Computational Economics (2023) 62:1751–1780
https://doi.org/10.1007/s10614-022-10317-8

Working Together: Optimal Control of Wolf Management Across Multiple States

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Accepted: 29 August 2022 / Published online: 28 September 2022

Abstract

The reintroduction of the gray wolf (*Canis lupus*) has been largely successful in the upper Rocky Mountain region (URM). This led the federal government to hand over the responsibility of managing the species to the individual states of Idaho, Montana, and Wyoming. As each state currently works mainly independently, this study examines if there are any spillover effects to jointly managing wolves in the region. We develop theoretical optimal control and system dynamics bioeconomic models to determine the steady states for the number of wolves, their management, and corresponding net benefits for Idaho, Montana, Wyoming, and the region as a whole from 2000 to 2030. Results from the models show potential benefits when states work together in the form of greater economic efficiencies in management and potentially larger wolf populations. Using a system dynamics model, we find the optimal management path under three different management scenarios with the possibility of improving net benefits by almost $1 million per year when states work together. Our results provide meaningful insights for policymakers which could potentially impact how states approach management of a species that can be both expensive and controversial.

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Keywords Optimal control model · Endangered species · Gray wolf · Wildlife management · System dynamics

JEL Classification Q57 · C61 · C63

1 Introduction

The protection of endangered and threatened species is often contentious and controversial. While most people understand the importance of preserving biodiversity, it can often place a large burden on specific groups that incur higher costs from the interaction with these species. Laws providing protection can often result in the loss of use of natural resources in order to preserve habitat. Individuals may incur direct financial loss in the form of livestock depredation or crop destruction or even experience a psychological and emotional hardships. Globally, the benefits of biodiversity are widely distributed while the costs are often borne by a much smaller group.

An example of this conflict can be seen in the reintroduction and restoration of the gray wolf in the upper Rocky Mountains (URM). Considered a pest and threat, they were essentially eradicated from the area since the mid 1940s, giving humans and the ecosystem time to adapt to the absence of a keystone species. However, the U.S. Fish and Game decided to bring back wolves to the area starting in 1995. Wolves bring with them a number of benefits both economic and ecologically. Beyond inherent value of their presence, it has been estimated that wolves account for approximately $34 million dollars in additional revenue per year for the region from tourism activities (Duffield et al., 2008). Additionally, there is some evidence that wolves have helped to restore and balance ecosystem functioning (for example see Beyer et al., 2007; Boyce, 2018). However, with their introduction a number of negative externalities have been created resulting in direct economic losses from livestock depredation and weight reduction, reduced hunting opportunities, and fear of individual safety (Naughton-Treves et al., 2003).

Initially, the United States Fish and Wildlife (USFW) created the management plan and implemented the reintroduction of the gray wolf into Yellowstone National Park (YNP) and central Idaho. The plan called for the USFW to establish a healthy population of wolves in the upper Rocky Mountain area and then turn over the management to the individual states of Idaho, Montana, and Wyoming (U.S. Fish & Wildlife Service, 1987). As each state developed and follows its own management plan, there appears to be little interaction and cooperation amongst them in the management of wolves. Therefore, individual states must maintain agencies responsible to manage a species that does not recognize geographical boundaries. Further, as mentioned earlier, the costs of these predators are often borne by a small group, while the benefits are enjoyed universally. As such, policymakers are tasked with an institutional mismatch such that the scale of externality imposed by the wolves exceeds the existing institutional solution, in which states are independently managing the wolf population (Ostrom, 2003; Rayamajhee & Paniagua, 2021).

Hitherto, regulators have ignored the nature of the externality produced by wolves to solve the collective action problem of managing wolves in the region.

In this study we try to model and compare the outcomes on efficiency and effectiveness of wolf management based on whether a state works independently or jointly with others in the region. First, we develop multiple optimal management paths using optimal control theory that maximizes the net benefits to society. Theoretically, the model can indicate differences in optimal paths, highlighting areas that may lead to greater efficiencies. Second, we use agent-based modeling to empirically evaluate these multiple scenarios. Using actual costs and revenues associated from the direct impact of wolves, we create a bioeconomic model that demonstrates the management paths under a variety of scenarios. While there are many indirect costs and benefits associated with having the predator species, we focus on measurable outcomes to replicate what wildlife managers are facing.

Results from both the theoretical and empirical models indicate efficiencies could be gained by cooperatively managing wolves. Most notably, and understandably, sharing management costs and activities across states provide an opportunity to increase overall economic benefits. Further, we show that with joint cooperation the number of wolves can be maintained at higher levels ensuring a healthier population. Specifically, we find the optimal number of wolves for the region to level out at approximately 2,300, almost 400 more than if states work independently. Maintaining this number suggests that approximately 615 will need to be harvested annually. Finally, we estimate that when states work together and lower management costs, the net benefit can be increased by almost $1 million. We believe these results provide important evidence that there are positive spillover effects from cooperative management of wolves in the URM region.

Our contribution to the literature is twofold. First, to the best of our knowledge, we are the first to determine an optimal management strategy for the reintroduction and management of a contentious species throughout the URM region. Second, we provide a unique application of optimal control theory and system dynamics. Our study complements and builds upon the recent work by Sims et al.(2020) that uses a bioeconomic approach to understanding the impacts on the local economy of delisting the gray wolf in the Greater Yellowstone Ecosystem. Our model can provide a foundation upon which managers can build to develop optimal strategies towards wolves and other important species worldwide.

The paper is divided into five sections. Section 2 presents the background to the problem and reviews the relevant literature. Section 3 develops the theorical optimal control models for the individual state and the joint-state management model. Section 4 presents the empirical models and the numerical results. Section 5 presents the conclusions.

2 Background

2.1 Study Area

We focus on the three main states of Idaho, Montana, and Wyoming that comprise most of the area of the upper Rocky Mountains and the former range of the Rocky

Mountain Gray wolf. While portions of Washington and Oregon have wolves that have migrated into the area the numbers remain low. As we are interested in the potential types of management, we use these three states as the representatives for the URM. The region is similar to what is often referenced as the Greater Yellowstone Ecosystem with Yellowstone National Park (YNP) centrally located within the three states.

In Fig. 1, we show the area of the URM where wolves were historically found in the URM. Considered a pest species and threat to more desirable species such as elk, the northern Rocky Mountain wolf was essentially eradicated from the area by the 1930s, including in YNP and surrounding states. After years of near extinction, in 1974 the gray wolf in the northern Rocky Mountains was considered to be endangered and placed under the protection of the Endangered Species Act (ESA). The U.S. Fish and Wildlife Service made the decision to restore wolves back into the area, and in 1995 and 1996, introduced 65 wolves into Idaho and YNP. The explosive population growth of wolves in the URM reached the restoration plan's goal of maintaining 300 wolves and 30 breeding pairs for three years in 2002. Reaching this milestone potentially allowed the USFWS to remove the ESA protections and turn over responsibility to individual states upon approval of proposed management plans. However, after many legal battles it was not until 2009 that the USFWS delisted them in Idaho and Montana. Wyoming's management plan remained unsatisfactory to the USFWS and therefore remained in federal control (International Wolf Center, 2019; National Park Service, 2018).

As part of the management plans, wolves were legally allowed to be hunted to control population numbers. Idaho and Montana had its first hunting season of

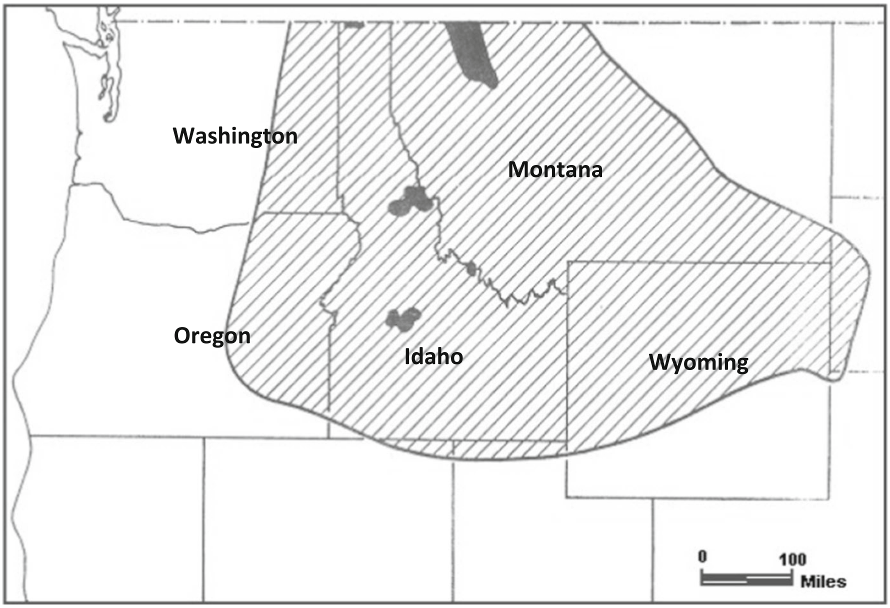

Fig. 1 Historical range of the Rocky Mountain Gray wolf. (USFW 1987)

wolves in 2009. However, in 2010 a federal judge reinstated ESA protection to the entire URM banning all hunting. After a year of more legal battles, wolves were once again delisted, and hunting wolves commenced once again in Idaho and Montana. Wyoming wolves were eventually delisted in 2012 and management was handed over to the state until 2014 when authority was taken away and given back to USFWS. It took three years for Wyoming to get back management of wolves in 2017 (International Wolf Center, 2019; National Park Service, 2018).

