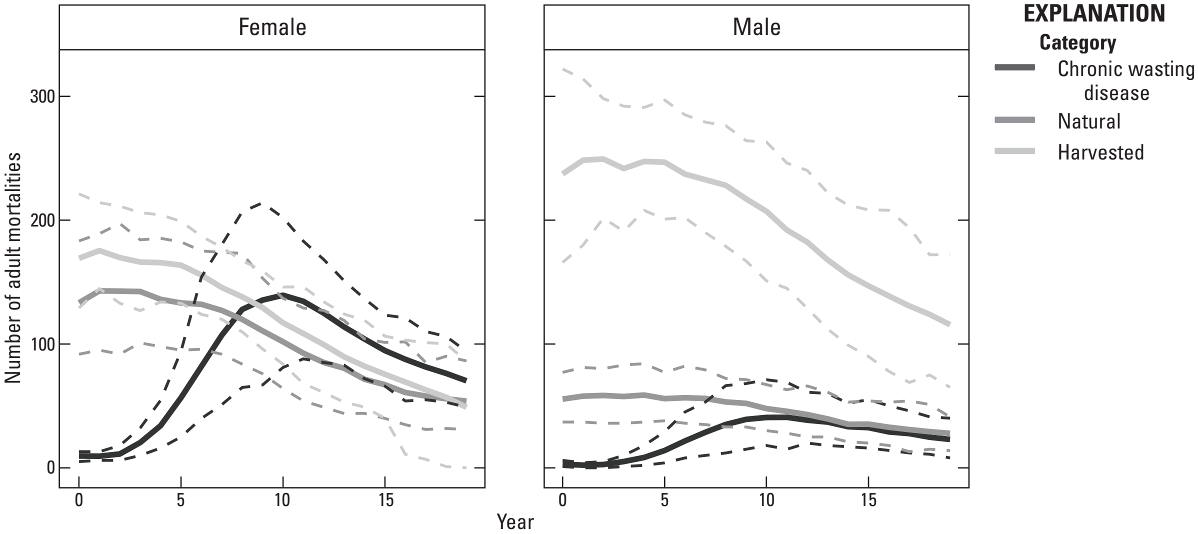

Figure 15. Predicted cause of mortalities for females and males over time in the Upper Green River herd unit for the feeding alternative. Dotted lines represent the 5th and 95th percentiles of 100 simulations.

the cumulative number harvested was similar across all alternatives relative to the variation in model projection (fig. 14). Simulation results suggested CWD will become the dominant cause of death for adult female elk around year 10 but remains low in adult male elk because the harvest rate of adult males is higher; therefore, a smaller fraction of males reach an age where they acquire and succumb to the disease (fig. 15). Although we assumed female elk harvest would be halted if the population reached half of the population objective, this was seldom triggered in our analyses (fig. 15).

4.3.2. Cumulative Effects

Many differences among the management alternatives became significant relative to our uncertainty when we evaluated all feedgrounds on FS property or within an HU. We did not include emergency feeding in our cumulative effects analysis because we lacked information on site-specific feeding triggers.

Elk populations are predicted to decline in all management alternatives (fig. 16). The Afton no feeding alternative on all feedgrounds had the smallest average decline of 33 percent, whereas the Upper Green River HU continued feeding alternative had the largest average decline of 66 percent by year 20 (fig. 16). The no feeding alternative resulted in early population declines, particularly if applied across all feedgrounds, but is predicted to have higher elk populations around year 10 onward (fig. 16). The phaseout alternative was intermediate on population declines compared to continued feeding or no feeding.

The projected CWD prevalence under continued feeding was lowest in the Afton HU (23 percent), which had the lowest proportion of elk that are fed compared to other HUs (figs. 17, 18). In Fall Creek, closure of FS feedgrounds are predicted to have limited impacts on CWD prevalence compared to continued feeding (28 and 31 percent, respectively) because of the low percentage of fed elk on FS feedgrounds in that HU; however, if all feedgrounds on Fall Creek were closed, the prevalence in year 20 was predicted to be much lower (14 percent). Phaseout of all feedgrounds after only 3 years results in a CWD prevalence of 16 to 20 percent, depending on the proportion of the HU that was fed (fig. 17). In the Upper Green River HU, 3 years of feeding resulted in a prevalence of 20 percent compared to 12 percent in year 20 without feeding.

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Generally, the no feeding alternatives tended to have higher numbers of elk harvested over the course of 20 years particularly if all feedgrounds are closed (fig. 19). In contrast, the continued feeding alternatives generally had the lowest number of harvested elk after 20 years because of high CWD prevalence in fed populations and associated reductions in population performance. The phaseout alternative tended to be intermediate in terms of harvest (fig. 19).

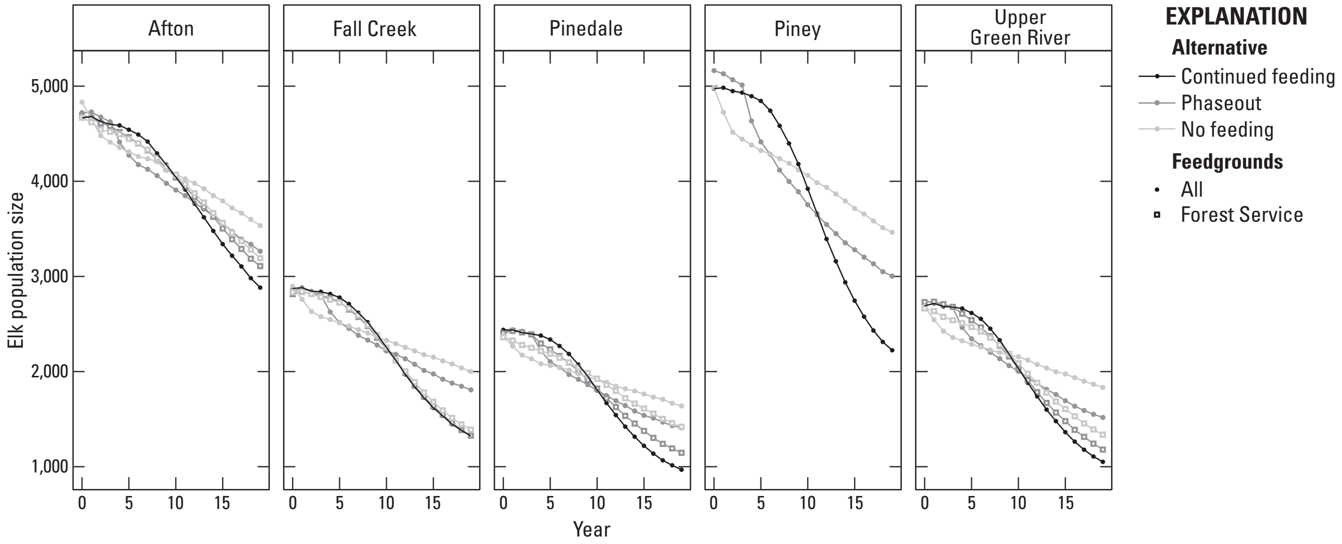

Figure 16. Predicted elk population sizes for different herd units for three management alternatives that are implemented on all feedgrounds or only on Bridger-Teton National Forest.

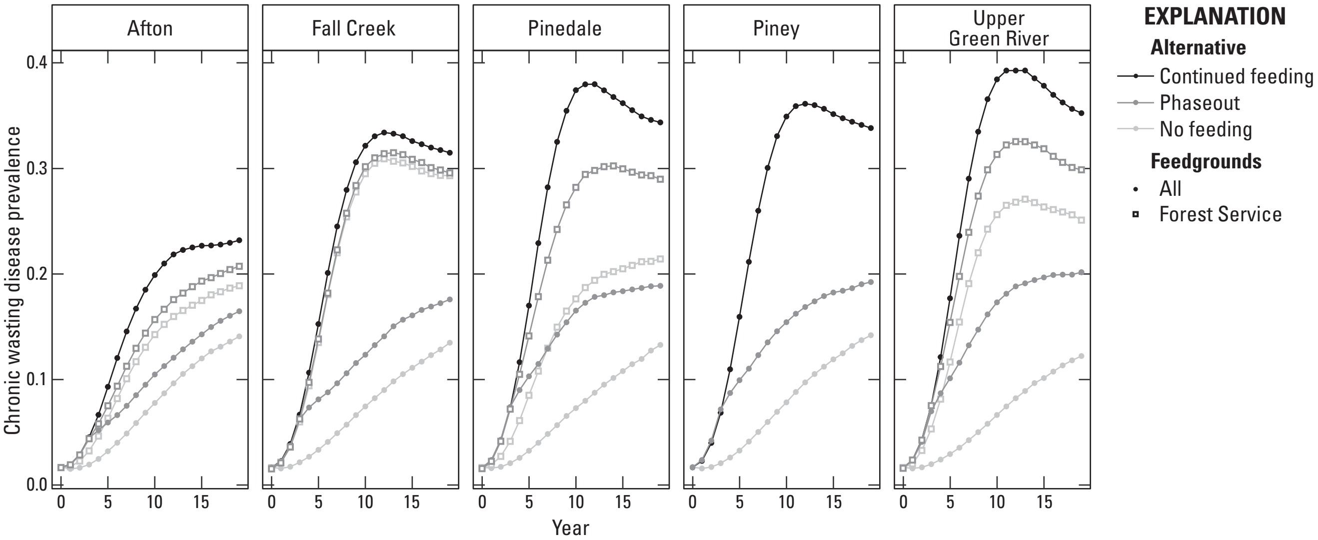

Figure 17. Chronic wasting disease prevalence for different herd units assuming all feedgrounds are fed, none of the feedgrounds are operational, or all feedgrounds are phased out. Circles represent all feedgrounds and squares indicate the management action occurs only on U.S. Department of Agriculture Forest Service feedgrounds.

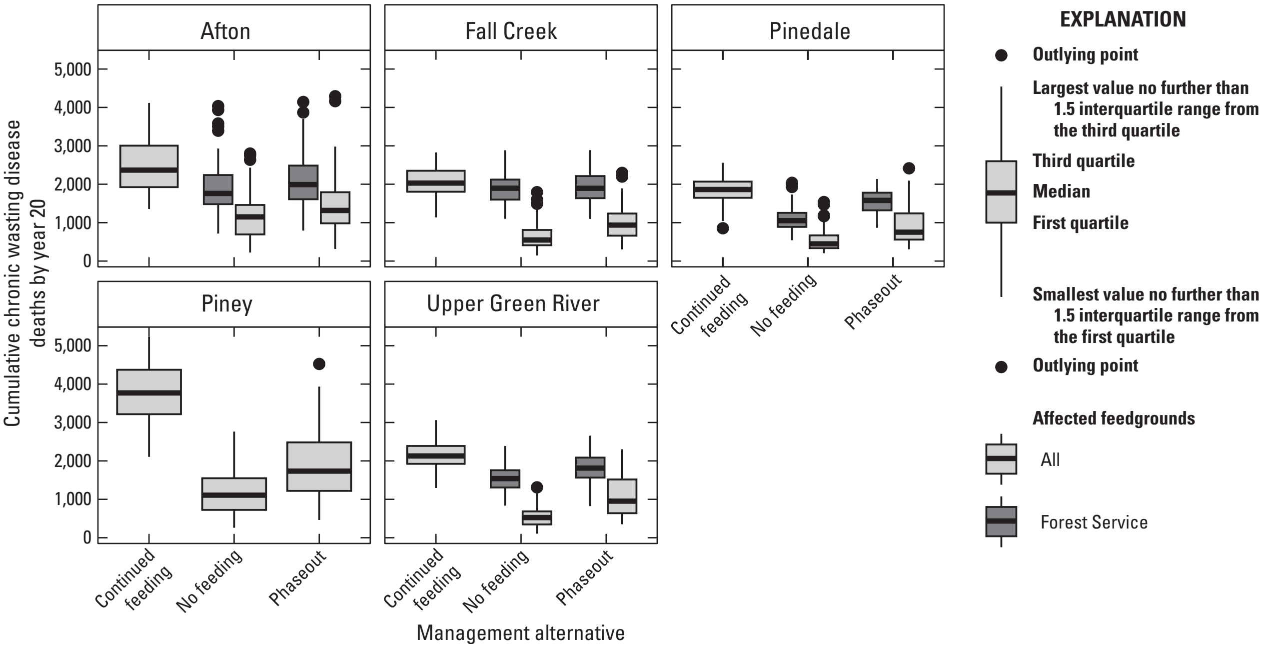

Figure 18. Boxplots of chronic wasting disease mortalities by year 20 for the no feeding, continued feeding, and phaseout alternative across five Wyoming herd units. For the no feeding or phaseout alternatives all feedgrounds in that herd unit or only those on U.S. Department of Agriculture Forest Service property. The Piney herd unit does not have any feedgrounds on U.S. Department of Agriculture Forest Service property.

