DRAFT - Do Not Quote Without Authors' Permission

Bioeconomic Grizzly Bear Management

A.J. Enriquez[a,*], D.C. Finnoff[a]

[a]*Department of Economics, College of Business, University of Wyoming*
1000 E. University Ave., Laramie, WY 82071, United States

Abstract

Grizzly bears are managed in accordance with the North American Model of Wildlife Conservation, which requires that wildlife be managed to balance tradeoffs from ecosystem services. Balancing competing ecosystem services of these animals is complicated by the legacy of past conflicts with humans, which initially led to population decline and listing under the Endangered Species Act (ESA). As grizzly bears have recovered and spread across the landscape, they have triggered a contentious, nationwide debate between alternative stakeholders on how best to manage the grizzly bears in the future. Listed or not, nuisance bears are managed by relocation or non-hunting mortality. If grizzly bears were to be delisted, we demonstrate the opportunity that exists for management agencies to capture more of the value associated with these iconic bears and to simultaneously reduce the risk of human-bear conflicts through the creation of a trophy hunting program. The key role non-hunting mortality plays in the growth and success of the species is a focal component of the analysis.

Keywords:
grizzly bears, multi-use species, linear optimal control, non-hunting mortality

---

[*] Corresponding author
Email address: `aenriqu1@uwyo.edu` (A.J. Enriquez)

Preprint submitted to BIOECON Annual Conference *May 6, 2019*

1. Introduction

Grizzly bears (*Ursus arctos horribilis*) are one of the most iconic species in the Greater Yellowstone Ecosystem (GYE) of North America, and they have become symbols of the wildness of the American West. Grizzly bears are large charismatic predators that are physically powerful, play a key role in ecosystem regulation, cause damage to humans and economic activity, and inspire both awe and fear. The predators evoke strong positive and negative emotions in people. For example, they are the species in Yellowstone National Park (YNP) that evoke the most emotion in park visitors (Bjornlie et al., 2017).

Grizzly bears are managed in accordance with the North American Model of Wildlife Conservation, which requires that wildlife be managed to balance tradeoffs from ecosystem services (Organ et al., 2012). Balancing competing ecosystem services of these animals is complicated by the legacy of past conflicts with humans, which initially led to population decline and listing under the Endangered Species Act (ESA). As grizzly bears have recovered and spread across the landscape, they have twice been delisted from the ESA. This has triggered a contentious, nationwide debate between alternative stakeholders on how best to manage the grizzly bears in the future. Listed or not, nuisance bears are managed by relocation or non-hunting mortality. If grizzly bears were to be delisted for a third time, an opportunity exists for state agencies to capture more of the value associated with the bears and to simultaneously reduce the risk of human-bear conflicts through the creation of trophy hunting programs.

The fierce recent battle over grizzly bear management traces back to 1975, when grizzly bears were first listed as a threatened species under the ESA. Around that time, the population estimate of GYE grizzly bears was thought to be around 136 bears. After the ESA listing, state and federal agencies engaged in recovery efforts to try to recover the population. Many steps were taken: grizzly bear hunting was halted, a grizzly bear recovery area was established, and the Interagency Grizzly Bear Study Team (IGBST) and Committee were established. The IGBST conducts research and monitoring and encourages cooperation between wildlife managers in recovery areas (National Park Service, 2018). In 2005, after recovery goals had been met for several years, the U.S. Fish & Wildlife Service (USFWS) proposed both establishing GYE grizzly bears as a distinct population segment (DPS) and removing the GYE grizzly bear DPS as a threatened species under the

ESA. In 2007, GYE grizzly bears were officially delisted from the ESA. Lawsuits followed, and the delisting decision was overturned by a federal judge in 2009. Two primary reasons led to the reversal: first, the District Court of Montana ruled that the USFWS had inadequately evaluated the whitebark pine threat, and second, the District Court ruled that the USFWS had called for inadequate regulatory mechanisms. The USFWS appealed the decision in 2010, but, an appeals court ruled in 2011 that grizzly bears should keep their threatened status (U.S. Fish and Wildlife Service, 2016; National Park Service, 2018).