2.2 Economic Valuation of Environmental Goods and Services

Analyses of the benefits and costs of environmental goods and services incorporate an economic valuation for the environment. In the traditional environmental economics analysis, the value of the environmental goods and services is attributed to them by humans in monetary terms. Because the environment provides many different types of good and services, environmental economists have created a classification scheme to describe these values. At its more general level, the value of environmental good and services are divided into use value and non-use value.

Use values are those that humans place on the tangible or physical values of the environment and it is associated with the traditional notion of value in the consumption of a good. For example, the use value of a forest can be the wood and minerals that humans obtain from using those resources. Other examples of use values can be the value that people place on hiking, fishing or just visiting an environmental site.

Non-use values are those that people obtain without actually applying or using the good or service. For example, some people may value an environmental site even if they do not intend to ever use or visit the site. Non-use values include four basic types: existence, option, altruistic and bequest. Existence value is the value that comes exclusively from knowing that the environmental good or service exists. For example, people may derive a benefit only because certain species exists (e.g., pandas, wolves, elephants). The option value is the value that comes exclusively from preserving the environment for possible future use. This is particularly important for environmental sites that people do not intend to visit in the immediate future but enjoy having the option for the future. The altruistic value comes exclusively from people deriving a benefit from someone else using the environmental good or service. A person may enjoy preserving a park or ecosystem just because other people obtain enjoyment from it. Finally, the bequest value refers to the value that comes exclusively from having a resource available for the enjoyment of future generations. For example, people might obtain value of preserving certain species or environmental site only because they want future generations to enjoy them.

2.3 Benefits and Costs of Wolves

Any optimal management of a wildlife species, especially an apex predator, must consider the benefits and costs associated with their presence. While costs tend to be more straightforward, usually in economic terms, the difficulty lies in ascertaining the value of a species. The problem arises that this value can be made up of many different components from the abstract, ecosystem service and intrinsic value, to monetized benefits such as park entrance fees or hunting license fees.

Like many keystone species, especially for predators, the removal of the wolf from an ecosystem can set forward a chain of events that can significantly alter the environment. Likewise, their introduction or reintroduction into an area in which it has been absent for a long period of time can have profound impacts as well. Since their eradication around 1926 in the URM area of Idaho, Montana, and Wyoming (see Fig. 1), the ecosystem went approximately 70 years adapting to the loss of a top predator. Ecological responses were great with elk populations increasing corresponding to a variety of landscape changes, including loss of aspen and willow groves and the deterioration of riparian habitat (Smith & Bangs, 2009).

Since their return and successful establishment over the last 20 years, the ecosystem has once again adapted. There is evidence that elk populations have been reduced and are genetically stronger, willow stands are rebounding along with associated wildlife species, and riparian ecosystems are healthier (Smith & Bangs, 2009). While causality may be tentative at this point, the biological evidence suggests that wolves play at least a partial role.

In an attempt to value the gray wolf, there can be a number of approaches. The direct economic benefits (use-value) stem mainly from wolf-related tourism activities and hunting license fees. Duffield and Neher (1996) estimated that reintroducing wolves back into Yellowstone National Park initially brought net benefits to the area in the range from \$5.8 to \$9.2 million. This has escalated in recent years to approximately \$34 million per year (Duffield et al., 2008). License fees for hunting in trapping of wolves can generate anywhere from \$100,000 to \$500,000 annually.

To estimate the non-use values of wolves, studies have focused on a willingness to pay (WTP) procedure. While this is not enough to evaluate their full worth, it hopefully identifies intrinsic worth as well as some of the services provided by wolves as seen by the general public. Chambers and Whitehead (2003) used a contingent valuation method to find a value of \$23 for wolves in Minnesota. While Richardson and Loomis (2009) showed a range of economic value for wolves ranging from \$22 to \$162, with an average of \$61, through a meta-analysis of a number of studies. Unfortunately, there have been limited studies specifically for the URM region.

The benefits associated with the presence of wolves need to be compared to the costs of their management. These mainly arise from management activities by government agencies along with direct loss of livestock. These costs will obviously fluctuate with the objectives and by the management plans instituted by each state or agency. Mech (1999) calculated the overall cost per wolf per year in Minnesota to range from \$71–110 over the 1979–1998 time period, and estimated costs to rise to \$146 during 2001–2005. This included both control related management costs and compensation for losses incurred by the public. While Chambers and Whitehead (2003) did not calculate a specific cost per wolf, their analysis of the costs and previously mentioned benefits of wolf management in Minnesota yielded an overall net benefit.

2.4 Dynamic Optimal Control and Bioeconomic Models of Wildlife

A number of studies have used optimal control or bioeconomic models to try and understand the dynamics of endangered or recovering species. Some studies focus on population dynamics, others look at the economic drivers, while still others try to understand the overall relationship between the two. Bioeconomic modeling of natural species introduces complexities from both the economic and ecological side of the analysis. Rondeau (2001) illustrates this when he developed an extensive model that demonstrates the difficulties associated with this type of analysis. He highlights the issues of determining the net benefits of wildlife species which can lead to shadow prices that can be either positive or negative.

More recent work by Sims et al. (2020) looks at the economic benefits of delisting an endangered species. They also focus on wolves in a subsection of the Greater Yellowstone Ecosystem. Interestingly, they find that there is an economic benefit to the local region when wolves were delisted from the ESA. However, there is a great deal of heterogeneity in who incurs the costs and benefits, especially cost savings, from wolf conservation. They also suggest that programs to compensate individuals that have losses in the form of livestock depredation should be expanded and possibly fall under federal mandate. Doing this would reduce the incentive for states to reduce wolf populations in an attempt to decrease livestock depredations.

Bodine et al. (2008) focused on augmentation of the species and which parameters of the environment are key to increasing numbers of individuals. They understandably find that ecological conditions are important to the management path of recovering species. Rondeau (1998) considered the reintroduction of endangered predators, with the flexibility of allowing for animal augmentation and harvesting, as well as human-wildlife interactions. This study showed that intense effort of increasing populations at the beginning is essential and should be followed by active population control. In other words, the initial "stock" of the population is essential for its long term survival (Rondeau, 1998).

Looking at Stellar sea lions, Finnoff and Tshirhart (2002) extended predator models in a slightly different form, to consider the impact of reintroduction on prey species. They looked at the potential indirect economic impacts and incentives of the complex system of predator/prey, environment, and human activities. Their results show when the prey of an introduced predator is also shared with human consumption, conservation efforts become much more difficult and should be considered in policy development.

Finally, other studies have focused on the economic component related to endangered species management. Linking human "use" of endangered species through national park tourism, it has been shown that there is an optimal level of ecotourism in parks to maximize revenue and conservation efforts (Bednar-Friedl et al., 2012).

3 Theoretical Model

The population of wolves in a given geographical area is determined by both biological and anthropogenic factors. Natural population dynamics, unique to every species, determine its natural rate of increase. This includes birth and death rates, carrying capacity of the landscape, competition, and predator–prey relationships. While very complex, this can be simplified to the general function $f(w)$, where the rate of increase is a function of the number of wolves. Initially, this function will be highly simplified in a basic logistic growth function, assuming the carrying capacity will capture some of the complexities. This could later be refined through empirical studies that have estimated the natural rate of increase of wolves for unmanaged populations (Mech & Fieberg, 2015). In Fig. 6 in "Appendix A", we illustrate a hypothetical logistic growth function.

Human management also plays a significant role in wolf numbers. As evidenced by their delisting from the ESA, conservation efforts have rebounded wolf populations from zero to "recovered" in the URM region, after humans essentially eradicated them from the region decades ago. The current problem that managers face is to maintain these population levels while balancing the impacts on society. Therefore, management activities can have positive (e.g., reintroduction, supplementation, protection from hunting) or negative (e.g., culling, hunting, translocation to other areas) impacts. While hunting remains a controversial and limited option, government wildlife agencies have taken lethal measures to control wolf populations (Bradley et al., 2014). However, given that wolf populations currently are at recovered levels, wolf management may be simply thought of as a harvesting rate or cost of harvesting. In what follows, a dot above a variable represents the derivative of the variable with respect to time. Therefore, the differential equation that serves as the law of motion equation and represents the change in the number of wolves over time can be written as:

$$\dot{w} = f(w) + m \tag{1}$$

Equation (1) above implies that the change in the wolf population over time ($\dot{w}$) is equal to the natural growth function of wolves $f(w)$ plus the management input m, which is the harvesting (or supplementation).

The initial decision to reintroduce wolves into the URM region has been made and implemented by the federal government. In accordance with the initial management plan, the success of these activities led to the management authority to be handed over to the individual states. In adherence to federal guidelines of delisting a species, the states are now tasked to maximize the benefits of wolf management to society.

The goal becomes to gain the most social benefits by maximizing direct economic benefits and minimizing damages and management costs while maintaining a genetically viable population of wolves. We follow Rondeau (2001), who developed a more generalized optimal control model for endangered species. However, we extend the model to include hypothetical joint management of wolves by a number of n states, where $n=1,\ldots,N$.

The benefits of wolves range from the non-use values including existence value, bequest value, provision of ecological services, and recreational activities. Hunting and closely connected sectors would make up the use value of wolves, however, it should be noted that this would retract from the existence values for some individuals. The benefits from the wolves are represented by the function $B(w)$ and the number of wolves as a function of time by $w(t)$. Thus, the total benefits can be captured as a function of wolves at time t given by $B(w(t))$.