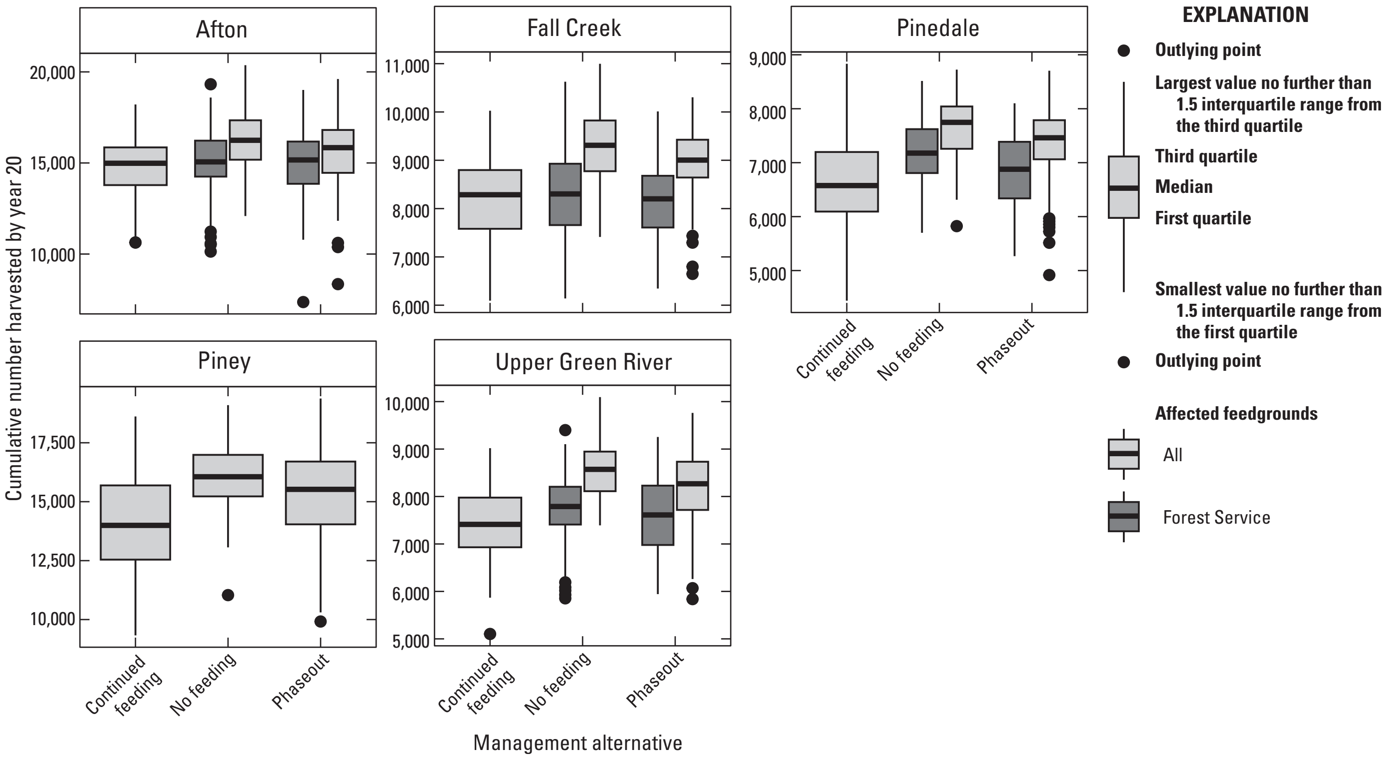

Figure 19. Boxplots of the simulated cumulative number of harvested elk by year 20 for the no feeding, continued feeding, and phaseout alternatives across five Wyoming herd units. For the no feeding or phaseout alternatives, all feedgrounds in that herd unit or only those on U.S. Department of Agriculture Forest Service property are closed. The Piney herd unit does not have any feedgrounds on U.S. Department of Agriculture Forest Service property.

5. Spatio-Temporal Analysis of Elk Distributions

5.1. Overview

Bridger-Teton National Forest managers identified two fundamental objectives related to the spatial distribution of elk. First, the Forest Plan requires Bridger-Teton National Forest to support other ungulate populations in addition to elk. Thus, it is important to understand how the selected alternatives affect competition between elk and other big game species, specifically mule deer (PM4a) and moose (PM4b), on winter ranges. In addition, managers want to minimize elk and private property overlap because of the potential for brucellosis transmission between elk and cattle (PM5b) and increased costs associated with elk depredation of haystacks and other agricultural resources (PM6a, described in Fundamental Objective 6 of Section 3). In this section, we estimated the consequences of the alternatives on these metrics (PM4a, PM4b, PM5b) by combining the temporal simulation results from Section 4 into a spatial analysis of elk distribution.

5.2. Methods

5.2.1. Habitat Selection and Use

There have been several analyses of elk selection and distribution on and around the supplemental feedgrounds of western Wyoming (Jones and others, 2014; Merkle and others, 2018; Maloney and others, 2020). We developed our analyses primarily based on Maloney and others (2020), from which we made several modifications. Maloney and others (2020) pooled data on 255 radio-collared elk that visited 20 of the WGFD-operated feedgrounds and 168 radio-collared elk from neighboring winter ranges (Banulis $n = 36$, Buffalo Valley $n = 15$, Hunt Area 99 $n = 22$, Riley Ridge $n = 77$, Spring Creek $n = 9$, Upper Green River $n = 9$). They then estimated resource selection function (RSF) coefficients, ϕ_{jk} for each month, j, in fed ($k = 1$) and native winter range elk ($k = 2$) populations on a third-order scale where availability was calculated from polygons representing each animal's area of use. We used the same coefficients and habitat covariates to capture seasonal changes in selection by elk as they moved up and downslope during spring and fall. We also accounted for the potential

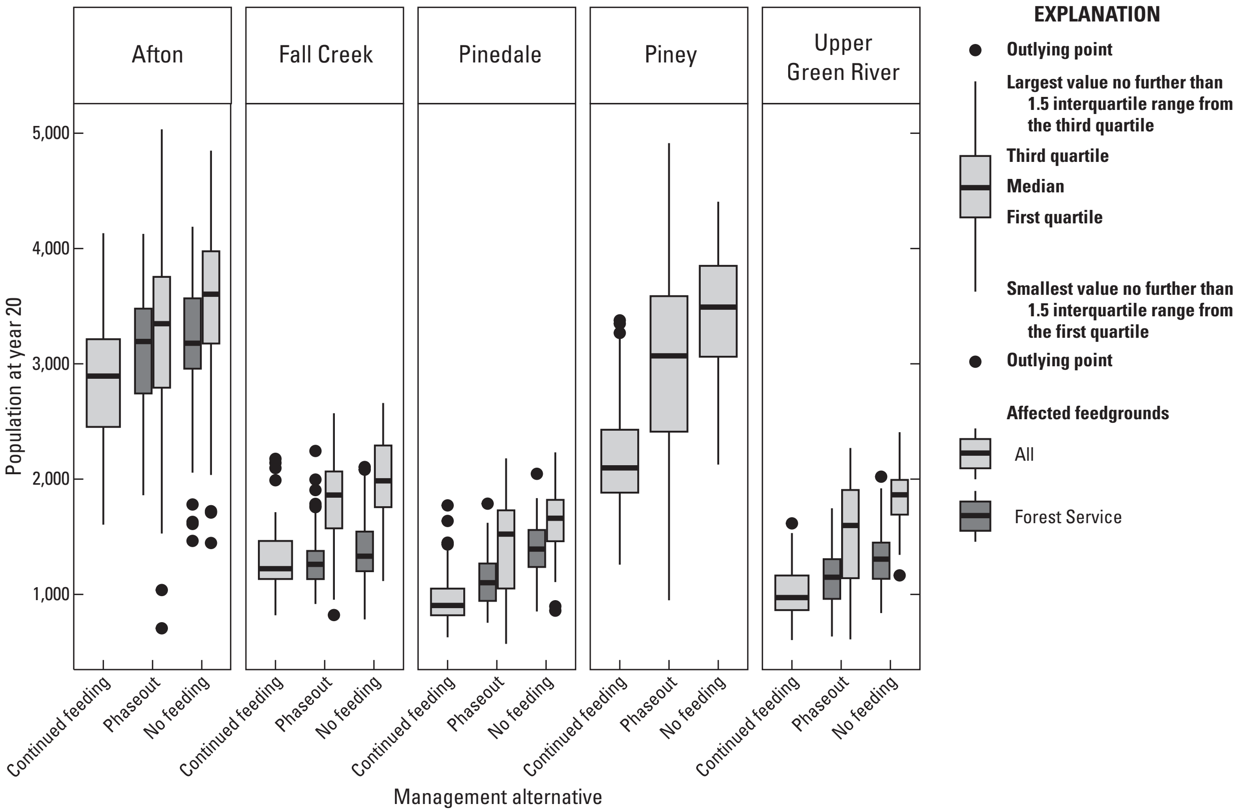

Figure 20. Boxplots of the simulated population size in year 20 for the no feeding, continued feeding, and phaseout alternatives across five Wyoming herd units. For the no feeding or phaseout alternatives, all feedgrounds in that herd unit or only those on U.S. Department of Agriculture Forest Service property are closed. The Piney herd unit does not have any feedgrounds on U.S. Department of Agriculture Forest Service property.

closure of feedgrounds by recalculating the distance to feedground covariate in the absence of those feedgrounds and applied that to the updated RSF.

We first calculated elk selection for a given 1-km^2 cell, s, as $w_{sjk} = \exp(\phi_{0jk} + x_{1sjk}\phi_{1sjk} + x_{2sjk}\phi_{2sjk} + \ldots + x_{7sjk}\phi_{7sjk})$, where $\boldsymbol{x}$ is a vector of mean values of each environmental variable within a 1-km^2 cell. The habitat covariates used were the annual integrated Normalized Difference Vegetation Index (250 m resolution); distance to feedground; elevation (30 m resolution); road density within 2.5 km; maximum snow water equivalent (1 km resolution); and percent forest and percent native herbaceous cover within 2.5 km (30 m resolution). To account for the availability of a resource (Boyce and McDonald, 1999), we converted the Maloney and others (2020) RSFs from a selection function to a probability of use function. We followed the approach of Schoenecker and others (2015) because we have continuous habitat covariates, binned our RSF values, w_{sjk} into 20 percentiles within each HU, l, and then used equation 5 to calculate the probability of use, $U(x_l)$ as:

$$U\left(x_{ljk}\right) = w\left(x_{ljk}\right)A\left(x_{ljk}\right) / \sum_{l} w\left(x_{ljk}\right)A\left(x_{ljk}\right), \qquad (5)$$

and estimated the number of elk in each bin is as:

$$n_{ljkt} = N_{jkt}\; U\left(x_{ljk}\right), \qquad (6)$$

where N_{jkt} is the predicted number of fed or unfed elk in month j and year t from the CWD simulation model. We did this for each HU to elucidate the differences of the alternatives on the metrics for each individual herd.

To relate elk spatial distribution to performance metrics, we derived the number of elk days per HU by multiplying the number of elk estimated in each cell by the number of days in each month of the year. We then summed the total number of elk days that occur on mule deer (PM4a) and moose winter ranges (PM4b), and the number of elk days on private lands. We initially calculated elk days on bighorn sheep winter ranges but removed this from the metrics as big horn sheep winter range only occurred minimally within our study area, and not at all in the Afton and Piney

HUs. We used these overlaps as indexes of forage competition with other big game species on winter ranges and as an index of elk damage to private property. The WGFD defined winter ranges using data from their winter observation survey data and Global Positioning System collar data (https://wgfd.wyo.gov/Wildlife-in-Wyoming/Geospatial-Data/Big-Game-GIS-Data) and derived private property from tax records from Wyoming GIS Parcel Data up to January 1, 2022 (Wyoming Statewide Parcel Viewer, 2022).

For brucellosis risk to cattle, we calculated the predicted number of elk abortions that occur on private property. Cross and others (2015) estimated the probability that an adult, seropositive female elk would have an abortion, ρ, per day, which we summed to a monthly basis. We assumed no abortions occurred from August to the end of January. The CWD model in Section 4 provided the number of fed or unfed female elk over age 2, F_{jkt}, monthly for 20 years. For each HU, we calculated the average brucellosis seroprevalence in adult females from 2010 to 2020 using data provided by WGFD. The total predicted number of fed or unfed elk abortions in a HU is then given as

$$a_{jkt} = F_{jkt}\rho_j\eta, \tag{7}$$

where

F_{jkt} is the number of adult females in an HU;
η is the average brucellosis seroprevalence for the HU;
j is an indicator variable for month;
k indicator for fed or unfed elk; and
t is an indicator variable for year.

We then allocated the abortions predicted from equation 7 in space similar to equation 6. We assumed all private properties are areas of potential cattle exposure over the next 20 years. Ideally, we would use the actual cattle distribution rather than all private properties; however, cattle distribution is private information. In addition, cattle distribution changes during the year and is expected to change over the next 20 years.

5.2.2. Implementation of Management Alternatives

We adapted this spatial model to evaluate and predict effects of the four alternatives on performance metrics 4a, 4b, and 5. For the CF alternative, no changes were required to the methods described in Section 5.2.1 other than to extract the number of elk days on different winter ranges or abortions on private land and sum over the 20-year timeframe. For the NF alternative on Dell Creek or Forest Park, we took the average population size on Dell Creek and Forest Park feedgrounds from 2016 to 2020 and assumed they are distributed to the native winter range as part of the unfed population of their respective HUs. We assumed when a feedground is closed there is no lag time in fed elk being distributed to native winter range within the same HU. In discussion with WGFD experts, there was uncertainty about whether feedground elk may move to another feedground rather than native winter range after a feedground closure. The existing GPS data indicate limited movement between Dell Creek, Forest Park, and other neighboring feedgrounds, while they are continuing to be fed. It is unclear whether that would be the case given a feedground closure. For the NF alternative, we recalculated the distance to feedground covariate assuming the feedground (Dell Creek or Forest Park) is closed and previously fed elk are no longer attracted to that area. For the PO alternative, we assumed elk on the target feedground selected the same landscapes as fed elk for the first 3 years and selected the same landscapes as native winter range elk for the next 17 years.