In 2013, after the USFWS found no evidence that the decline of whitebark pines had negatively impacted the GYE grizzly bear population, grizzly bears were once again recommended for removal from ESA protections (U.S. Fish and Wildlife Service, 2016; National Park Service, 2018). The USFWS reremoved the GYE grizzly bear DPS as a threatened species in 2017. At the time of the second delisting, it was estimated that there were over 700 grizzly bears within the GYE (National Park Service, 2018). Delisting opened the door for Idaho, Montana, and Wyoming to establish grizzly bear hunts within their state management plans (U.S. Fish and Wildlife Service, 2016). While Montana decided to refrain from attempting to establish a hunt in the fall of 2018, Idaho and Wyoming planned for hunting seasons (National Park Service, 2018). Wyoming set a quota of 12 grizzly bears within the demographic monitoring area and a quota of up to 12 more in non-suitable grizzly bear habitat (Peterson, 2018; Wyoming Game & Fish Department, 2018). This outraged animal advocates, some of which formed the "Shoot 'Em With A Camera, Not A Gun" campaign. As part of the campaign, citizens against the hunting of grizzly bears entered the Wyoming grizzly bear lottery in the hopes of drawing a grizzly bear tag. Members of the campaign agreed that, if they were to draw a tag, they would help each other pay the full license fee, and then during the season they would go out and take pictures of grizzly bears rather than use the license to hunt a grizzly bear (Wilkinson, 2018). The grizzly bears' delisted status did not last long, however, as a U.S. District Judge reinstated ESA protections in 2018. This forced Wyoming and Idaho to cancel their proposed hunts (National Park Service, 2018). To retaliate against this ruling, Wyoming Governor Mark Gordon signed Senate Bill 93 in February of 2019. Part of the bill gives the Wyoming Game and Fish Commission the authority to issue a grizzly bear hunt (Kudelska, 2019).

Clearly, there has been a long and complicated history of endangered species litigation surrounding grizzly bears. The species induce strong emotions in a variety of different types of wildlife "users," many of which value the species in contrasting ways. On one hand, users such as tourists, outdoor enthusiasts, and hunters may value seeing live grizzly bears. On the other hand, people from these groups occasionally find themselves in dangerous situations that result in either human or grizzly bear injuries or deaths. Meanwhile, ranchers occasionally suffer damages from grizzly bear-livestock depredation incidents. If these incidents are severe enough, state wildlife agencies make management removals of grizzly bears.

Just as the grizzly bear population has been rising over time, so too has the number of non-hunting grizzly bear mortalities. Non-hunting mortality can be split into three types of mortality: human-caused, natural, and unknown. The human-caused category, which includes self-defense kills and management removals, largely drives total non-hunting mortality. We show that there is a clear relationship between grizzly bear population size and non-hunting mortality: as the population size increases, so too does non-hunting mortality. Two functional form specifications are tested: first, one in which each additional grizzly bear increases non-hunting mortality by the same amount (a linear specification); second, one in which an additional grizzly bear increases non-hunting mortality by more at higher population sizes (a convex specification). A convex specification is a better fit. The relationship between population and non-hunting mortality implies that even in a state of the world without grizzly bear hunts, humans remove a higher number of grizzly bears from the grizzly bear population when the population is higher. This complicates grizzly bear management.

A bioeconomic framework is established in which a representative state wildlife agency manages the grizzly bear population according to the North American Model of Wildlife Conservation by maximizing net social benefits. Bioeconomic management suggests that the grizzly bears be managed as a natural asset that provides returns to society. The method yields a natural asset equilibrium condition that provides a conserve or exploit (invest or spend) rule such that the rate of return to society from maintaining a certain population of grizzly bears just balances what an alternative investment might earn. The grizzly bear stock in a state of nature as is (e.g., without hunting) is compared to level of stock to that in which hunting is allowed. Accounting for the relationship between increased grizzly bear population and increased total grizzly bear mortality significantly affects the outcomes, which implies that mortality is a key factor that an agency should take into account when determining optimal grizzly bear management.

2. Background

The USFWS currently has three demographic recovery criteria in place that it uses to evaluate grizzly bear recovery efforts. The first criterion is that there should be at least 500 grizzly bears and at least 48 female grizzly bear with cubs in the demographic monitoring area. This criterion ensures the genetic health of the population. If the criterion is ever unmet for three years in a row, then the criterion is failed. The second criterion is that female grizzly bears with young should always occupy at least 16 of the 18 bear management units within the primary conservation area and that no two adjacent bear management units should ever be unoccupied. This criterion ensures that females do not become concentrated in any one location. The third criterion is that the population should be maintained around its 2002-2014 average of 674 grizzly bears; this is achieved through proper annual mortality limits. If mortality limits are ever exceeded for three years in a row and the population falls below 612 grizzly bears, then the IGBST will be tasked with coming up with a management response. If the population ever falls below 600 grizzly bears, then this criterion will be failed, and the only mortality allowed will be that necessary to ensure human safety (U.S. Fish and Wildlife Service, 2016).