It is likely that the marginal benefit of a wolf when populations are low is relatively high but will taper off as numbers increase. Therefore, it is assumed that the function is increasing and concave, $B_w > 0$ and $B_{ww} < 0$.

Wolf interactions with human activities will lead to direct damage costs such as the loss of livestock and pets. The function $D(w(t))$ is the wolf dependent function of damage that is assumed to be increasing at an increasing rate. Higher populations will increase human-wolf interactions, and inter- and intra-specific competition will lead to exponentially greater damage as they turn to alternative food sources. Therefore, $D_w > 0$ and $D_{ww} > 0$.

Finally, the cost associated with the management of a species is given by the function $C(m(t))$, where $m(t)$ is the level of management "effort" which in this case translates to population augmentation or harvesting. While this is not a direct cost per se, this effort can loosely be thought of in a monetary sense, for example the monitoring and sustaining a target population, relocation and culling, and managing hunting activities. These costs can be significant, as indicated by a Montana bill appropriating $900,000 per year for "wolf management" (Bradley et al., 2014). It is important to note that this cost function is not dependent on wolf populations. Understandably, this overlooks some of the inherent relationship associated with density, such as repayment of livestock losses and relocations. However, many of the costs will exist regardless of numbers, including activities such as monitoring, public outreach, protecting vital areas, and genetic testing. Therefore, we assume that management efforts are independent of the number of wolves, and, to keep the model tractable, we assume that it is increasing and convex, $C_m > 0$ and $C_{mm} > 0$. The net benefit (NB) from wolves is given by the following equation:

$$NB(w) = B(w(t)) - D(w(t)) - C(m(t)) \tag{2}$$

We use an optimal control model to determine the best wolf management path that maximizes the net benefits to society given by Eq. (2) above. We develop two separate models to illustrate the differences between states acting independently versus jointly. Benefits are maximized indefinitely into the future assuming that society will always choose and benefit from wolf existence in the region.

3.1 Individual State Management

The wolf manager within each state maximizes the infinite discounted value of the social net benefits given by Eq. (2) subject to the law of motion of the wolf population given by Eq. (1) as follows:

$$\max \int_0^\infty e^{-\delta t}[B(w(t)) - D(w(t)) - C(m(t))]dt$$
$$s.t. \quad \dot{w} = f(w) + m$$
$$w(t) \geq 0$$
$$w(0) = w_0 isgiven$$

where δ is the discount factor and m is the management effort (harvesting or supplementation). As justified by Rondeau (2001), the cost and benefit functions in the net benefits are inputted separately based on the idea that an existence value for one person may be a direct loss (of livestock for example) for another.

The current value Hamiltonian becomes:

$$H = B(w(t)) - D(w(t)) - C(m(t)) + \mu[f(w) - m] \tag{3}$$

The first order conditions are given by the following:

$$H_m = C_m - \mu = 0 \tag{4}$$

$$-H_w = \dot{\mu} - \delta\mu = -B_w + D_w - \mu(f_w) \tag{5}$$

$$H_\mu = \dot{w} = f(w) - m \tag{6}$$

We take the derivative of Eq. (4) with respect to time and solve for $\dot{m}$ to obtain the following optimal management path:

$$\dot{m} = \frac{\dot{\mu}}{C_{mm}} \tag{7}$$

We substitute $\dot{\mu}$ from Eq. (5) and $\mu = C_m$ from Eq. (4) into Eq. (7) to obtain the following optimal management or harvesting path of wolves:

$$\dot{m} = \frac{\delta\mu - B_w + D_w - \mu f_w}{C_{mm}} = \frac{C_m(\delta - f_w) - B_w + D_w}{C_{mm}} \tag{8}$$

Equation (8) shows that the optimal path of management effort in the single state problem depends on the marginal benefits, costs and damages of the wolf population. In subsection 3.3, we provide a more detailed intuitive explanation of Eq. (8).

3.2 Multiple State Joint Management

Although our main motivation is the wolf management in the three states of Idaho, Montana, and Wyoming, we develop a joint management model for n states. In the numerical section, we perform a numerical simulation for only those three states.

The main idea behind a joint management program is that it could potentially reduce overall management costs, as redundant activities could be streamlined. Other benefits from joint management would also include better monitoring and understanding of wolf population dynamics and movements across the entire region.

As wolf movements often ignore state borders, uncertainty of wolf activity can exist. Improved networking, outreach, and damage control could also arise from joint efforts. Moreover, the change in the population would be dependent upon all the wolves in the region.

When the states work together, the wolf manager maximizes the net social benefits and wolf population through the following problem:

$$\max \int_0^\infty e^{-\delta t}\left[\sum_{n=1}^{N}\left(B(w(t))_n - D(w(t))_n - C(m(t))_n\right)\right]dt$$

$$s.t. \quad \dot{w}_n = f_n(w_n, \ldots, w_N) - m_n$$

$$w_n(t) \geq 0$$

$$w_n(0) = w_0 \; is \; given$$

where $n = 1, \ldots, N$ and δ is the discount factor. The Hamiltonian of the joint-management problem is the following:

$$H = \sum_{n=1}^{N}\left[\left(B(w(t))_n - D(w(t))_n - C(m(t))_n\right) + \mu_n[f_n(w_n, \ldots, w_N) - m_n]\right]$$

Which yields the optimal management effort paths for each state n of (see "Appendix B" for the derivation):

$$\dot{m}_n = \frac{C_{m_n}\delta - B_{wn} + D_{w_n} - \sum_{n=1}^{N} C_{mn} f_{n,w_n}}{C_{m_n m_n}} \quad \forall n = 1, \ldots, N \tag{9}$$

Equation (9) for the multiple management state has many similarities to Eq. (8) for the single state. The biggest difference is the last term numerator of Eq. (9). The optimal management path for state n depends on the state's marginal benefits, damages, costs of the wolf population (as in Eq. 8) but it is also affected by the marginal costs of the wolf population in other states. In Sect. 3.4 we provide a more detailed intuitive explanation of Eq. (9).

3.3 Theoretical Model Individual State Management Results

Equation (8) provides the optimal management effort path for wolves in a single management state model. There are different interpretations to the management model, but it is more accurately represented as that of harvesting wolves. Thus, positive management effort is interpreted as the removal of wolves and a negative management effort as the supplementation wolves. Consequently, $\dot{m} = 0$ represents a management effort (removal or supplementation) that does not change over time and we call it the zero-growth management effort curve. The deviation from the zero-growth wolf management curve ($\dot{m} = 0$ in Eq. 8) is the more important aspect when it comes to costs. A larger separation from the zero-growth management effort curve indicates bigger management costs, whether they come from supplementing or removing wolves from the population. This path is based on a discounted marginal cost along with the positive or negative marginal growth, marginal benefit, and marginal damage of wolves. Remembering the assumption that $C_{mm}>0$, the denominator is positive. Therefore, if the marginal benefit is low relative to the marginal damage and marginal costs, which would be the case of when wolf populations are high, this would cause the management effort over time to be positive ($\dot{m} > 0$) and of higher magnitude. The manager should decrease the number of wolves by increasing the level of harvesting. On the other side, with high marginal benefits assumedly with low numbers, then the numerator is negative causing the management effort over time to be negative ($\dot{m} < 0$). At this point, to stay in the optimal management effort path of wolves the manager needs to increase the population of wolves by supplementing the wolf population. The increase in population of wolves decreases their marginal benefit which can come from non-use values as well as hunting and tourism revenues, among others.

The dynamics of the system can be illustrated using the two differential equations from the model to conduct a phase diagram. We first introduce the isocline $\dot{w} = 0$. This isocline represents the combinations of wolf management (removal or supplementation) and wolf population that generate no growth over time in the wolf population. That is, the $\dot{w} = 0$ isocline is the zero-growth wolf population curve. Moreover, the $\dot{w}$ isocline is just the logistic wolf growth function when $\dot{w} = 0$.

The second isocline is $\dot{m} = 0$ and represents the combinations of management effort and wolf population that produce no change over time in the amount of management effort (removal or supplementation). As mentioned before, $\dot{m} = 0$ represents the zero-growth management effort curve. Setting $\dot{m} = 0$ to find the isocline reveals the following economic equilibrium condition:

$$\delta = f_w + \frac{B_w - D_w}{C_m} \tag{10}$$

where the rate of return for both outside investment and investment in the wolves must be equal. In other words, the marginal net benefits in relation to management costs along with the marginal growth rate of wolves must be equal to what would be obtained elsewhere. The shape of the zero-growth management effort curve is still ambiguous. The equilibrium level of management effort and wolf population take place when the zero-growth wolf population curve ($\dot{w} = 0$) and the zero-growth management effort curve ($\dot{m} = 0$) cross each other. In "Appendix C", we assume a previously used shape for the zero-growth management effort curve to show the possible theoretical solutions to the single and joint-state models.

3.4 Theoretical Models Multiple State Joint Management Results

We now consider the situation when the three states work together, and Eq. (9) gives the optimal management path for each state n. While each state is unique, in essence all three act the same way. The optimal management path under the joint-management problem for a given state given by Eq. (9) is similar to the optimal management path for the single state model given by Eq. (8). Therefore, the intuition provided for Eq. (8) is also similar to that of Eq. (9) with two notable differences. In

Eq. (9), the optimal management effort paths for a given state now includes influence from each of the other two states, the marginal wolf growth (f_{n,w_n}) and marginal costs (C_{mn}) for each state is now incorporated into the decision path. This suggests a spillover effect amongst the wolf management throughout the region.