For the EF alternative, we assumed emergency feeding is triggered every year on the Dell Creek feedground and in 70 percent of years at Forest Park (based on Singer and others, 1997). The distribution of elk during intermittent closures is uncertain; however, *Cervus elaphus* (red deer) continued to revisit feeding locations even after feeding activities stopped (Putman and Staines, 2004). We assumed Forest Park and Dell Creek elk continued to select habitats as fed elk and are attracted to feedgrounds every year even though feeding is intermittent or slightly delayed.

5.2.3. Cumulative Effects

For the cumulative effects analyses, we only modeled the CF, PO, and NF alternatives because emergency feeding may be implemented differently at feedgrounds depending on whether the trigger is related to livestock disease risk or elk calf survival. We modeled scenarios where all feedgrounds were managed the same way—either open, closed, or phased out at the same time. We also modeled scenarios where management actions were implemented only on feedgrounds located on FS property, whereas other feedgrounds remained operational.

5.3. Results

5.3.1. Dell Creek and Forest Park

Supplemental feedgrounds concentrate elk during winter at a small number of locations compared to more widely distributed native winter ranges that tend to be at lower elevations (figs. 21, 22). In figure 23, we showed the predicted, unfed elk use relative to the WGFD winter observation data of elk off feedgrounds. The agreement between predictions and observed data appeared to be better for the Jackson, Fall Creek, and Afton HUs. The Piney HU had more winter elk observations across a broader landscape, which is reflected in the predictions. The Upper Green River and Pinedale HUs showed some discrepancies between predicted areas of winter use and observations (fig. 23). The Upper Green River HU had a strong elevational gradient and limited area of low elevation because we assumed elk are contained within HU for this modeling analysis. In contrast, the Pinedale HU had a broad area of lower elevation over which the model predicts unfed elk are likely to spend the winter. In these two HUs, existing private lands may limit the migratory movements of elk from going farther downslope in the fall migration. In addition, winter observations of elk off feedgrounds may still be affected by the existence of feedgrounds. For this reason, we did not do a formal comparison of winter unfed elk observations and predicted use.

Whether fed or native winter range elk are predicted to spend more or less time on private property depends on the extent and location of private property relative to feedground locations (figs. 22, 24). In figure 24, we summed the predicted monthly use, *U*, on different land types and divided by 12 to estimate the proportion of time a fed or unfed elk would likely spend on those land types over a year. Approximately 19 percent of the Afton and Upper Green River HUs are private property. In the Afton HU and considering the CF, fed elk are predicted to spend a little over 20 percent of their time on private property, whereas unfed elk are predicted to spend over 35 percent of their time on private property (fig. 24). We predicted native winter range elk have more overlap with private property across all alternatives in the Afton HU (fig. 24). In the Upper Green River HU, however, if Dell Creek is not feeding, then fed elk are predicted to spend slightly more time on private property than unfed elk (fig. 24). Model results indicated fed elk have more overlap with moose critical winter ranges than unfed elk in both the Afton and Upper Green River HUs.

We estimated the predicted number of elk abortions on private land was lower for the continued feeding and emergency feeding alternatives in the Afton and Upper Green River HUs compared to the phaseout or no feeding alternatives (fig. 25). This is likely because of the increased spatial overlap between unfed elk and private property during March–May (fig. 26) as well as the higher elk population sizes associated with the no feeding alternative (fig. 13). The spatial overlap between elk and private property and moose or mule deer critical winter ranges differed among alternatives in the Afton HU compared to the Upper Green River HU (fig. 27).

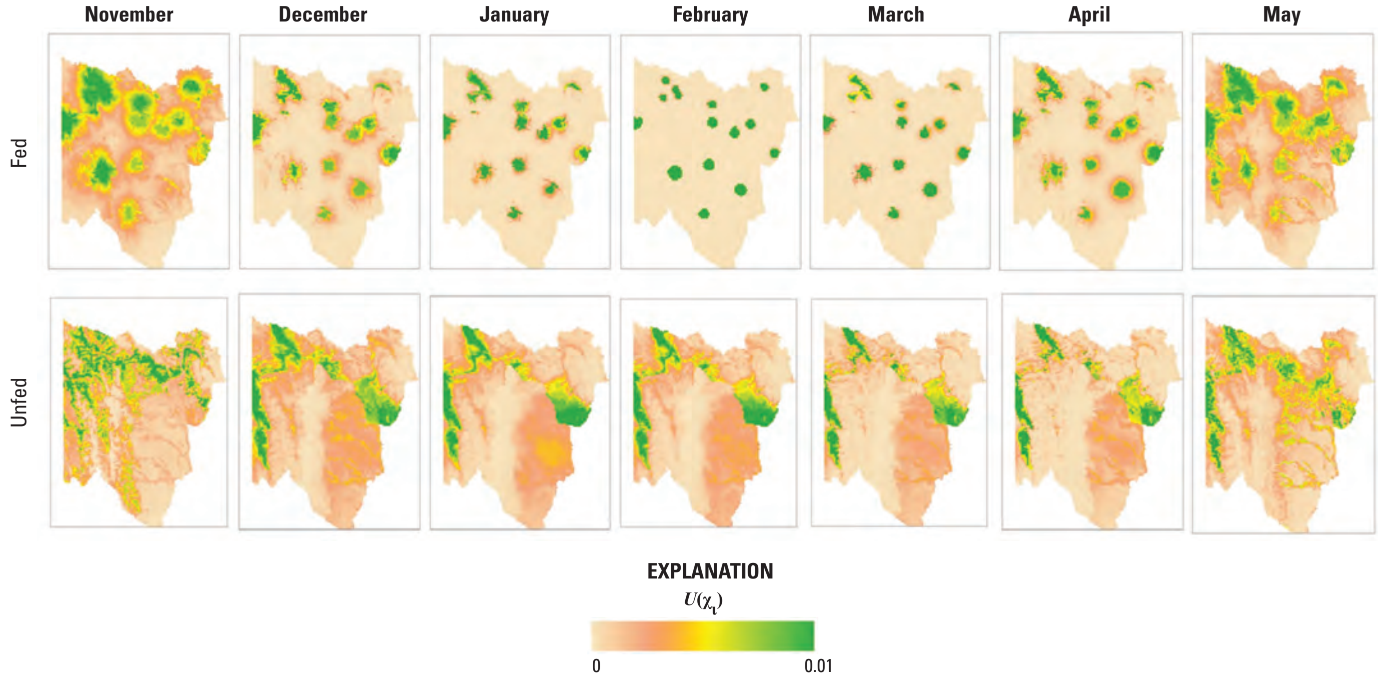

Figure 21. Predicted monthly per capita elk use U(x_{ljk}) for elk that use native winter ranges (unfed elk) and elk that use feedgrounds (feedground elk) for the Afton, Upper Green River, Fall Creek, and Piney herd units in western Wyoming. Maps are based on the parameters estimated by Maloney and others (2020).

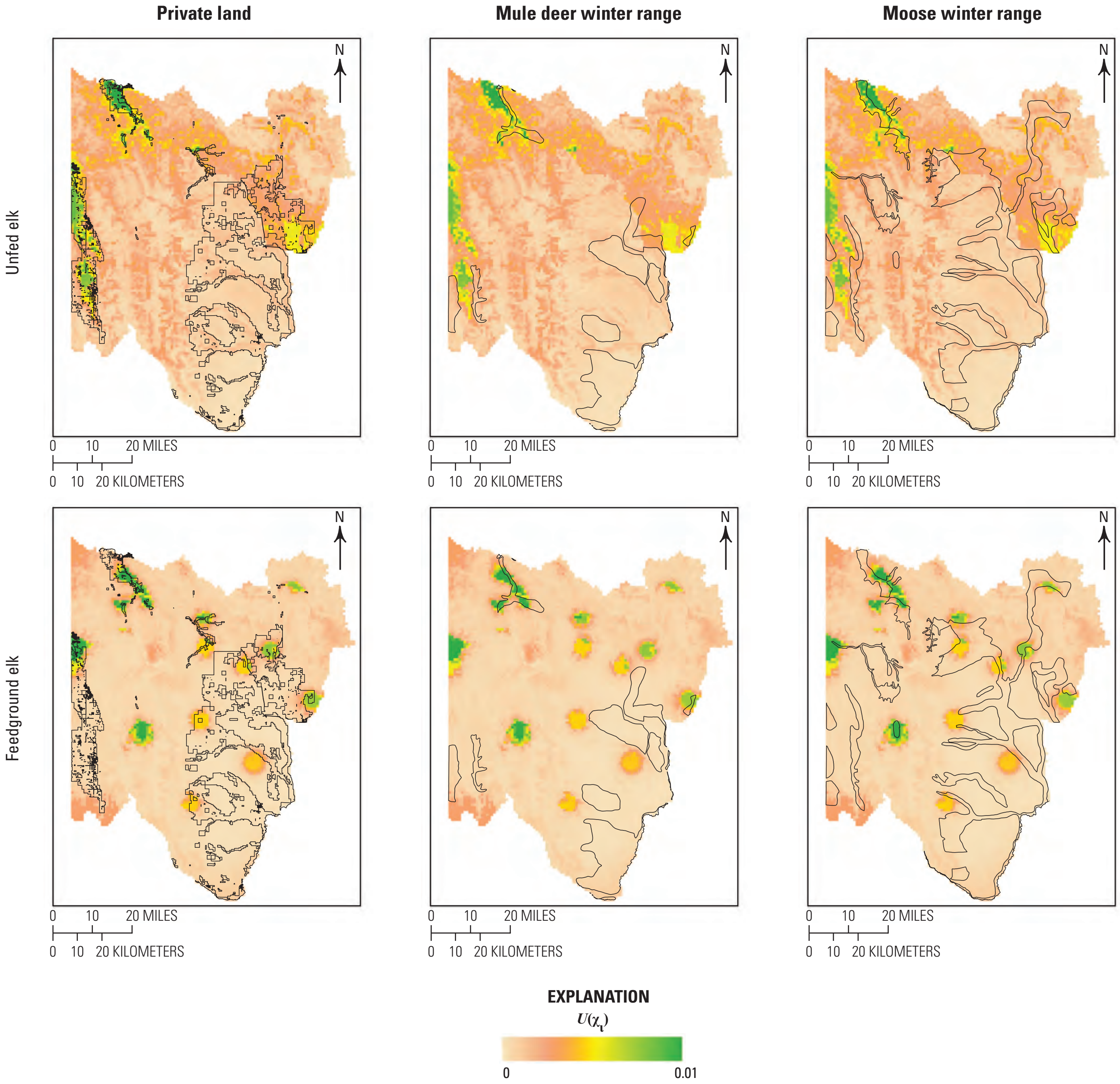

Figure 22. Land ownership, mule deer critical winter ranges, and moose critical winter ranges overlayed with average per capita elk use $\Sigma_j U(x_{ljk}) \div 12$ for elk that use native winter ranges (unfed elk) and elk that use feedgrounds (feedground elk) in the Afton, Upper Green River, Fall Creek, and Piney herd units in western Wyoming. Map is based on the parameters estimated by Maloney and others (2020).

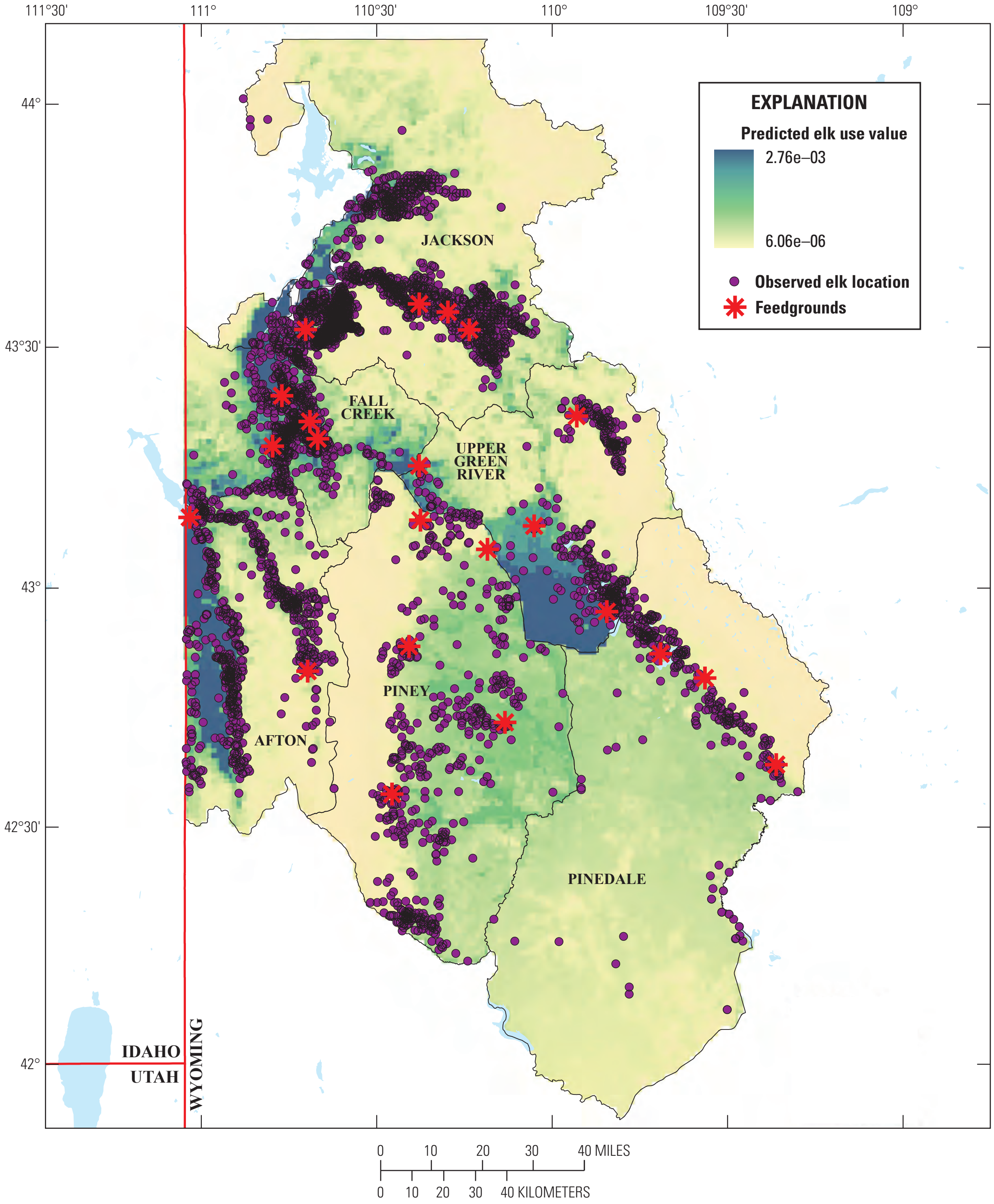

Figure 23. Winter elk locations from Wyoming Game and Fish Department surveys (1980–2021; Wyoming Game and Fish Department, 2020a, and references therein) with the predicted per capita elk use $U(x_{ljk})$ raster for unfed elk during the month of February. Darker blue represents higher probability of use and light yellow a lower probability of use. Probability of use was calculated independently for each herd unit.