2.1. Grizzly Bear Growth

The IGBST provides annual population estimates of grizzly bears using a model-averaged Chao2 method (van Manen et al., 2018; U.S. Fish and Wildlife Service, 2016). The underlying goal of the method is to use grizzly bear observation frequencies to estimate numbers of unobserved grizzly bears. Prior to using the Chao2 method, researchers used estimates of unique females with cubs of the year (Fcoy) to estimate relative population size. There were significant problems with using these estimates make the population size estimates, including higher sampling effort across time, the combination of both standardized and non-standardized estimates, and shifting grizzly bear range. The Chao2 method attempts to solve some of these problems. Estimates are still based around frequencies of Fcoy, but Fcoy seen once a season and Fcoy seen twice a season are differentiated to better estimate unobserved individuals. The method is by no means perfect, as estimates are still sensitive to changes in sighting probability and effort (Doak and Cutler, 2014).

The IGBST itself is aware of the shortcomings of the method, but, to date, the method remains the best available science (Doak and Cutler, 2014; U.S. Fish and Wildlife Service, 2016).

Doak and Cutler (2014) report that, because grizzly bears do not reproduce every year, the number of Fcoy in a given year represents about 30% of the total number of adult females. Eberhardt and Knight (1996) report that 27.4% of the grizzly bear population is made up of adult females. The two rates are used to construct a conversion factor, Δ, that allows us to convert Chao2 estimates of Fcoy into total population estimates:

$$\frac{\text{Fcoy}}{\Delta} = \text{total population}, \tag{1}$$

in which

$$\Delta = \frac{\text{Fcoy}}{\text{all females}} \cdot \frac{\text{all females}}{\text{total population}} = (0.30) \cdot (0.274) = 0.09042.$$

Figure 1 shows the total GYE grizzly bear population has been increasing over time since 1983. Our population estimates indicate that the population has been greater than 500 grizzly bears since 2006, which implies that the first of the demographic recovery criteria has been satisfied since then.

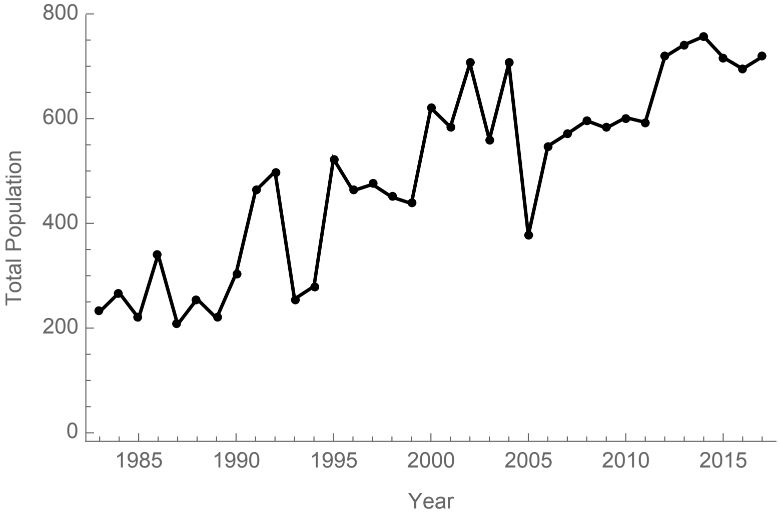


Figure 1: The GYE total grizzly bear population over time.

Our population estimates are used to estimate a simple logistic growth function

$$F(G(t)) = rG(t)\left(1 - \frac{G(t)}{K}\right), \tag{2}$$

in which F is growth, $G(t)$ is the grizzly bear population size at time t, r is the intrinsic growth rate, and K is the carrying capacity. Solving the differential equation yields

$$G(t) = \frac{G_0 K e^{rt}}{G_0(e^{rt} - 1) + K}, \tag{3}$$

in which G_0 is the initial grizzly bear population size. Equation (3) is used to numerically fit r and K by minimizing the sum of squared errors (SSE) between observed and predicted grizzly bear population estimates. In Section 3, these parameters are utilized in Model S, a simple bieoconomic model which does not explicitly account for non-hunting mortality. Figure 2 shows the parameterized logistic function overlaid with the observed grizzly bear population estimates.