These added effects follow similar tradeoffs as in the individual case but now they apply to the whole region. When wolf numbers are low in state n, the marginal costs (C_{mn}) are high, and the marginal growth is positive ($f_{n,w_n} > 0$). Moreover, in this case, marginal benefits (B_{wn}) are high compared to the marginal damages (D_{w_n}) which would cause management effort over time ($\dot{m}$) to be large, negative, and expensive for state n. However, augmentation to the population can now come from surrounding states from faster population growth or translocation. Therefore, the optimal management effort path in each state is supported by the other two, spreading some of the "costs".[1]

After a species has recovered and has been delisted, the management burden then falls mainly on the individual state. Assuming the marginal growth is now negative as populations are high, most managers are harvesting the population to maximize net benefits (while minimizing damage costs). Large wolf numbers would suggest greater damage and management costs. This would cause managers to increase harvesting rates. Realizing the actions in one state will impact the others, some of the management duties will fall outside of its borders. The joint control of individual numbers will help reduce a feeding effect from one state to another, reducing costs throughout the entire region.

As in the single state model the wolf population growth ($\dot{w}_n$) isocline is the logistic growth function when $\dot{w}_n = 0$. Setting $\dot{m}_n = 0$ to find the isocline reveals the following economic equilibrium condition:

$$\delta = f_{w_I} + \frac{B^I_{w_I} - D^I_{w_I}}{C^I_{m_I}} + \frac{C^M_{m_M} g_{w_I}}{C^I_{m_I}} + \frac{C^W_{m_W} h_{w_I}}{C^I_{m_I}} \tag{11}$$

As mentioned in the single-state model section, we cannot determine the exact shape of the zero-growth wolf population curve for a given state ($\dot{m}_n = 0$). In "Appendix C", we use a previously assumed shape of the zero-growth wolf population curve for a given state to illustrate the differences between single and the joint management models.

4 Empirical Model

Since the theoretical model does not allow us to obtain all the dynamics of the single and joint state management problem, we develop a bioeconomic system dynamics model that can help illustrate the optimal management of wolves under a variety of scenarios. System dynamics is a derivative of the work developed by Forrester (1971) of MIT, in which he introduced a methodology that enables modeling systems with multiloop feedbacks (Mamkhezri et al., 2021; Sterman, 2002).

[1] This occurs under federal protection of the ESA, therefore each state is assisted in these costs externally.

The empirical model attempts to capture the complexity of connecting population dynamics of wolves to their direct economic impacts, allowing managers to optimize the net benefit of wolves. To address these interconnected relationships, we develop a complex system dynamics model. After we have calibrated the necessary values of the model, we simulated the dynamics of the model using Powersim Studio, which solves the model using a multiloop feedback approach. Under this technique, the net benefits are maximized incorporating the law of motion. Using this information, we estimate a management cost function, benefit function, and damage function which allows us to find the optimal population and harvesting ratios. We only consider measurable costs and revenues in our analysis, including agency management costs, livestock depredations, and license fee revenues. Unfortunately, due to the lack of information we are unable to include estimates of indirect costs and benefits such as improved ecosystem services, non-use value, and increased hardships. However, these can easily be added to the model as data becomes more readily available.

4.1 Methods and Data

Our empirical model incorporates three main components including the biological population dynamics, direct costs, and benefits of wolves to help understand the complex nature between management, policy, and societal benefit. We generate a baseline model using functional forms that are incorporated into a system dynamics model allowing for the interconnection of multiple variables under a number of different scenarios. Taking an agent-based approach, we calibrate the model using actual historical data from approximately the past 20 years (2000–2020). This generates a representative and accurate model of historical trends as well as allowing for future predictions. Further, since there is inherent uncertainty in the values of some variables, we use Monte Carlo simulations to create confidence intervals around the output from the model.

In particular, we assume the following functional forms in the empirical model. For the wolf population dynamics, denoted as $\dot{w}$ in the theoretical model, we assume a logistic growth function. Following standard biological theory where population numbers initially follow an exponential growth curve, they eventually reach a saturation point, or carrying capacity, in the environment. This creates an s-shaped curve as the population growth slows at higher levels due to lack of resources and intra- and interspecific competition. Therefore, instantaneous growth is dictated by an intrinsic rate of increase, incorporating complexities such births and deaths, competition, and carrying capacity. A significant impact on wolf numbers also comes from management by respective state and federal wildlife agencies through supplementation or reduction. It is this component that is of great interest as it signifies the optimal management path, $\dot{m}$. Due to their successful population growth, after the initial reintroduction of 65 animals, management of wolf numbers only comes in the form of removal in our model. The main tools for managers to reduce the population comes in the form of harvesting, permitted hunting and trapping, and wildlife agency removal.

The wolf dynamics are a key component in determining the economic benefits in the URM region. As explained in the theoretical model, both the benefits and costs are a function of wolf numbers. Benefits are simplified to the revenue created from the management of wolves through hunting and trapping permit sales. As previously mentioned, this is the main tool used to maintain population numbers but also generates a significant source of revenue to help fund management activities. Greater wolf numbers allow permit sales to increase, generating more income. We ignore the additional local economic revenue generated from tourism as it is fairly constant, not directly related to wolf numbers, and is difficult to isolate across the three states.

Costs come in the form of management agency costs and reimbursements for livestock depredations from wolves. These are also considered population dependent as larger number of wolves potentially lead to greater human-wildlife conflict leading to more damages and agency action. While agency control stays fairly constant with budgetary constraints, problem animals and packs removal are costly and variable. State funded reimbursements for livestock depredations should have a positive relationship with populations numbers, despite fluctuations in livestock prices.

Results from the theoretical model justify the need to create a number of different scenarios for the model. Generally, the optimal management paths of individual states differ from the joint scenario in two ways, management costs and wolf growth dynamics. Initially, we estimate outcomes for each state individually using historical data. We then create a joint model that approaches wolf management collaboratively across all three states. We develop three different scenarios where we assume different management costs. These are then compared to the cumulative results, by simply summing the results from the individual state models.

We calibrate the model using a regression-based estimation approach to obtain reasonable inputs based on previous research and literature. The benefits functions and their coefficients are estimated via ordinary least squares using historical hunting license revenues from 2009–2017 for Montana, 2011–2019 for Idaho and 2012–2019 for Wyoming. These data were obtained from each of the state's Fish and Wildlife Services Department. Historical wolf population dynamics data and management costs are drawn from the individual state agency wolf monitoring reports [for example see (Idaho Department of Fish & Game, 2016; Montana Fish, Wildlife & Parks, 2019; Wyoming Game and Fish Department et al., 2018)].[2] We also obtain target population levels from these agency reports allowing us to reasonably estimate wolf carrying capacities for both individual and joint scenarios. In order to develop a reasonable estimate for the intrinsic growth rate of wolves, we use a variety of previous studies for different populations of gray wolves in various regions of the (Tanner, 1975; Varley & Boyce, 2006). The lack of data or previously used functional forms for management costs prevents us from estimating the management cost functions. Management cost is estimated "internally" by the state agencies in the form of a designated budget. In other words, publicly, the state agencies provide an overall budget on a yearly basis (i.e., one number per year). This caused our lack of data problem, and we were unable to back out the functional form from historical data similar to what we did with the other functional forms as these figures are sparse

[2] See also (Hoylan et al., 2011; Idaho Fish and Game, 2018, 2019, 2020; Mack et al., 2010; Montana Fish, Wildlife & Parks, 2010, 2011, 2013, 2014, 2015, 2016, 2017a, b, 2018, 2019; Nadeau et al., 2006, 2007; Wyoming Game and Fish Department et al., 2013, 2014, 2016, 2018, 2020).

in timing and nature. Thus, to make up for a lack of functional form, we discounted those costs into “low,” “medium,” and “high” by simply reducing the overall join management costs by 10% per state each time. Table 2 of “Appendix D” summarizes the main calibrated variables used in our system dynamics model.

4.1.1 Simulation Results for Individual States

The system dynamics model allows us to compare multiple scenarios across all states under the two types of management structures. Figure 2 shows the individual states modeled outcomes for number of wolves and harvesting levels using historical data through 2020. We then extend the model into the future in order to find a stabilized equilibrium for maximized net benefits, number of wolves, and harvesting levels. The level of wolves removed from the system (harvesting rate), either by hunting or government actions, can be considered the management path that controls the wolf population and balances the costs and benefits gained from wolves.

Results from the model indicate that a stable equilibrium has been or potentially can be reached for each state. While there are a number of steady states for population numbers the difference here is that our model indicates a relative steady state that agency managers can use as a guideline in order to maximize societal net benefits. We find that an optimal number of wolves, $\dot{w}^*$, for Idaho, Montana, a Wyoming is approximately 957, 787, and 226 respectively. These estimates reflect the current ratio of wolf populations but are indeed different than current estimates of the number of wolves for each state. It is important to note that the Wyoming wolf estimate is only for the Wolf Trophy Management Area and not the entire state. Areas outside of this region do not usually require a permit to kill wolves often considering them to be a pest species. We also estimate the corresponding management level, $\dot{m}^*$, for Idaho, Montana, and Wyoming at 303, 228, and 75 wolves, respectively. This is the level of harvest required to optimize net benefits.