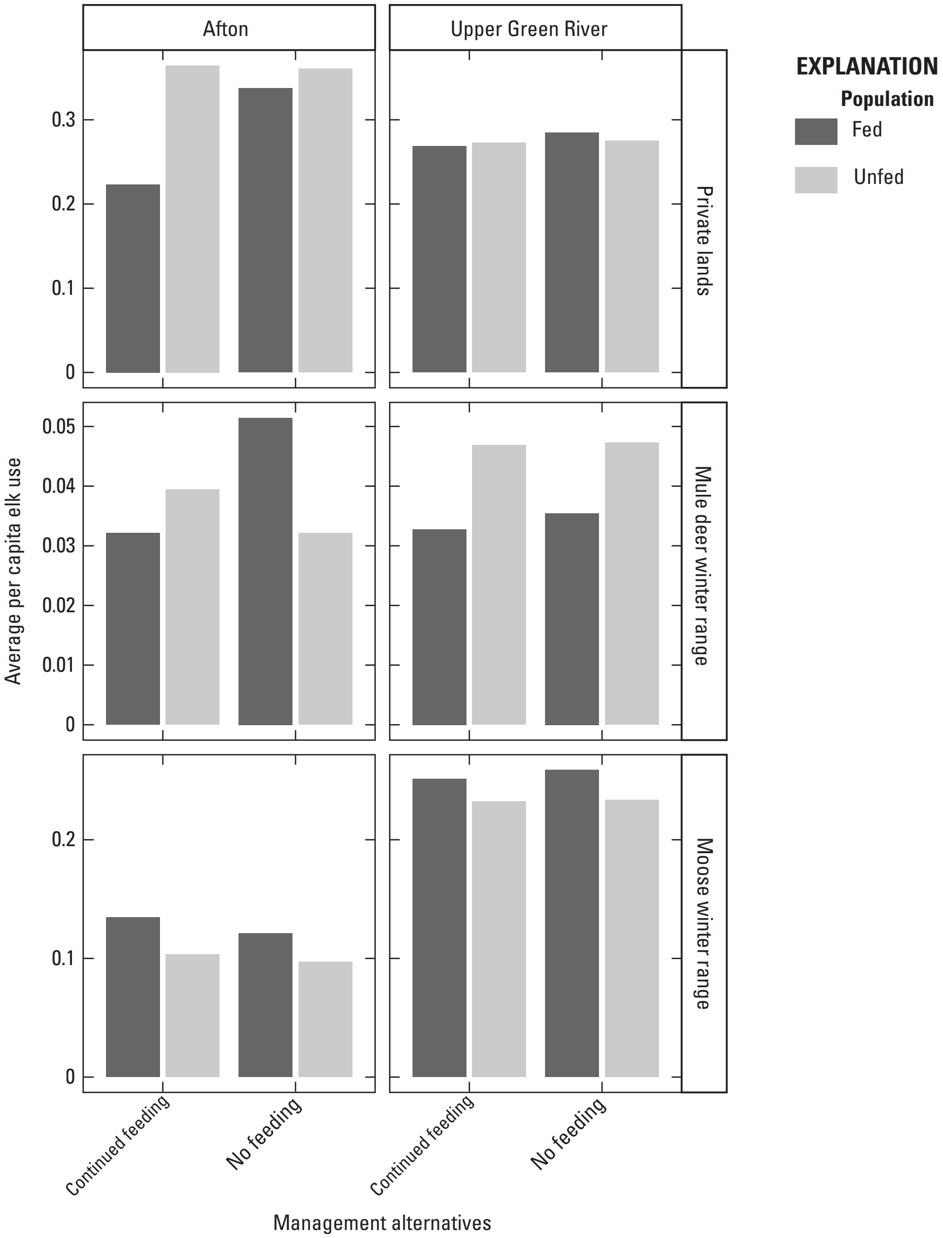

Figure 24. Average per capita elk use, $\Sigma_j U(x_{ljk}) \div 12$, on different land types (private property, mule deer critical range, and moose critical range) for the continued feeding and no feeding alternatives applied to Dell Creek (Afton herd unit) and Forest Park (Upper Green River herd unit).

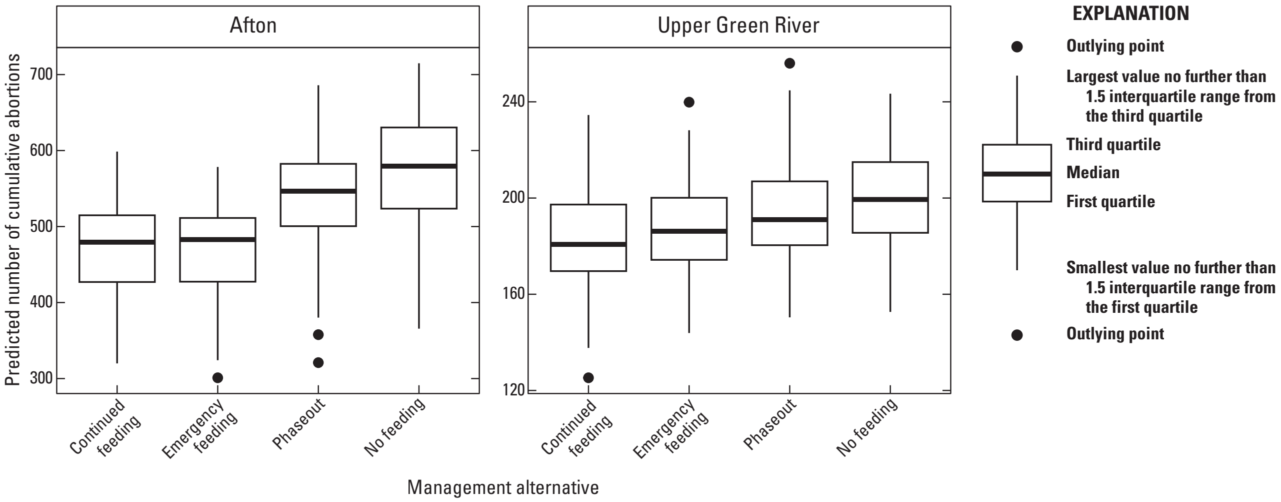

Figure 25. The predicted number of cumulative elk abortions on private property over 20 years for the Afton and Upper Green River herd units.

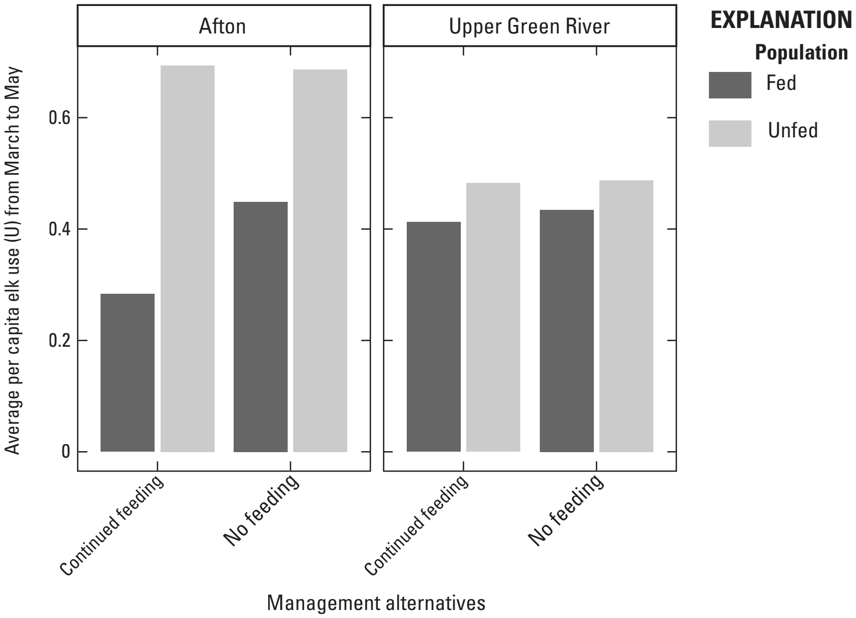

Figure 26. The average per capita elk use, (*U*) from March to May on private property for the continued feeding and no feeding alternatives applied to Dell Creek or Forest Park feedgrounds. March–May is the riskiest time of year for brucellosis transmission from elk to cattle.

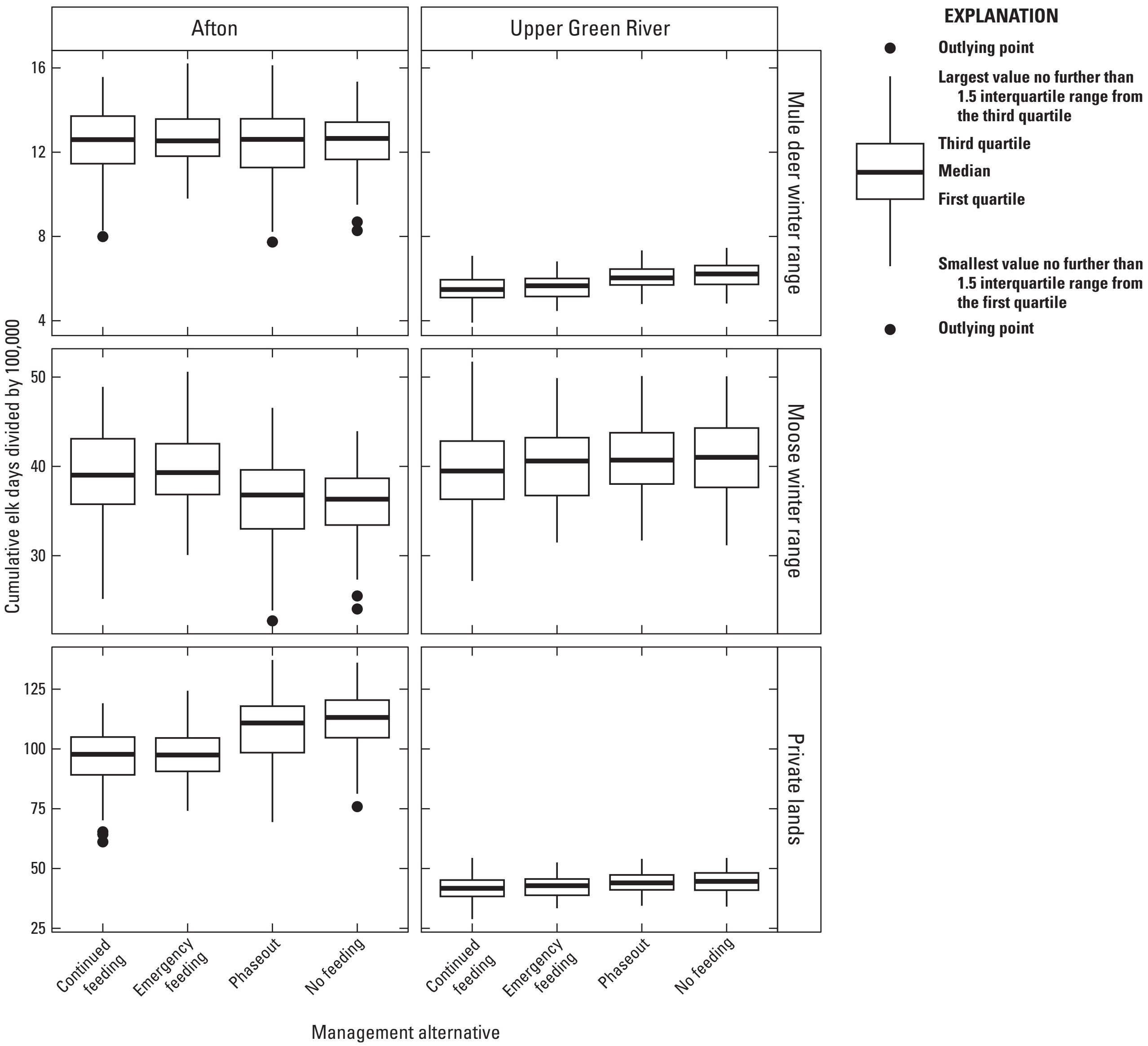

Figure 27. The cumulative number of elk days divided by 100,000 on different land use types (private property, moose critical winter range, and mule deer critical winter ranges) in the Afton and Upper Green River herd units for the four alternatives.