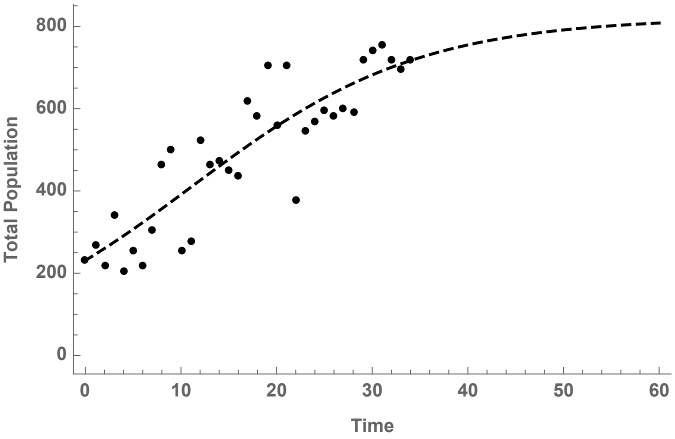


Figure 2: GYE grizzly bear mortality over time, by type.

2.2. Grizzly Bear Mortality

As stressed in the third demographic recovery criterion, mortality is a key part of the story. Annual grizzly bear mortality estimates are available both in the IGBST annual reports and from USGS.gov. The structure of mortality is shown in Figure 3. As discussed in Section 1, non-hunting mortality is

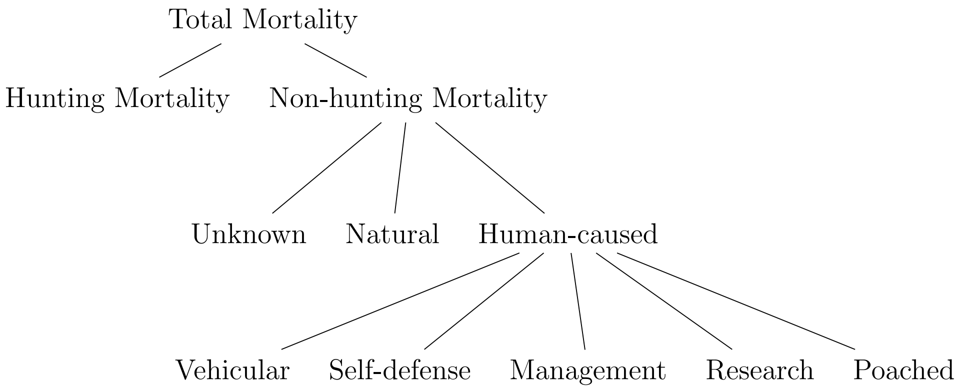


Figure 3: GYE grizzly bear mortality types.

split into three main types: human-caused, natural, and unknown. Figure 4 shows how the counts of these three types of mortalities have been increasing over time. Human-caused mortality can be further split into multiple categories. These include management kills, self-defense kills, hunter-mistake kills, vehicular kills, research and handling kills, and malicious kills. The main drivers of human-caused mortality are management and self-defense kills. Both of these types of human-caused mortality have been increasing over time, as shown in Figure 5.

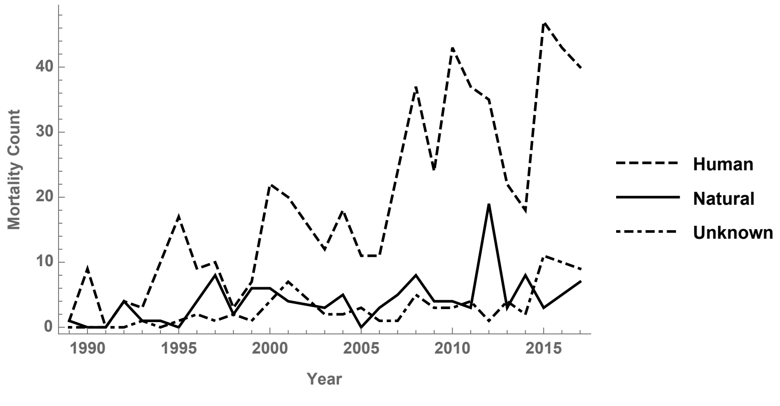


Figure 4: GYE grizzly bear mortality over time, by type.