Figure 3 shows how the net benefits from wolves has progressed over time and where it stabilizes as the population and management of wolf equalizes. Except in the case of Idaho, it is clear that the benefits are actually negative. It is important to remember however, that we have chosen to disregard the $34 million of economic revenue for the surrounding area generated from wolf tourism activities which greatly exceeds all management costs. We are more interested in optimizing the management cost and benefits that are in the control of the managers. Additionally, focus should be on the portions of the graphs that correspond to when the states actually took over managing wolves. For Idaho and Montana this is in 2009, where there is a large increase in benefits for Montana as hunting is opened up and revenue is generated through license sales. This drops off during the yearlong hunting ban across the region in 2010. After this period, Idaho shows a large increase as wolf hunting is reinstated. As discussed earlier, Wyoming is a special case as wolves have gone in and out of protection until 2017. Further, hunting permit revenue tends to be smaller than the other two states as the population of wolves and the areas requiring permits is small.

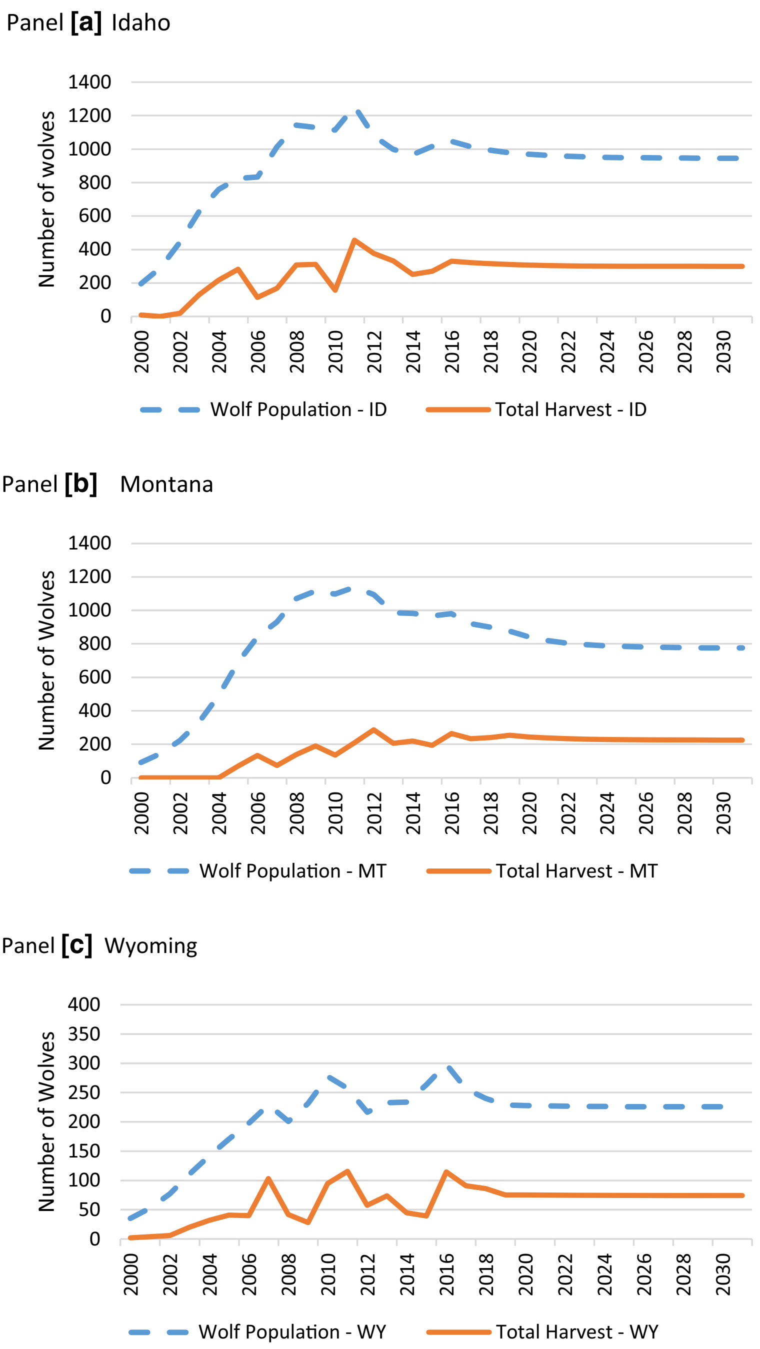

Fig. 2 Wolf populations and harvesting paths

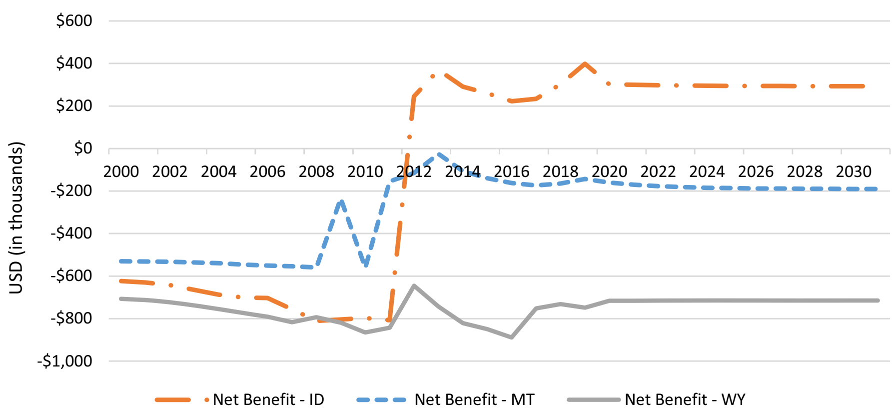

Fig. 3 Net benefits for individual states

4.1.2 Simulation Results for Joint Management

As previously discussed in the theoretical section, overall management costs were one possible difference between individual state and cooperative management strategies. The idea of creating one agency responsible for wolf management for the three states could potentially reduce redundancy and allow the URM area to be managed much more efficiently. To illustrate this, we assess three different scenarios for management costs: low, medium, and high. The high scenario replicates the actual cumulative costs incurred when states work independently as calculated from historical data. We then assume the economic efficiencies of a ten percent reduction in management costs from one scenario to the next and input these into the model. Figure 4 shows how the net benefit for the region changes under each scenario. As expected, the cumulative and high management cost scenario net benefits are approximately the same. Reducing overall management costs understandably results

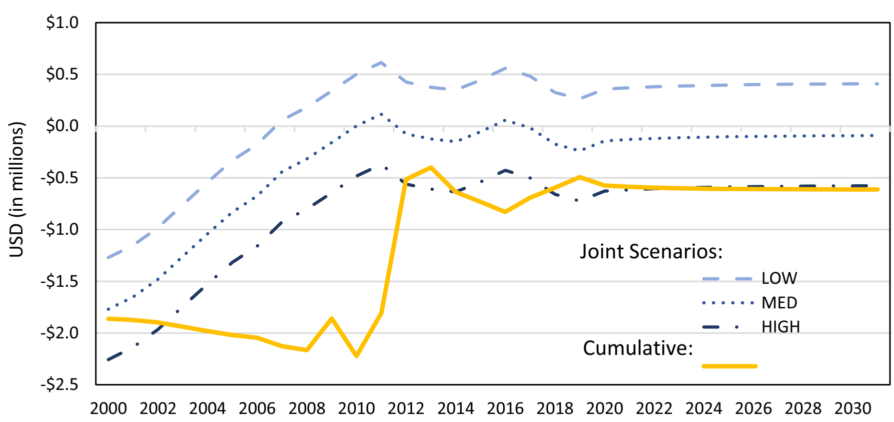

Fig. 4 Net benefit of joint wolf management under different scenarios and when states act independently

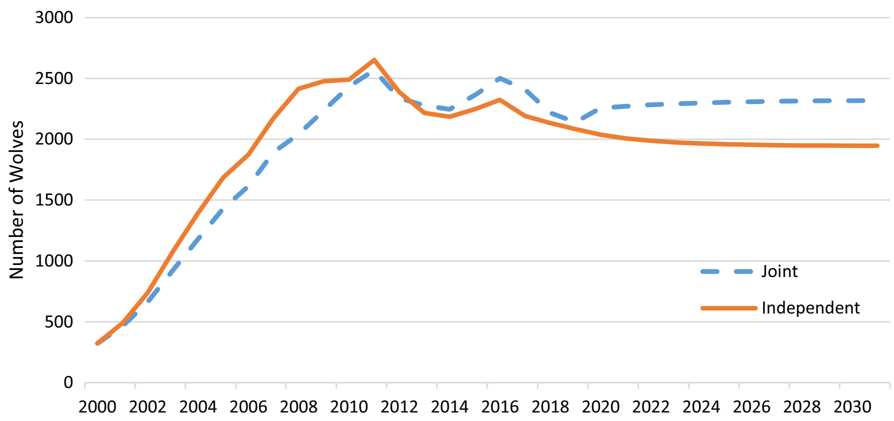

Fig. 5 Wolf populations under independent and joint management

in higher benefits, with the low-cost scenario leveling off at around \$410, 000 yearly. Small reductions in management costs can lead to large increases net benefits where a ten percent decrease can boost benefits by one hundred percent.

In addition to greater economic returns, the model also predicts that in the joint management scenarios that the equilibrium wolf populations are higher than when states act independently. As seen in Fig. 5, there would be approximately 400 more wolves under cooperative management. As the state boundaries arbitrarily divide the URM with respect to population dynamics, taking a wider approach to managing populations takes into account the mobility of the species throughout the region.