5.3.2. Cumulative Effects

Similar to the Dell Creek and Forest Park analyses, we found that whether fed or native winter range elk had more spatial overlap with private property or moose and mule deer winter ranges varied by HU (fig. 28). For example, per capita, fed elk in the Fall Creek HU are predicted to spend more time on mule deer winter ranges than unfed elk, but the reverse occurs in the Piney HU (fig. 28). The potential closure of feedgrounds on FS property did not change whether fed or unfed elk had more spatial overlap with private property and moose and mule deer critical winter ranges except for private property in the Upper Green River HU (fig. 28).

We predicted the no feeding and phaseout alternatives would result in more elk on private land during periods of brucellosis transmission risk, with the exception of the Pinedale HU (fig. 29). We predicted the no feeding and phaseout alternatives would result in more elk on private land during periods of brucellosis transmission risk, with the exception of the Pinedale HU (fig. 29). In year 1, we predicted the no feeding alternative would result in about 102 (SD = 9) abortions on private land across all five HUs relative to 88 (SD = 7) for continued feeding. By year 20, the no feeding alternative is predicted to have 69 (SD = 7) elk abortions on private land compared to 40 (SD = 5) for the continued feeding alternative. These standard deviations only included variation in female elk population size; thus, are underestimates of the total uncertainty.

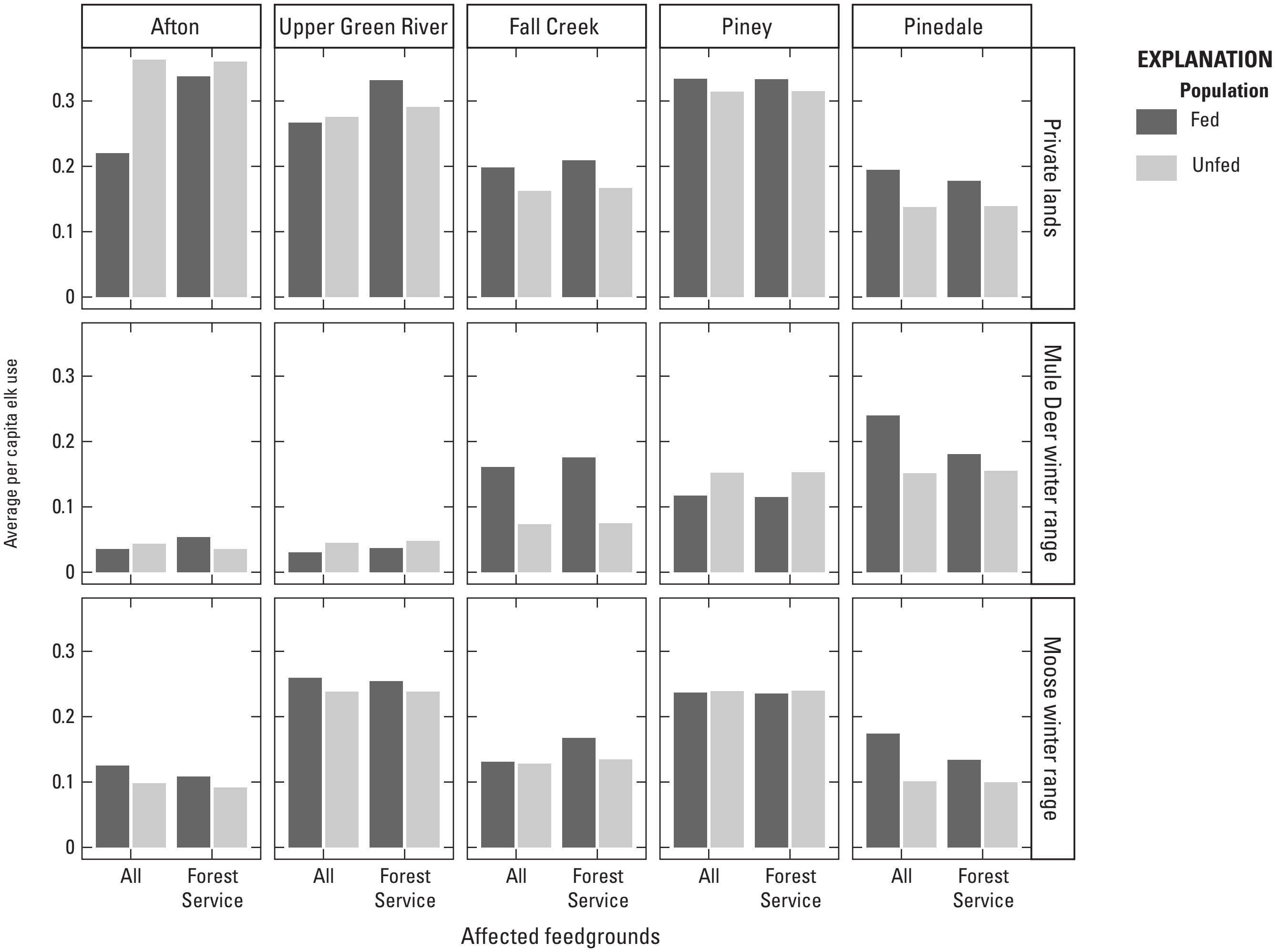

Figure 28. Graphs showing the average per capita elk use on different land types assuming all feedgrounds are operational compared to feedgrounds on U.S. Department of Agriculture Forest Service properties are closed.

Predicted per capita elk use of private lands varied by herd unit and depended on which feedgrounds were operational (fig. 28). Incorporating the temporal changes in elk population size, no feeding was associated with an increase in the use of private property over 20 year in Afton and Upper Green River HUs relative to continued feeding. However, the Pinedale HU was predicted to have less use of private land in the no feeding alternative (fig. 30). Summing across all HUs, we predicted that the cumulative number of elk days on private property will be higher, on average, for the no feeding (31.5 million elk days, SD = 1.8 million) compared to continued feeding alternatives (29.6 million elk days, SD = 1.9 million). If the management alternatives are only applied to feedgrounds on FS property, then the results depended on the fraction of elk on those FS feedgrounds and where those feedgrounds are located. For example, in the Fall Creek unit only the Dog Creek feedground is on FS property and it is smaller than the other feedground in that unit. The closure of Dog Creek feedground is predicted to have little effect on elk overlap with mule deer critical winter range and private property, in contrast to the closure of all feedgrounds in the Fall Creek HU (figs. 30, 31). The no feeding alternative is also generally associated with a reduction in use of moose critical winter ranges in the Pinedale HU but increasing use of moose winter range in the Fall Creek HU (fig. 32). Summing across all HUs, we predicted that the cumulative number of elk days on moose winter range would be similar between the no feeding (19.8 million elk days, SD = 1.0 million) and continued feeding alternatives (19.7 million elk days, SD = 1.3 million).

5.4. Discussion

One objective of supplemental feeding in Wyoming is to minimize elk and cattle contact during spring to reduce the potential for brucellosis transmission (McWhirter and others, 2021). With the exception of the Pinedale HU, our spatial analyses supported the assertion unfed elk would have more

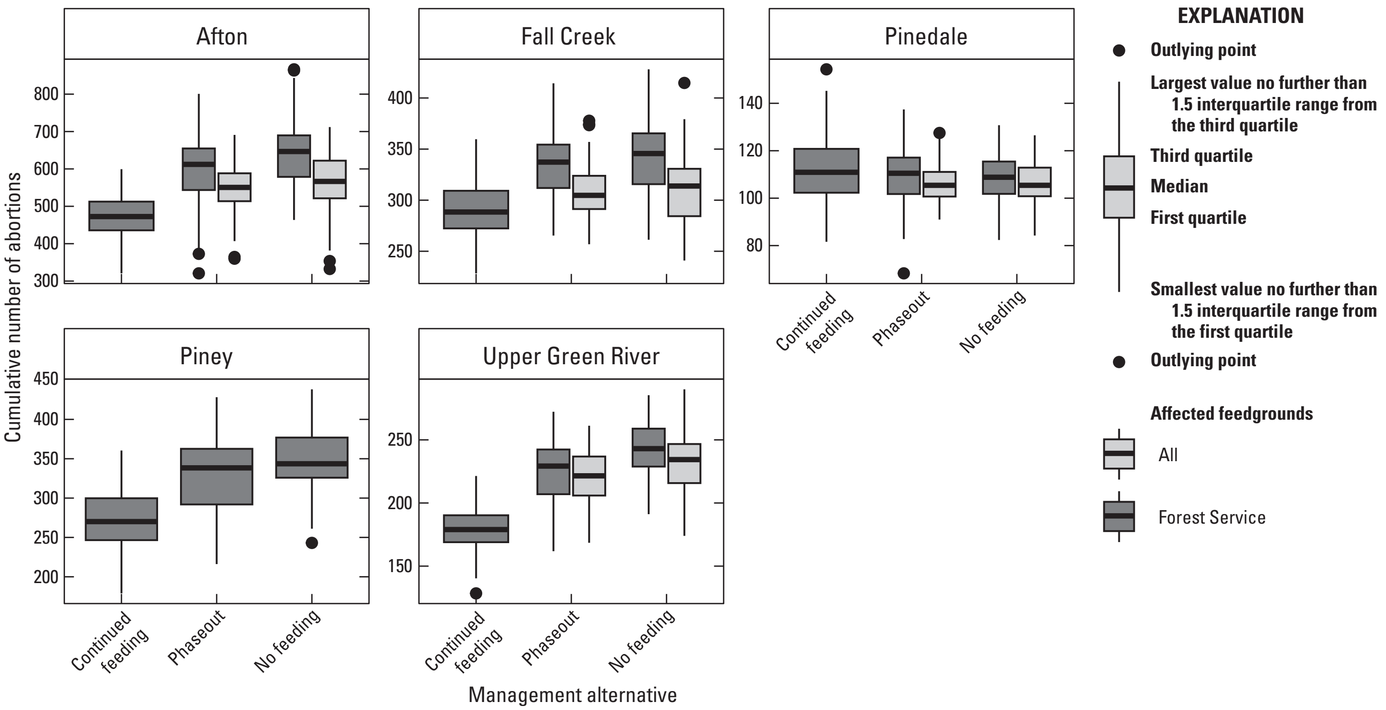

Figure 29. Boxplots of the cumulative number of elk abortions on private property over 20 years as an index of brucellosis risk to cattle. The three management alternatives were continued feeding, phaseout, and no feeding. Dark boxes assume that management alternatives are implemented on all feedgrounds as opposed to just feedgrounds on U.S. Department of Agriculture Forest Service property.

overlap with private properties during the time of potential brucellosis transmission (figs. 25, 26, 29). We predicted the closure of the Forest Park feedground would result in 23 percent (SD = 20 percent) more elk abortions on private property in the Afton HU, whereas the closure of Dell Creek feedground would result in 10 percent (SD = 15 percent) more abortions on private property. This difference would increase to 34 percent (SD = 25 percent) in the Afton HU if all feedgrounds were closed. The locations of feedgrounds relative to private properties, moose and mule deer winter ranges created the possibility where the best management alternatives may differ among HUs. For example, the habitat model predicts that feedground closures could result in similar brucellosis risk on private property in the Pinedale HU across all alternatives compared to all other HUs where the no feeding alternative increases brucellosis risk (fig. 29). We developed consequences further in Section 6.

Our results are based on a few key assumptions related to elk behavior. First, we assumed elk remained within their existing HU regardless of the management alternative. We also assumed all fed elk relocated to native winter ranges in the same HU when feeding stops or starts without a time lag and select habitats similar to unfed elk. These assumptions could be modified but would require expert judgment or additional experiments in monitoring fed elk responses when feedgrounds are closed. Further, we assumed elk redistributed equally to preferred native winter ranges when feedgrounds are closed or opened despite their proximity to feedgrounds (for example, Star Valley in the Afton HU, fig. 22). This is unlikely, at least initially, because of the learned behavior of elk, which leads them to return to specific feedgrounds or find new ones during winter. From a modeling perspective, incorporating alternative behaviors (for example, memory) into the analyses would require complicated and computationally demanding techniques (Merkle and others, 2018). More complex modeling might be appropriate for the first few years of projections but would lose value (in other words, be less reliable) over longer time horizons because of uncertain changes to future conditions. An additional assumption that may have affected the results was elk were unaffected by localized barriers, such as elk-proof fencing. The RSF assumed all pixels are equally accessible to elk because we lacked data to inform the presence of barriers to elk movement. Future work could exclude some regions from the analyses based on expert opinion and fencing data.