We utilize a Monte Carlo simulation as a sensitivity analysis, accounting for the uncertainty surrounding our results and the historical data. We created normal

Table 1 Monte Carlo results

	Mean (Confidence Interval)
Wolf population	
Idaho	947 (636–1,448)
Montana	799 (542–1,088)
Wyoming	227 (133–312)
Joint	2,277 (1,324–3,212)
Management level (harvest)	
Idaho	298 (196–418)
Montana	229 (136–290)
Wyoming	74 (46–99)
Joint	609 (377–841)
Joint management net benefit	
Low Scenario	\$385,982 (− \$698,616–\$1,680,758)
Medium Scenario	− \$111,295 (− \$1,212,767–\$1,206,725)
High Scenario	− \$596,284 (− \$1,577,554–\$803,499)

distributions for all the constant variables used in the baseline model with the mean of the original value and 10% of this value as the standard deviation. We use Monte Carlo simulations to estimate a mean and confidence interval for our variables of interest, which are the wolf population, harvesting, and net benefits estimates. Table 1 provides the estimates from the simulations. In each case the average is similar to the estimates above. However, the confidence interval around these values provide insight into how these might fluctuate.

5 Conclusions

As states get the responsibility of managing important formerly endangered species, such as the gray wolf, they must try and maximize the benefits of its presence while limiting damage and costs. Because each state has its own wildlife agency and budgets, it is likely that they often manage species without fully considering surrounding states. The ability to collaborate with neighboring states has the potential for reducing overall management levels and optimizing net benefit for the region. We develop theoretical optimal control and system dynamics bioeconomic models to illustrate the tradeoffs and problems face by managers. Given the ambiguity of the theoretical model we develop a numerical simulation to determine the steady states of number of wolves and their management and corresponding net benefits by Idaho, Montana, and Wyoming independently and jointly from 2000 to 2030.

The results in this study suggest that there could be possible positive spillover effects when states work together versus individually. By controlling the population levels of wolves in a coordinated effort, each state's cost decrease. State borders are arbitrary in the sense of wildlife, and management and policy decisions should incorporate this into their plans. The positive spillover effect of collaboration begs the question of why the states have yet to collectively manage the gray wolf problem in the URM region. There are two possible explanations: (1) high transaction cost of cooperation among the states (Coase, 2013) and (2) ignoring the environmental benefits of wolves by regulators. Transaction costs stemming from reaching an agreement and coordinating tasks amongst states' Fish, Wildlife, and Park agencies (i.e., who should do what) is a costly process, which could reduce or surpass our net benefits finding of $1 million. Secondly, states political and bureaucratic regulators in the region are driven by personal gains to get reelected, thus, focusing only on the regional costs of the wolves rather than the global environmental benefits, which in turn further hinders collaboration amongst the agencies. This is not to argue that management once again be taken from local state authority and placed into federal control, although this could be justified. It merely highlights the efficiencies gained from a unified approach.

Our findings corroborates with the literature (Johnson, 2020; Sims et al., 2020; Smith et al., 2016). For example, similar to Sims et al. (2020), our results suggest that Wyoming should take a rather conservative approach in harvesting wolves to ensure the minimum requirement set forth by the federal government, while Montana and Idaho can be more aggressive in their approach. While they suggest that trying to spread responsibilities and cost savings from delisting could reduce regional net benefits, it is also possible that cooperative management could allow for flexibility in management efforts in the URM area. Specifically, states could divide up regional management responsibilities such as genetic testing, monitoring, agency removal, and public outreach that each would have to individually provide each state when self managing. All states would approach wolf management at the URM level as opposed to the individual state and would allow for cooperative information sharing. Additionally, their suggestion of establishing a federally controlled compensation program for wolf damages could correspond similarly to our joint model scenarios.[3] They find that this reduces the incentive to keep wolf populations low suggesting higher equilibrium populations as estimated by our joint model compared to the cumulative results from independent state management.

While our results indicate there is some positive spillover effect in general, this was based on a number of assumptions that could be challenged and can potentially affect our results. Future work could relax the assumption of identical benefit, cost, and damage functions across states. Future work should also account for transaction cost of collective action policies using simulations as data for this type of cost are absent. While the logistic growth function of wolves seems suitable it could also be extended. Additionally, we assume that all states are putting forth effort to manage the wolf population. It may be possible for some states to free ride on the agreement taking advantage of other’s efforts, which we do not capture in the current work. Nevertheless, our results support that under reasonable assumptions a collaborative management effort could reduce costs. We believe that these findings provide valuable insights for conservationists, policymakers, and other stakeholders.

Appendix A: Example of Hypothetical Growth Function

In this Appendix we show a graph of a hypothetical logistic growth function with respect to the wolf population dynamics. The y-axis represents the wolf population while the x-axis represents time.

In this hypothetical logistic function example, the initial wolf population starts at W_0 with low growth rates. After a period of time the population experiences increasing growth rates, reaches maximum growth and the growth rates decrease until the population reaches the carrying capacity (Fig. 6).

[3] Sims et al. (2020) do not clarify the source of funding. However, such a federal program could be funded through tax money since hunting licenses revenue are earned and spent by the Fish and Wildlife Service department of each state.

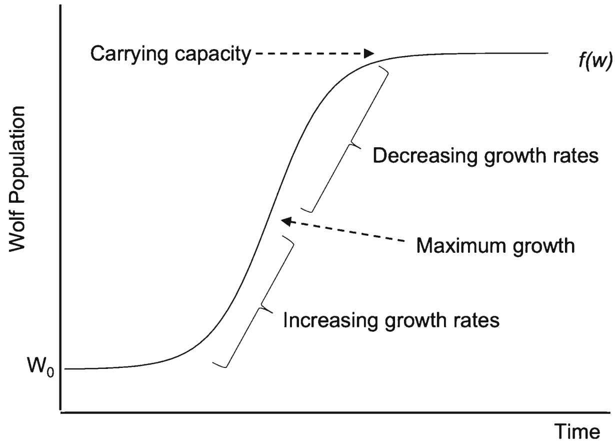

Fig. 6 Hypothetical growth function

Appendix B: Full Solution to the Joint Management Model

From Sect. 3.2 we obtain the Hamiltonian of the joint management model:

$$H = \sum_{n=1}^{N} \left[\left(B(w(t))_n - D(w(t))_n - C(m(t))_n \right) + \mu_n [f_n(w_n, \ldots, w_N) - m_n] \right]$$

Taking the first order conditions we get:

$$H_{m_n} = C_{mn} - \mu_n = 0 \quad \forall n = 1, \ldots, N \tag{12}$$

$$-H_{w_n} = \dot{\mu}_n - \delta\mu_n = -B_{w_n} + D_{wn} - \sum_{n=1}^{N} \mu_n f_{w_n} \quad \forall n = 1, \ldots, N \tag{13}$$

Taking the time derivative of Equations (A.1) we obtain the following:

$$C_{m_n m_n} \dot{m}_n = \dot{\mu}_n \rightarrow \dot{m}_n = \frac{\dot{\mu}_n}{C_{m_n m_n}} \tag{14}$$

substituting in μ_n and $\dot{\mu}_n$ into Equation (14) and rearranging gives the optimal management paths given by Eq. (6) in the text:

$$\dot{m}_n = \frac{C_{m_n}\delta - B_{wn} + D_{w_n} - \sum_{n=1}^{N} C_{mn} f_{n,w_n}}{C_{m_n m_n}} \quad \forall n = 1, \ldots, N$$

Appendix C: Phase Diagram of the Single and Joint State Management Model

In this Appendix we assume a shape of the $\dot{m} = 0$ isocline to illustrate some of the important dynamics of the single and joint state model. Rondeau (2001) shows through very similar dynamics that the shape of the $\dot{m} = 0$ isocline is two discontinuous curves, and we use for illustrations purposes.[4] Figure 7 shows the phase diagram in the population (w)-management (m) space with three potential equilibria (when $\dot{m} = 0$ and $\dot{w} = 0$ cross each other). The discontinuous isocline m represents that of the single state and m_n is that of the joint-state problem. In the joint problem the wolf population is now based on all wolves in the region, the $\dot{w} = 0$ isocline gets shifted upward and outward compared to the single state problem. As mentioned in the text, the equilibrium condition for $\dot{m} = 0$ given by Eq. (11) suggests that investment in wolves can come from surrounding states as well. Thus, it seems plausible that this spillover effect would shift the individual $\dot{m}$ isocline curves in the joint problem downward compared to the single state problem. Under these assumptions the optimal solution of the individual state management (harvesting) level would drop, from m^* to m_n^*, and theoretically costs less. This all relies on the assumption that the number of wolves is high enough that the path is heading

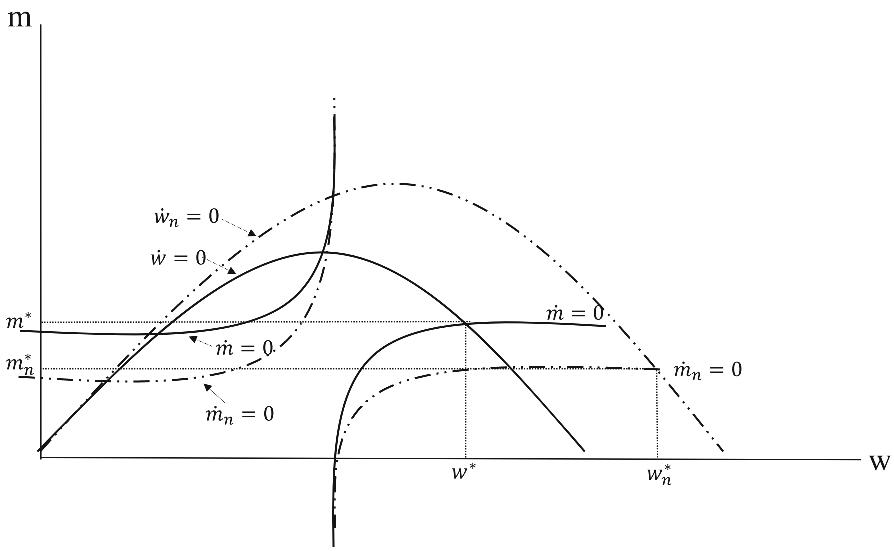

Fig. 7 Comparison of two management options. Individual management is denoted by a solid line and the joint management is in the dashed line

[4] Although Rondeau (2001) caution that these curves could potentially take on a number of different shapes giving a number of potential equilibria.

towards the furthest equilibrium. However, near the middle equilibrium it can be seen that individual management may actually increase with cooperation.

Appendix D: Empirical Model Variables and Additional Results

In Table 2 we provide all the variables that were used in the empirical model. Inputted data came from a variety of sources listed in the last column of the table and ranged from individual state monitoring reports to previous estimations in the literature. Estimated variables were generated using regression models and historical data. Finally, we make assumptions on the management levels for the three different scenarios based on the cumulative management costs of the three states over time.

Table 2 Calibrated and Estimated variables used in the empirical models

Parameter in the theoretical model	Variable in the empirical model	Definition	Unit	Value	Monte—Carlo*	Calibration Method
Population						
w_0^{ID}	INITIAL WOLVES—ID	Initial wolf population in the ID model	wolf	196 wolves	NO—fixed	Agency Reports
w_0^{MT}	INITIAL WOLVES -MT	Initial wolf population in the MT model	wolf	92 wolves	NO—fixed	Agency Reports
w_0^{WY}	INITIAL WOLVES—WY	Initial wolf population in the WY model	wolf	35 wolves	NO—fixed	Agency Reports
w_0^{joint}	INITIAL WOLVES—ID WY MT	Initial wolf population in the joint model	wolf	323 wolves	NO—fixed	Agency Reports
$f(w)_{growth}^{joint}$	Wolf Growth—ID WY MT	Intrinsic wolf population growth rate in the joint model	%/yr	Function**	YES	Literature
$f(w)_{growth}^{ID}$	Wolf Growth—ID	Intrinsic wolf population growth rate in the ID model	%/yr	Function**	YES	Literature
$f(w)_{growth}^{MT}$	Wolf Growth—MT	Intrinsic wolf population growth rate in the MT model	%/yr	Function**	YES	Literature
$f(w)_{growth}^{MT}$	Wolf Growth—WY	Intrinsic wolf population growth rate in the WY model	%/yr	Function**	YES	Literature
$f(w)_{joint}^{cc}$	Carrying Capacity- ID WY MT	Carrying Capacity for the joint model	wolf	5,000 wolves	YES	Agency Reports
$f(w)_{ID}^{cc}$	Carrying Capacity- ID	Carrying Capacity for the ID model	wolf	1,500 wolves	YES	Agency Reports
$f(w)_{MT}^{cc}$	Carrying Capacity MT	Carrying Capacity for the MT model	wolf	1,500 wolves	YES	Agency Reports
$f(w)_{WY}^{cc}$	Carrying Capacity- WY	Carrying Capacity for the WY model	wolf	500 wolves	YES	Agency Reports

Table 2 continued

Parameter in the theoretical model	Variable in the empirical model	Definition	Unit	Value	Monte—Carlo*	Calibration Method
Management						
$m(t)^{joint}$	harvest—ID WY MT	Harvesting function in the joint model	wolf/yr	Function***	YES	Estimated
$m(t)^{ID}$	harvest—ID	Harvesting function in the ID model	wolf/yr	Function***	YES	Estimated
$m(t)^{MT}$	harvest—MT	Harvesting function in the MT model	wolf/yr	Function***	YES	Estimated
$m(t)^{WY}$	harvest—WY	Harvesting function in the WY model	wolf/yr	Function***	YES	Estimated
Economic benefit						
$C(m(t))_{joint}^{low}$	LOW M	Low management cost scenario	USD	$\alpha \times m^{1+\beta} = \$750,000$ $\forall\alpha > 0\&\beta > 0$	YES	Assumed
$C(m(t))_{joint}^{Medium}$	MEDIUM M	Medium management cost scenario	USD	$\alpha \times m^{1+\beta} = \$1,250,000$ $\forall\alpha > 0\&\beta > 0$	YES	Assumed
$C(m(t))_{joint}^{High}$	HIGH M	High management cost scenario	USD	$1,734,989.3****	YES	Assumed
$C(m(t))_{Joint}$	management cost sce—ID WY MT	Management cost function in the joint model	USD	$Low; Medium; High$	YES	Estimated
$C(m(t))_{ID}$	management cost—ID	Management cost function in the ID model	USD	$\$600,000$	YES	Estimated
$C(m(t))_{MT}$	management cost—MT	Management cost function in the MT model	USD	$\$500,000$	YES	Estimated
$C(m(t))_{WY}$	management cost—WY	Management cost function in the WY model	USD	$\$634,989.3$	YES	Estimated
$B(w(t))_{joint}$	benefit fcnt—joint	Benefit function in the joint model	USD	$924.12w(t) - 485158$	YES	Estimated
$B(w(t))_{ID}$	benefit fcnt—ID	Benefit function in the ID model	USD	$693.75w(t) + 371056$	YES	Estimated
$B(w(t))_{MT}$	benefit fcnt	Benefit function in the MT model	USD	$500w(t) - 29589$	YES	Estimated
$B(w(t))_{WY}$	benefit fcnt—WY	Benefit function in the WY model	USD	$287.48w(t) + 34544$	YES	Estimated

Table 2 continued

Parameter in the theoretical model	Variable in the empirical model	Definition	Unit	Value	Monte—Carlo*	Calibration Method
$D(w(t))_{joint}$	damage fnct—joint	Damage function in the joint model	USD	$313196e^{.0002w(t)}$	YES	Estimated
$D(w(t))_{ID}$	damage fnct—ID	Damage function in the ID model	USD	$15199e^{.0032w(t)}$	YES	Estimated
$D(w(t))_{MT}$	damage fnct	Damage function in the MT model	USD	$28076e^{.0007w(t)}$	YES	Estimated
$D(w(t))_{WY}$	damage fnct—WY	Damage function in the WY model	USD	$60627e^{.0048w(t)}$	YES	Estimated
$NB(w)_{Joint}$	NB- Joint	Net benefit function in the joint model	USD	Function*****	YES	Estimated
$NB(w)_{ID}$	NB- ID	Net benefit function in the ID model	USD	Function*****	YES	Estimated
$NB(w)_{MT}$	NB-MT	Net benefit function in the MT model	USD	Function*****	YES	Estimated
$NB(w)_{WY}$	NB—WY	Net benefit function in the WY model	USD	Function*****	YES	Estimated

*"Yes" indicates that the variable had a normal distribution with the mean of the original value and 10% of that as the standard deviation, while "No-fixed" indicates the variable was used in the Monte-Carlo simulation but was assumed to be fixed at the original value. We created normal distributions for every constant variable existed in the baseline model

**$GrowthRate_i \times w(t)_i \times \left(1 - \frac{w(t)_i}{f(w)_i^{cc}}\right) - f(w)_i^{cc}$ is carrying capacity for state i

*** $If w(t-1)_i < federalrequirement$, 0 wolf, otherwise $w(t)_i \times harvestingrate$—where arvesting rate includes both hunting rate and lethal control rate

****The *High* management cost scenario is the summation of the average management costs of the three states obtained from reporting from state agencies.

*****$NB(w)_i = B(w(t))_i - D(w(t))_i - C(m(t))_i$

Funding The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interest to disclose.

References

Bednar-Friedl, B., Behrens, D., & Getzner, M. (2012). Optimal dynamic control of visitors and endangered species in a national park. *Environmental and Resource Economics, 52*(1), 22.

Beyer, H. L., Merrill, E. H., Varley, N., & Boyce, M. S. (2007). Willow on Yellowstone's northern range: Evidence for a trophic cascade? *Ecological Applications, 17*(6), 1563–1571. https://doi.org/10.1890/06-1254.1

Bodine, E., Gross, L., & Lenhart, S. (2008). Optimal control applied to a model for species augmentation. *Mathematical Biosciences and Engineering, 5*(4), 669–680. https://doi.org/10.3934/mbe.2008.5.669

Boyce, M. S. (2018). Wolves for Yellowstone: Dynamics in time and space. *Journal of Mammalogy, 99*(5), 1021–1031. https://doi.org/10.1093/jmammal/gyy115

Bradley, L., Gude, N., Lance, N., Laudon, K., Messer, A., Nelson, A., Pauley, K., Podruzny, K., Smucker, T., & Steuber, J. (2014). *Montana gray wolf conservation management: 2013 Annual Report* (p. 54). Montana Fish, Wildlife & Parks.

Chambers, C. M., & Whitehead, J. C. (2003). A contingent valuation estimate of the benefits of wolves in Minnesota. *Environmental and Resource Economics, 26*(2), 249–267.

Coase, R. H. (2013). The problem of social cost. *The Journal of Law and Economics, 56*(4), 837–877.

Duffield, J., & Neher, C. (1996). Economics of Wolf Recovery in Yellowstone National Park. *Transactions of the 61st North American Wildlife and Natural Resources Conference*, 285–292.