Our assessment of brucellosis risk assumed all private properties have cattle and brucellosis seroprevalence in elk will be unaffected by feedground closures. In addition, we did not include livestock grazing allotments as likely locations of risk. Although many elk abortions do occur on FS properties (Merkle and others, 2018), most of the grazing allotments only allow livestock later in the season after most brucellosis risk as passed (Cross and others, 2019). Previous work found the end date of the elk feeding season correlated with winter snowpack and feeding season length correlated with elk brucellosis

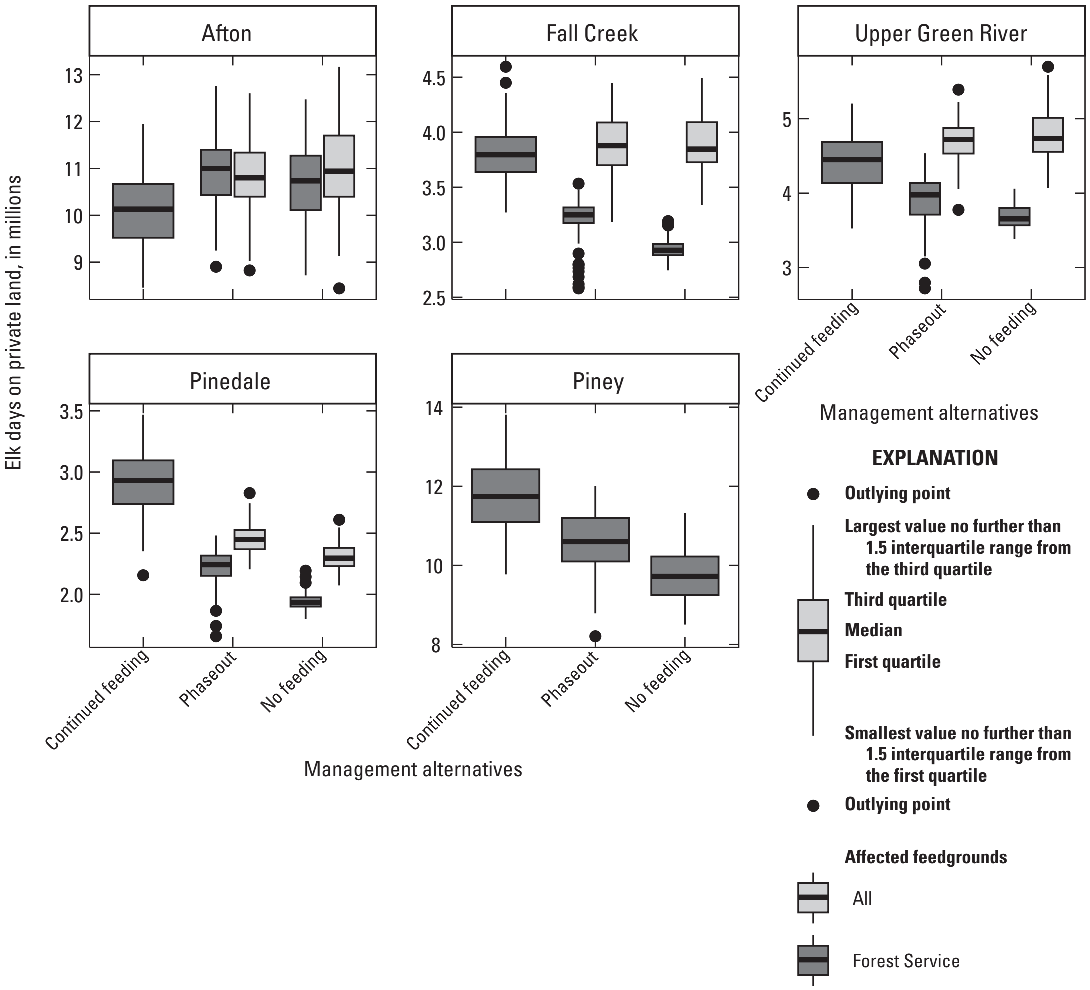

Figure 30. Boxplots of the cumulative elk days on private property over 20 years. The three management alternatives were continued feeding, phaseout, and no feeding. Dark boxes assume that management alternatives are implemented on all feedgrounds as opposed to just feedgrounds on U.S. Department of Agriculture Forest Service property.

seroprevalence (Cross and others, 2007). However, subsequent increases in brucellosis among unfed elk populations creates some uncertainty about the relative contributions of snowpack and feeding to brucellosis seroprevalence (Cross, Cole, and others, 2010; Cross, Heisey, and others, 2010; Proffitt and others, 2015; Brennan and others, 2017; Cotterill and others, 2020).

These analyses likely underrepresent uncertainty because we did not incorporate variation in RSF coefficient estimates. We did, however, include the variation in population counts estimated in Section 4. We conclude the variation in population projections represents the largest source of uncertainty in our spatial predictions. Future work could draw the ϕ_{jk} coefficients from multivariate normal distributions and then recalculate the predicted w and U values for each timestep of the simulations.

6. Consequences

6.1. Overview

This report developed a set of linked analyses in support of a FS decision on whether to permit elk feeding on Dell Creek and Forest Park sites for the next 20 years. The analyses were designed through a series of meetings with the FS and cooperating agencies and built on a long history of empirical study, model development, and scientific inference on elk and other big game species in and around Greater Yellowstone Ecosystem. We also drew on the expertise of a scientific panel composed of WGFD, Federal agency, and academic researchers to estimate important, but unknown, CWD transmission parameters in fed and unfed elk population segments. The results (in other words, consequences) of the four alternatives are presented as 11 performance metrics that

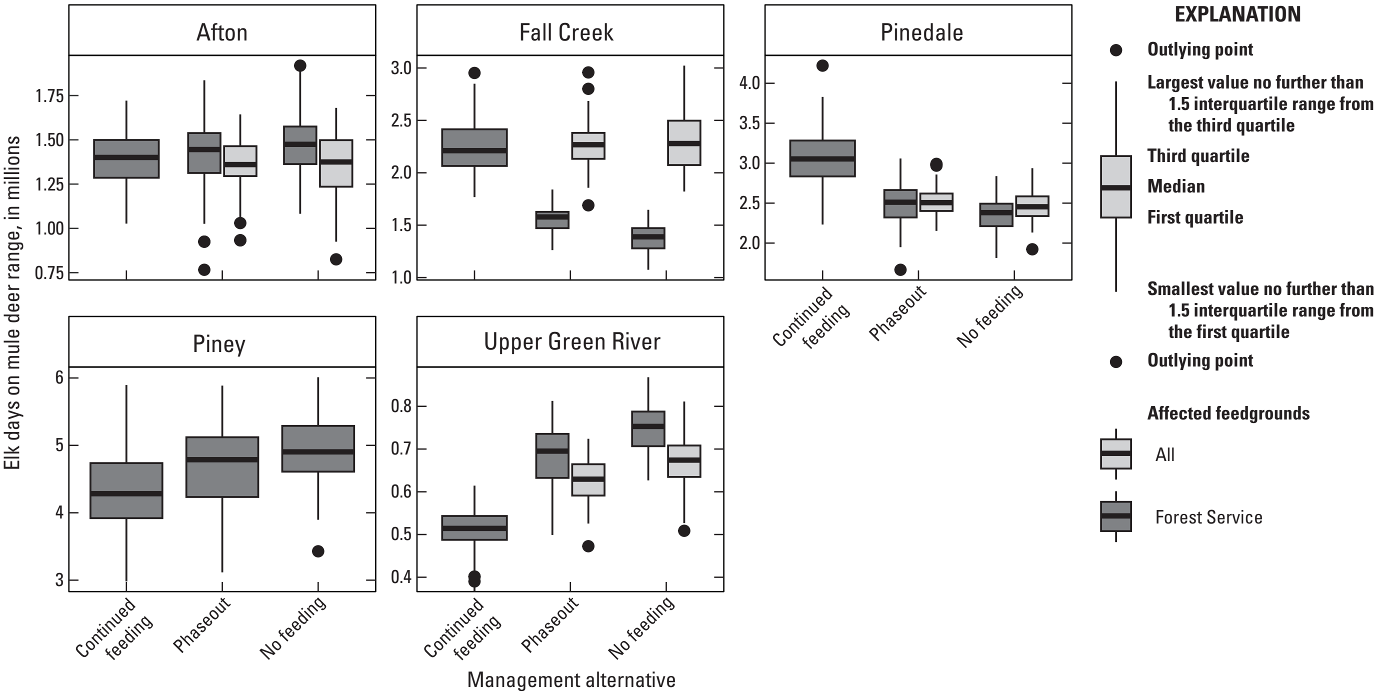

Figure 31. Boxplots of the cumulative number of elk days on mule deer critical winter range over 20 years for three management alternatives: continued feeding, phaseout, and no feeding. Dark boxes assume that management alternatives are implemented on all feedgrounds as opposed to just feedgrounds on U.S. Department of Agriculture Forest Service property.

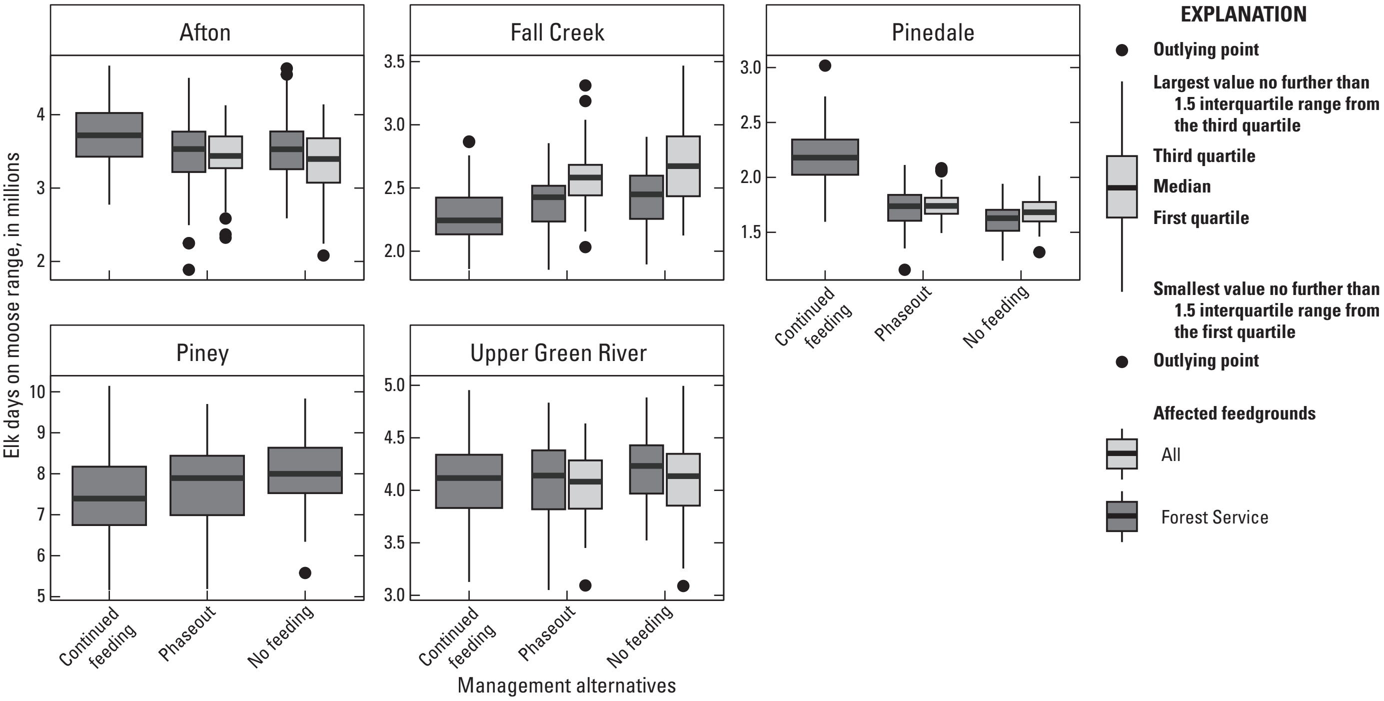

Figure 32. Boxplots of the elk days on moose critical winter range over 20 years as an index of competition between elk and moose. Three management alternatives were continued feeding, phaseout, and no feeding. Dark boxes assume that management alternatives are implemented on all feedgrounds as opposed to just feedgrounds on U.S. Department of Agriculture Forest Service property.

measure the fundamental objectives of the FS as they consider whether to continue to permit supplemental feeding of elk on Forest Park and Dell Creek sites.

Sections 4 and 5 developed the methods and presented the results of performance metrics designed to measure the consequences of decision alternatives on Fundamental Objectives 1–4. Therefore, these findings will not be revisited in detail in this section; however, many of the socioeconomic metrics designed to evaluate the performance of alternatives on Fundamental Objectives 5 and 6 were developed separately for the draft EIS (U.S. Department of Agriculture Forest Service, in press). These economic indicators used information from Sections 4 and 5 on elk population size, number of elk available for harvest, CWD prevalence, and elk days on private lands to assess the proportional increase or decrease of these metrics relative to current conditions. The economic indicators are then adjusted for the net present value using a discounting rate of 3 percent per year (Maloney and others, 2020).

6.2. Results

Fundamental Objective 5, minimize conflict with agricultural and public stakeholders, was measured using two performance metrics (PM5a and PM5b). The first performance metric associated with Fundamental Objective 5 was a measurement of elk depredation of privately owned haystacks across the four alternatives. We based this estimate on average annual damages for the Afton and Upper Green River HUs of $418 and $2,571 per year (McWhirter and others, 2021), which were then adjusted for the proportional changes in elk days on private property (Section 5) and net present value (U.S. Department of Agriculture Forest Service, in press). These costs were small relative to the other economic metrics, and the differences among alternatives were less than $2,000 over 20 years (tables 7, 8). The second performance metric for Fundamental Objective 5 measured the predicted costs associated with brucellosis spillover from elk to cattle. This metric was based on the estimated number of cattle outbreaks per year in the region (Brennan and others, 2017), our predicted number of elk abortions on private land, and the average cost of an outbreak to a producer (Boroff and others, 2016; U.S. Department of Agriculture Forest Service, in press). Brucellosis costs to producers were highest for the NF alternative and lowest for the CF and EF alternatives in the Afton and Upper Green River HUs.

Fundamental Objective 6, maximize the prosperity of resource-supported economies, was measured using four performance metrics (PM6a, b, c, and d). The first performance metric quantified the consequences of alternatives on hay sales associated with elk feeding programs based on McWhirter and others (2021). This metric varied as expected across the different alternatives with the CF alternative having the highest revenue associated with hay sales and the NF alternative having the lowest for the Afton and Upper Green River HUs. The second performance metric for this objective measured WGFD revenues associated with resident and nonresident harvest tag sales. The calculation of this metric was based on the average number of resident and nonresident hunters from 2016 to 2020 in each HU, which was then adjusted for net present value and declines in the elk population assuming hunting licenses are proportional to the elk population (U.S. Department of Agriculture Forest Service, in press). For this metric, we assumed nonresident and resident hunters were less likely to buy licenses as CWD prevalence increases based on Needham and others (2006). Resident and nonresident license sales were assumed to decline by 20–25 percent when CWD prevalence was 40 percent (Needham and others, 2006; U.S. Department of Agriculture Forest Service, in press). Projected harvest tag revenues under these assumptions are closely matched among alternatives, although on average no feeding had the highest tag revenues, in the Afton and Upper Green River HUs given the projected variation (tables 7, 8). The third performance metric used to evaluate Fundamental Objective 6 was a measurement of hunting related inputs to the regional economy, which mirrored the hunter tag revenue results. This metric was the largest across the 20-year permit period ($26–47 million dollars), but the differences among alternatives were small (for example, $2.4 million between the NF and CF alternative in the Afton HU) relative to the standard deviations of $3 to $6 million (tables 7, 8). The last metric measured the effect of alternatives on outfitter revenues, which was based on the predicted number of nonresident hunters (U.S. Department of Agriculture Forest Service, in press). The standard deviation in outfitter revenues for an alternative was approximately 2 times larger than the average difference among alternatives (tables 7, 8). In table 9, we summarized some of the performance metrics across all five of the analyzed HUs.

6.3. Discussion

There are several important tradeoffs across the four alternatives and two HUs. Generally, we found no single alternative performed best on all fundamental objectives and performance metrics (tables 7, 8, and 9). Similarly, no single alternative performed the worst across all performance metrics. For the Afton and Upper Green River HUs, the management alternatives that minimized feeding (NF and PO) also minimized CWD and maximized elk population size at year 20 relative to the continued feeding and emergency feeding alternatives (tables 7, 8). However, NF and PO alternatives underperformed relative to EF and CF alternatives on brucellosis related costs and private hay sale revenues. These tradeoffs are consistent with the uses and effects of elk feedgrounds and expectations if they were to be closed (McWhirter and others, 2021).

Table 7. Consequence table showing the 11 performance metrics and 4 alternatives for the Afton herd unit (includes Forest Park feedground).

[Color gradient indicates desirability of outcomes ranging from dark blue for more desirable outcomes to light blue for less desirable outcomes. Values in parentheses indicate CWD prevalence. CWD, chronic wasting disease; SD, standard deviation; min., minimum; max., maximum; —, no data]

Performance metric	Units	Direction	Continued feeding		Emergency feeding		Phaseout		No feeding	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD
CWD mortalities[1]	Cumulative elk	Min.	2,598 (0.20)	702	2,490 (0.20)	607	2,251 (0.19)	820	1,930 (0.17)	687
Elk population size	Elk at year 20	Max.	3,091	659	3,221	568	3,251	749	3,551	668
Number of harvested elk	Cumulative elk	Max.	14,959	1,826	14,938	1,637	14,923	1,824	15,249	1,665
Elk use of mule deer range	Elk days (millions)[2]	Min.	1.25	0.16	1.27	0.14	1.24	0.16	1.27	0.15
Elk use of moose range	Elk days (millions)[2]	Min.	3.91	0.51	3.96	0.42	3.63	0.47	3.64	0.41
Elk depredation costs	Dollars (thousands)[2]	Min.	5.49	0.70	5.54	0.59	6.13	0.77	6.42	0.71
Cost of brucellosis	Dollars (thousands)[2]	Min.	68.91	9.02	68.34	8.98	77.65	9.81	83.00	11.06
Hay sales revenue	Dollars (thousands)[2]	Max.	559.05	85.85	378.85	54.99	133.56	20.91	0.00	0.00
Harvest tag sales[3]	Dollars (millions)[2]	Max.	8.43	1.14	8.73	1.13	8.68	1.22	8.95	1.20
Regional economic inputs[3]	Dollars (millions)[2]	Max.	44.73	5.95	46.27	5.92	45.87	6.27	47.17	6.23
Revenue of outfitters[3]	Dollars (millions)[2]	Max.	10.96	1.50	11.36	1.48	11.30	1.60	11.67	1.57

[1] Chronic wasting disease prevalence at year 20 is noted in parentheses.

[2] Cumulative across the 20-year simulation.

[3] Assumes a decline in hunter participation at high levels of chronic wasting disease (Needham and others, 2006; U.S. Department of Agriculture Forest Service, in press).

Table 8. Consequence table showing the 11 performance metrics and 4 alternatives for the Upper Green River herd unit (includes Dell Creek feedground).

[Color gradient indicates desirability of outcomes ranging from dark blue for more desirable outcomes to light blue for less desirable outcomes. Values in parentheses indicate CWD prevalence. CWD, chronic wasting disease; SD, standard deviation; min., minimum; max., maximum; —, no data]

Performance metric	Units	Direction	Continued feeding		Emergency feeding		Phaseout		No feeding	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD
CWD mortalities[1]	Cumulative elk	Min.	2,106 (0.30)	407	2,100 (0.30)	336	1,942 (0.27)	391	1,910 (0.27)	367
Elk population size	Elk at year 20	Max.	1,158	288	1,241	289	1,234	316	1,267	337
Number of harvested elk	Cumulative elk	Max.	7,562	970	7,765	845	7,598	835	7,679	1,005
Elk use of mule deer range	Elk days (millions)[2]	Min.	0.55	0.06	0.56	0.06	0.61	0.06	0.62	0.06
Elk use of moose range	Elk days (millions)[2]	Min.	3.95	0.47	4.02	0.43	4.10	0.42	4.12	0.45
Elk depredation costs	Dollars (thousands)[2]	Min.	28.91	3.16	29.33	2.86	30.55	2.84	30.88	3.11
Cost of brucellosis	Dollars (thousands)[2]	Min.	27.36	3.01	27.93	2.72	28.75	2.82	29.44	3.06
Hay sales revenue	Dollars (thousands)[2]	Max.	531.44	63.46	431.40	44.65	133.75	11.24	0.00	0.00
Harvest tag sales[3]	Dollars (millions)[2]	Max.	3.75	0.49	3.87	0.46	3.91	0.48	3.94	0.55
Regional economic inputs[3]	Dollars (millions)[2]	Max.	26.34	3.25	27.12	3.07	27.32	3.16	27.54	3.66
Revenue of outfitters[3]	Dollars (millions)[2]	Max.	5.40	0.72	5.57	0.67	5.63	0.71	5.68	0.81

[1] Chronic wasting disease prevalence at year 20 is noted in parentheses.

[2] Cumulative across the 20-year simulation.

[3] Assumes a decline in hunter participation at high levels of chronic wasting disease (Needham and others, 2006; U.S. Department of Agriculture Forest Service, in press).

Table 9. Cumulative effects table showing seven performance metrics and chronic wasting disease prevalence for three alternatives on all feedgrounds and those on U.S. Department of Agriculture Forest Service lands. Data are summarized for the Afton, Fall Creek, Upper Green River, Piney, and Pinedale herd units.

[Color gradient indicates desirability of outcomes ranging from dark blue for more desirable outcomes to light blue for less desirable outcomes. FS, U.S. Department of Agriculture Forest Service; CWD, chronic wasting disease; SD, standard deviation; min., minimum; max., maximum; —, no data]

Performance metric	Units	Direction	Proposed action		Phaseout all		Phaseout FS		No feeding all		No feeding FS	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
CWD mortalities	Cumulative elk (thousands)	Min.	12.34	1.60	6.38	1.90	9.31	1.28	4.06	0.96	7.61	1.13
CWD prevalence	Prevalence	Min.	0.29	0.04	0.16	0.05	0.22	0.04	0.13	0.03	0.19	0.04
Elk population size	Elk at year 20 (thousands)	Max.	8.29	0.74	11.00	1.63	9.65	1.09	12.46	0.98	10.70	0.89
Number of harvested elk	Cumulative elk (thousands)	Max.	51.12	3.82	55.30	3.20	52.92	3.05	57.72	2.60	54.24	2.92
Harvest tag sales[2]	Dollars (millions)[1]	Max.	25.81	1.64	27.54	2.02	27.05	2.15	28.74	1.70	28.13	1.88
Regional economic inputs[2]	Dollars (millions)[1]	Max.	173.46	10.46	182.31	12.95	180.28	13.31	190.10	10.69	187.53	11.84
Revenue of outfitters[2]	Dollars (millions)[1]	Max.	31.30	2.04	33.66	2.53	32.95	2.71	35.17	2.15	34.30	2.36
Cost of brucellosis	Dollars (thousands)[1]	Min.	194.62	11.54	230.42	15.35	220.81	11.73	242.97	15.05	227.32	13.73

[1] Cumulative for the 20-year simulation.

[2] Assumes a decline in hunter participation at high levels of chronic wasting disease (Needham and others, 2006; U.S. Department of Agriculture Forest Service, in press).

7. Conclusions and Future Directions

Our work suggested the removal of feedgrounds or a high chronic wasting disease (CWD) prevalence is likely to cause large reductions in the western Wyoming elk populations. We predict, however, population declines associated with feedground closures will be more than offset by the benefits of reducing the negative consequences of CWD such that the no feeding alternative tends to result in higher elk populations by year 20. The high concentrations of elk on feedgrounds led our expert panel to estimate high levels of environmental contamination of prions that result in persistent hotspots of disease with the potential to infect elk and mule deer for many years to come. The differences among alternatives in some performance metrics are small relative to our prediction uncertainties when we consider just the Dell Creek and Forest Park decisions because of the small percentage of elk on Dell Creek and Forest Park feedgrounds relative to the entire herd unit (HU).

To assess the cumulative effects across many feedgrounds, we analyzed the continued feeding, phaseout, and no feeding decision alternatives across all feedgrounds on five HUs and found the overall magnitude of effect depended on the percentage of fed elk relative to the total HU population. In some cases, the differences between the continued feeding (CF) and no feeding (NF) alternatives were large. We found CWD prevalence on the Piney HU could be limited to 14 percent ([5th and 95th percentiles = [3 percent, 28 percent]) if all feedgrounds were closed relative to 33 percent ([5th and 95th percentiles = [23 percent, 44 percent]) prevalence under the continued feeding alternative. The same alternatives on the Afton HU reduced CWD prevalence from 23 percent to 14 percent in year 20 (fig. 17). The no feeding alternative led to rapid reductions of elk after feedground closures; however, elk population sizes under the CF alternative also declined because of high CWD-associated mortality, and in most cases, fell below the NF alternative after 10 years.

The cumulative effects analysis highlighted a cost associated with CWD when management actions are delayed under the phaseout alternative. Our results indicate the phaseout alternative allowed CWD to grow rapidly within the fed population and elevate CWD prevalence across HUs. For example, the CWD prevalence in the Upper Green River HU was predicted to be 20 percent in year 20 if all feedgrounds were phased out after 3 years compared to 12 percent if feeding is stopped immediately. When feedgrounds were then closed after the 3-year delay, we predicted larger population declines when compared against the NF alternative because of a lack of winter range and higher CWD prevalence. Thus, early action is often more effective, but it coincides with a high degree of uncertainty in outcomes and waiting for more information may have consequences.

Our predictions do not include all potential uncertainties. To inform our assumptions and modeling techniques, we relied on published literature, empirical estimates, and expert judgement; however, there remain sources of uncertainty that will affect our projections. We conclude the key uncertainties are: (1) the magnitude of elk population declines in the absence of feeding, (2) the magnitude of CWD transmission rates in fed and unfed elk, and (3) the behavior and movement of elk in response to closures. Our estimate of elk population declines due to feedground closures depended on current estimates of elk winter range. In the absence of feedgrounds, elk may utilize areas that are not currently considered elk winter range. If so, we may be overestimating the population declines that would be associated with feedground closures. However, if feedground closures result in more use of private land, then this may affect hunting regulations and elk population size in ways that are hard to predict. In addition, we did not include variation in brucellosis transmission rates or elk brucellosis seroprevalence over time or across regions.

Future analysis could evaluate this system as a series of linked decisions at both the individual feedground scale and at the scale of the feedground program in western Wyoming. If feedground closures result in elk relocating to another feedground, then the ordering of feedground closures could be important so elk are not further concentrated on feedgrounds with the greatest potential for conflict. Future analysis could also consider the effects changes in climate and snowpack have on space use and feeding patterns. The Greater Yellowstone Ecosystem climate assessment predicts a 30–40 percent reduction in April snowpacks for the upper Green and Snake River watersheds by mid-century, which will likely translate into shorter feeding seasons (Hostetler and others, 2021).