Duffield, J. W., Neher, C. J., & Patterson, D. A. (2008). Wolf recovery in Yellowstone: Park visitor attitudes, expenditures, and economic impacts. *The George Wright Forum*, *25*(1), 13–19. https://www.jstor.org/stable/43598061

Finnoff, D., & Tshirhart, J. (2002). *Protecting an endangered species while harvesting its prey in a general equilibrium ecosystem model*. http://www.uwyo.edu/tschirhart/land_9-03.pdf

Forrester, J. W. (1971). Counterintuitive behavior of social systems. *Theory and Decision, 2*(2), 109–140. https://doi.org/10.1007/BF00148991

Hoylan, J, Holder, K., Cronce, J., & Mack, C. (2011). *Wolf conservation and management in Idaho progress report 2010* (p. 90). Idaho Department of Fish and Game, Nez Perce Tribe.

Idaho Department of Fish and Game. (2016). *2015 Idaho Wolf Monitoring Progress Report* (p. 81). Idaho Department of Fish and Game.

Idaho Fish and Game. (2018). *2017 Director's Annual Report to the Commission*.

Idaho Fish and Game. (2019). *2018 Director's Annual Report to the Commission*.

Idaho Fish and Game. (2020). *2019 Director's Annual Report to the Commission*.

International Wolf Center. (2019). *Gray Wolf Timeline for the Contiguous United States*. 8/22/2018. https://wolf.org/gray-wolf-timeline/

Johnson, J. (2020). Grizzly bear restoration and economic restructuring in the Greater Yellowstone Ecosystem. *Parks Stewardship Forum*. https://doi.org/10.5070/P536349867

Mack, C., Rachael, J., Hoylan, J., Husseman, J., Lucid, M., & Thomas, B. (2010). *Wolf conservation and management in Idaho progress report 2009* (p. 67). Idaho Department of Fish and Game, Nez Perce Tribe.

Mamkhezri, J., Malczynski, L. A., & Chermak, J. M. (2021). Assessing the economic and environmental impacts of alternative renewable portfolio standards: Winners and losers. *Energies, 14*(11), 3319. https://doi.org/10.3390/en14113319

Mech, L. D. (1999). Estimated costs of maintaining a recovered wolf population in agricultural regions of Minnesota. *Wildlife Society Bulletin, 26*(4), 817–822.
Mech, L. D., & Fieberg, J. (2015). Growth rates and variances of unexploited wolf populations in dynamic equilibria: Unexploited Wolf Populations. *Wildlife Society Bulletin, 39*(1), 41–48. https://doi.org/10.1002/wsb.511
Montana Fish, Wildlife & Parks. (2010). *2009 Montana Wolf Hunting Season Report* (p. 2).
Montana Fish, Wildlife & Parks. (2011). *Montana gray wolf conservation and management 2010 annual report* (p. 168).
Montana Fish, Wildlife & Parks. (2013). *2012 Montana wolf hunting season report* (p. 2).
Montana Fish, Wildlife & Parks. (2014). *2013 Montana Wolf Hunting Season Report* (p. 2).
Montana Fish, Wildlife & Parks. (2015). *2014 Montana wolf hunting season report* (p. 2).
Montana Fish, Wildlife & Parks. (2016). *2015 Montana wolf hunting season report* (p. 2).
Montana Fish, Wildlife & Parks. (2017a). *2016 Montana wolf hunting season report* (p. 2).
Montana Fish, Wildlife & Parks. (2017b). *Montana gray wolf conservation and management 2016 annual report* (p. 71).
Montana Fish, Wildlife & Parks. (2018). *2017 Montana wolf hunting season report* (p. 2).
Montana Fish, Wildlife & Parks. (2019). *Montana gray wolf conservation and management 2018 annual report* (p. 77).
Nadeau, M. S., Mack, C., Hoylan, J., Husseman, J., Lucid, M., & Thomas, B. (2006). *Wolf conservation and management in Idaho progress report 2005* (p. 61). Idaho Department of Fish and Game, Nez Perce Tribe.
Nadeau, M. S., Mack, C., Hoylan, J., Husseman, J., Lucid, M., Thomas, B., & Frame, P. (2007). *Wolf conservation and management in Idaho progress report 2006* (p. 73). Idaho Department of Fish and Game, Nez Perce Tribe.
National Park Service. (2018). *Wolf Restoration*. https://www.nps.gov/yell/learn/nature/wolf-restoration.htm
Naughton-Treves, L., Grossberg, R., & Treves, A. (2003). Paying for tolerance: rural citizens' attitudes toward wolf depredation and compensation. *Conservation Biology, 17*(6), 1500–1511.
Ostrom, E. (2003). How types of goods and property rights jointly affect collective action. *Journal of Theoretical Politics, 15*(3), 239–270. https://doi.org/10.1177/0951692803015003002
Rayamajhee, V., & Paniagua, P. (2021). The Ostroms and the contestable nature of goods: Beyond taxonomies and toward institutional polycentricity. *Journal of Institutional Economics, 17*(1), 71–89. https://doi.org/10.1017/S1744137420000338
Richardson, L., & Loomis, J. (2009). The total economic value of threatened, endangered and rare species: An updated meta-analysis. *Ecological Economics, 68*(5), 1535–1548. https://doi.org/10.1016/j.ecolecon.2008.10.016
Rondeau, D. (1998). *The dynamics of reintroducing, supplementing and controlling endangered predator species* [Paper]. American Association of Agricultural Economics, Salt Lake City, Utah. http://ageconsearch.umn.edu/bitstream/20812/1/sprond01.pdf
Rondeau, D. (2001). Along the way back from the brink. *Journal of Environmental Economics and Management, 42*(2), 156–182.
Sims, C., Aadland, D., Finnoff, D., & Hochard, J. (2020). What are the benefits of delisting endangered species and who receives them?: Lessons from the gray wolf recovery in Greater Yellowstone. *Ecological Economics, 174*, 106656. https://doi.org/10.1016/j.ecolecon.2020.106656
Smith, D., & Bangs, E. (2009). Reintroduction of wolves to yellowstone national park: hIstory, values and ecosytem restoration. In M. Hayward & M. Somers (Eds.), *Reintroduction of top-order predators* (pp. 92–125). John Wiley & Sons. http://books.google.com/books?hl=en&lr=&id=zv_l3a8RwywC&oi=fnd&pg=PR7&dq=%22Matt+W..+Reintroduction+of+Top-Order+Predators.+Hoboken,+NJ,+USA:+Wiley-Blackwell,+2009.+ProQuest+ebrary.+Web.+21+October%22+%22Matt+W..+Reintroduction+of+Top-Order+Predators.+Hoboken,+NJ,+USA:+Wiley-Blackwell,+2009.+ProQuest+ebrary.+Web.+21+October%22+&ots=Gl3mYr6z1V&sig=1ILdTh7iBIAy2spSznif_gIIGp4
Smith, D. W., White, P. J., Stahler, D. R., Wydeven, A., & Hallac, D. E. (2016). Managing wolves in the Yellowstone area: Balancing goals across jurisdictional boundaries. *Wildlife Society Bulletin, 40*(3), 436–445. https://doi.org/10.1002/wsb.677
Sterman, J. (2002). *System dynamics: systems thinking and modeling for a complex world* [working paper]. Massachusetts Institute of Technology. Engineering Systems Division. https://dspace.mit.edu/handle/1721.1/102741

Tanner, J. T. (1975). The stability and the intrinsic growth rates of prey and predator populations. *Ecology, 56*(4), 855–867. https://doi.org/10.2307/1936296

U.S. Fish and Wildlife Service. (1987). *Northern Rocky mountain wolf recovery plan.* U.S. Fish and Wildlife Service, Denver, Colorado.

Varley, N., & Boyce, M. S. (2006). Adaptive management for reintroductions: Updating a wolf recovery model for Yellowstone National Park. *Ecological Modelling, 193*(3–4), 315–339. https://doi.org/10.1016/j.ecolmodel.2005.09.001

Wyoming Game and Fish Department, U.S. Fish and Wildlife Service, National Park Service, USDA-APHIS-Wildlife Services, & Eastern Shoshone and Northern Arapahoe Tribal Fish and Game Department. (2013). *2012 Wyoming gray wolf population monitoring and management annual report* (p. 38).

Wyoming Game and Fish Department, U.S. Fish and Wildlife Service, National Park Service, USDA-APHIS-Wildlife Services, & Eastern Shoshone and Northern Arapahoe Tribal Fish and Game Department. (2014). *2013 Wyoming gray wolf population monitoring and management annual report* (p. 43).

Wyoming Game and Fish Department, U.S. Fish and Wildlife Service, National Park Service, USDA-APHIS-Wildlife Services, & Eastern Shoshone and Northern Arapahoe Tribal Fish and Game Department. (2016). *Wyoming wolf recovery 2016 annual report* (p. 18).

Wyoming Game and Fish Department, U.S. Fish and Wildlife Service, National Park Service, USDA-APHIS-Wildlife Services, & Eastern Shoshone and Northern Arapahoe Tribal Fish and Game Department. (2018). *Wyoming gray wolf monitoring and management 2017 annual report* (p. 32).

Wyoming Game and Fish Department, U.S. Fish and Wildlife Service, National Park Service, USDA-APHIS-Wildlife Services, & Eastern Shoshone and Northern Arapahoe Tribal Fish and Game Department. (2020). *Wyoming gray wolf monitoring and management 2019 annual report* (p. 36).