If feeding is not permitted on Dell Creek or Forest Park feedgrounds, there is an opportunity to study those impacts, which would be informative for future feeding decisions. Both feedgrounds are in areas with high winter snowpacks; thus, they have prolonged feeding seasons relative to other feedgrounds. We expect winter-associated declines in elk populations would be most severe on these two feedgrounds under a no feeding alternative; however, these would be the first tests of our assumed 23-percent declines without feeding. There is also an opportunity to learn more about long-term CWD dynamics in fed and unfed elk population segments, but it will be important to design CWD surveillance programs with sufficient statistical power.

The consequences of the different management alternatives for Forest Park and Dell Creek feedgrounds show there are tradeoffs across objectives in the choice of a preferred alternative. That is, to identify a preferred alternative, the FS, in consultation with its stakeholders and cooperating agencies, will have to balance the relative importance of the different objectives when selecting the alternative that has the highest performance. The field of decision analysis offers a set of tools to help decision makers and stakeholders through deliberations and associated tradeoffs, thus, providing a transparent way to communicate how tradeoffs were navigated to identify a preferred alternative. We developed the analyses in this report so tools like multicriteria decision analysis can be used to evaluate and understand complex tradeoffs.

The U.S. Department of Agriculture Forest Service and Wyoming Game and Fish Department could work collaboratively to develop future management alternatives beyond those we considered here. There may be alternatives that help reduce CWD and brucellosis effects and also address the potential loss of population productivity and changing space use patterns that could occur without feeding. Potential mitigation measures include habitat enhancements and restoration, increased harvest during feedground closures, and working with local landowners to minimize brucellosis transmission risk and lessen private property damage. The continued use of decision analysis to frame and evaluate future decisions allows for the development of research that is specific to the needs of the decision maker, improved communication with stakeholders, and a better understanding of the role that scientific uncertainty plays in a decision-making context. Understanding the importance of scientific uncertainty for future elk management decisions can direct research to the appropriate places to reduce uncertainty and improve our understanding of future outcomes under a diversity of management alternatives in this interconnected and dynamic system.

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Appendix 1. Additional Chronic Wasting Disease Analysis Details

Table 1.1. Names and affiliations (at the time of the elicitation) of expert panelists who provided judgment on estimates of chronic wasting disease transmission parameters.

Expert	Affiliation
Emily Almberg	Montana Department of Fish, Wildlife, and Parks
Justin Binfet	Wyoming Game and Fish Department
Hank Edwards	Wyoming Game and Fish Department
Nathan Galloway	National Park Service
Glen Sargeant	U.S. Geological Survey
Brant Schumaker	University of Wyoming
Daniel Walsh	U.S. Geological Survey
Benjamin Wise	Wyoming Game and Fish Department

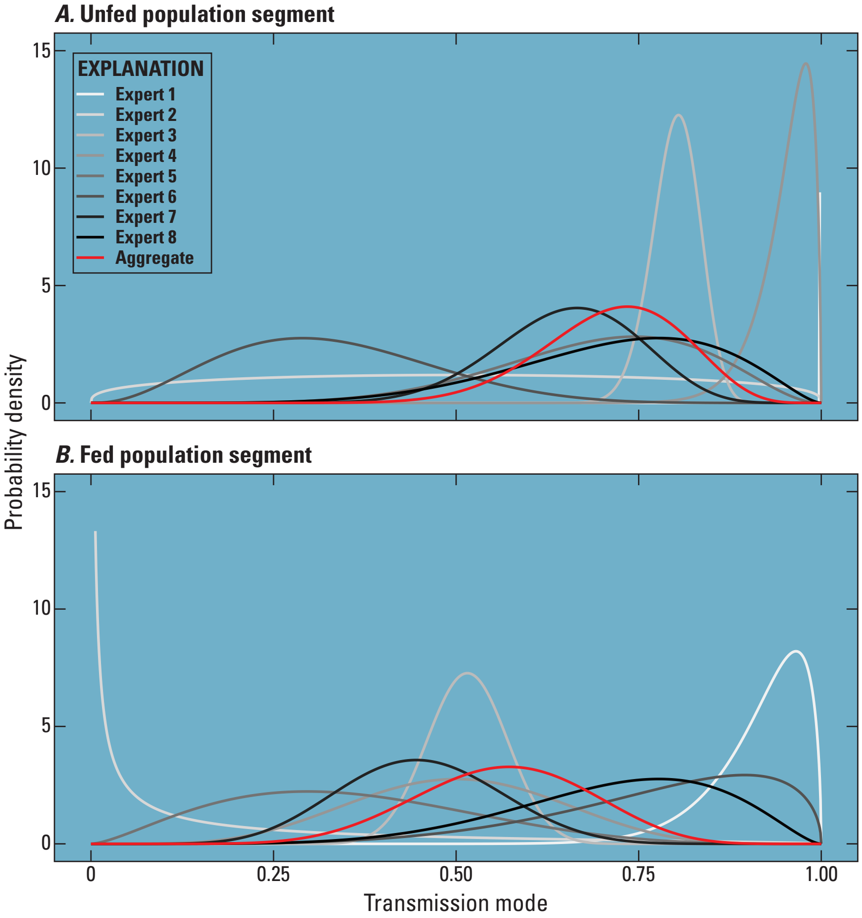

Figure 1.1. Individual and aggregate distributions for chronic wasting disease transmission modes in *A*, unfed (native winter range) and *B*, fed elk population segments. A value of zero on the x-axis represents density-dependent disease transmission whereas a value of one represents frequency-dependent transmission.

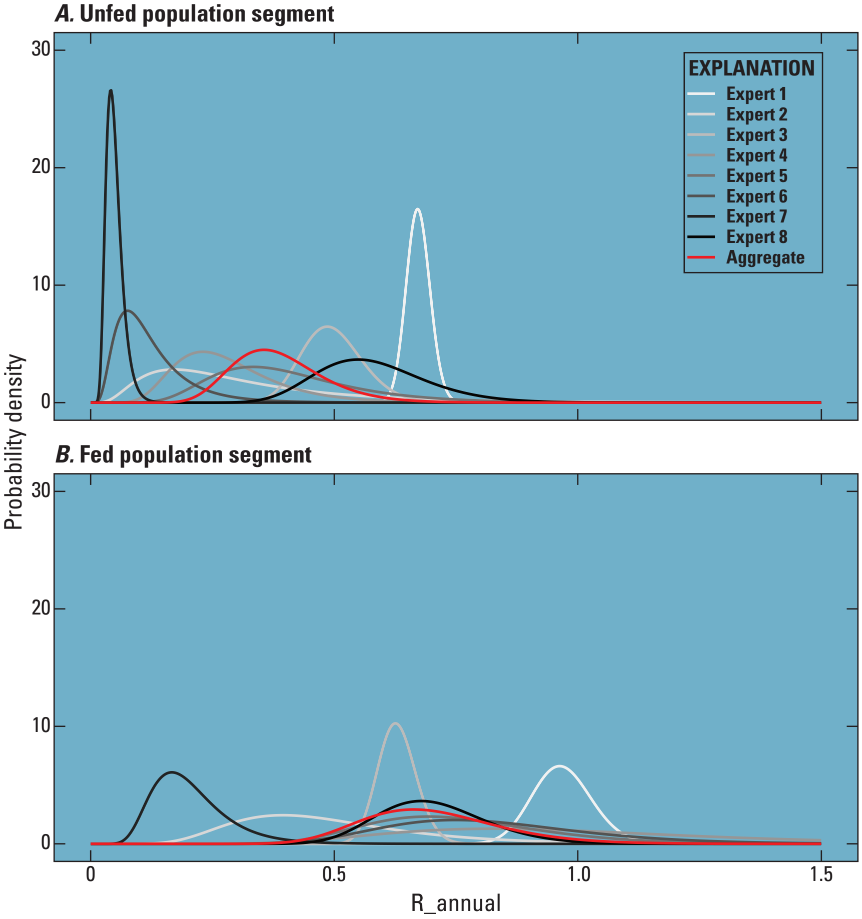

Figure 1.2. Individual and aggregate distributions for direct chronic wasting disease transmission rates in *A*, unfed (native winter range) and *B*, fed elk population segments.

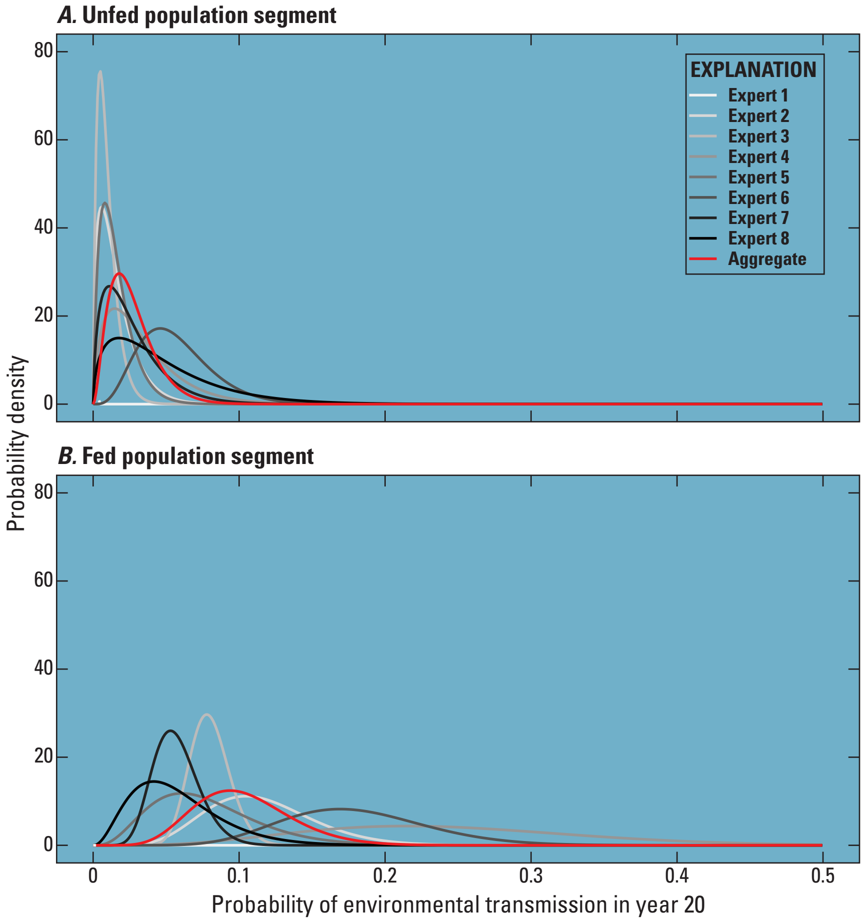

Figure 1.3. Individual and aggregate distributions for indirect chronic wasting disease transmission rates in *A*, unfed (native winter range) and *B*, fed elk population segments.

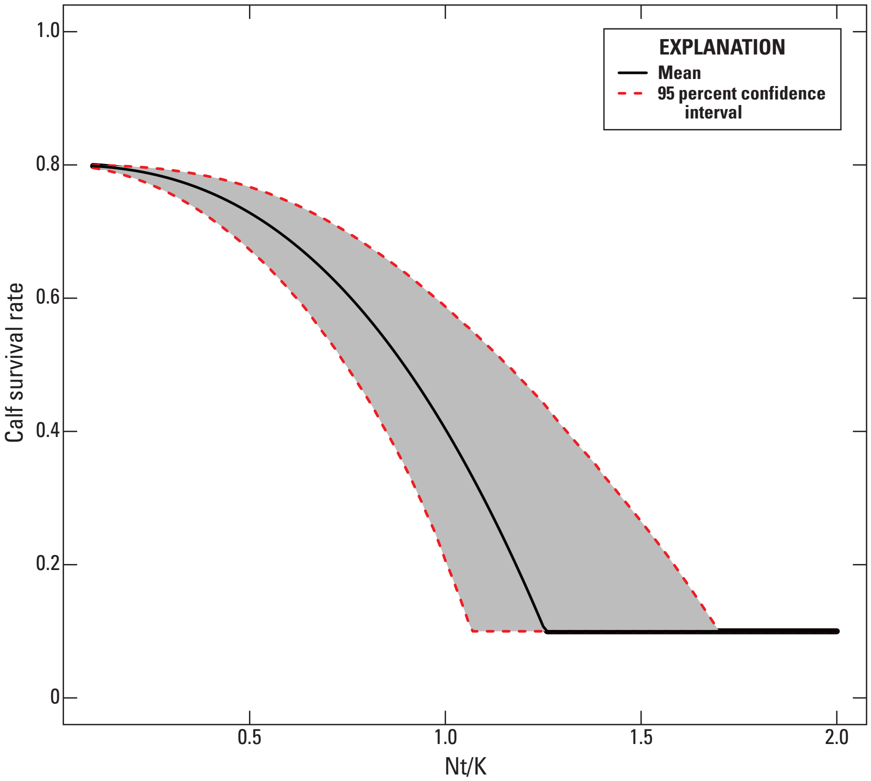

Figure 1.4. Annual calf survival probability as a function of elk population size (Nt) divided by carrying capacity (K), Nt/k. The maximum and minimum annual calf survival rates were 0.8 and 0.1, respectively.

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