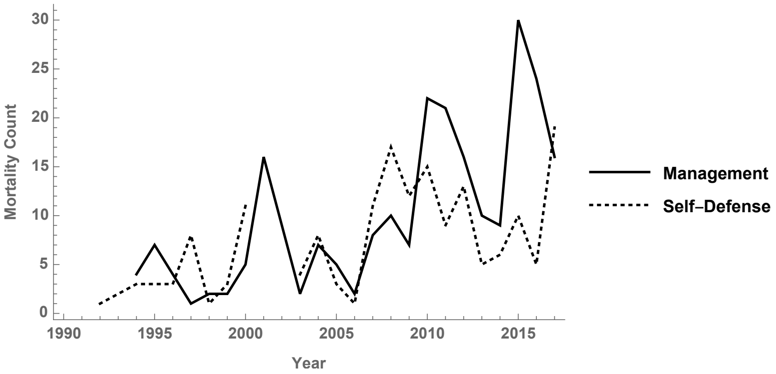


Figure 5: Number of management and self-defense kills of GYE grizzly bears, over time.

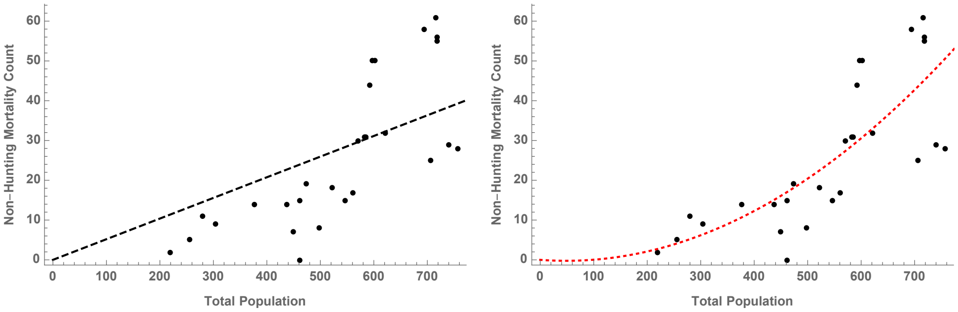
The relationship between population size and non-hunting mortality, M, is shown in the scatterplots in Figure 6. As population size increases, so too does the count of non-hunting mortalities. A linear trendline is fit to the data in Figure 6a, with equation

$$M(G) = m_1 G, \tag{4}$$

in which m_1 is a parameter that minimizes the SSE between observed and predicted non-hunting mortality estimates. Figure 6b presents a fitted convex trendline with equation

$$M(G) = m_1 G + m_2 G^2, \tag{5}$$

in which m_1 and m_2 are parameters that minimize the SSE between observed and predicted non-hunting mortality estimates. Parameter estimates are given in Table 1. The SSE is lower for the convex specification than for the linear specification.



(a) (b)

Figure 6: Relationship between grizzly bear total population size and non-hunting mortality with: (a) linear trendline, (b) convex trendline.

Parameter	**Linear**	**Convex**
m_1	0.051897	-0.009775
m_2	0	0.000101
SSE	4,961.832	3,724.752

Table 1: Parameter estimates and fit of mortality trendlines.

Of course, there any many other factors than just grizzley bear density that likely affect grizzly bear mortality. For example, in years with a higher number of tourists to Yellowstone and Grand Teton National Parks, there could be a greater number of grizzly bear-human conflicts. A higher number of grizzly bear-human conflicts in turn often leads to a higher number of grizzly bear mortalities. We constructed a visitation ($VISIT$) variable based on National Park Service visitation statistics for the two national parks.[1] Annual visitation is given in Figure 7.

---

[1] Visitor use statistics were obtained from `https://irma.nps.gov/Stats/`. The site has data on annual park recreation visitation for the years 1989 and up for both Yellowstone and Grand Teton National Parks. the number of recreation visitors from the two parks were summed to obtain total visitation to the parks in the Greater Yellowstone Ecosystem.

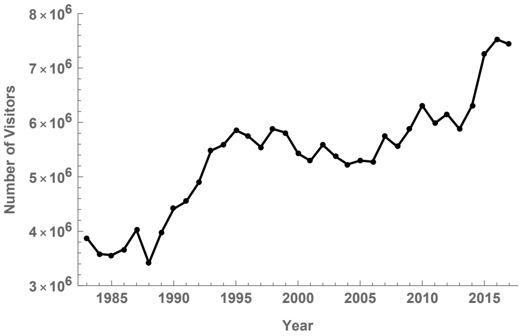
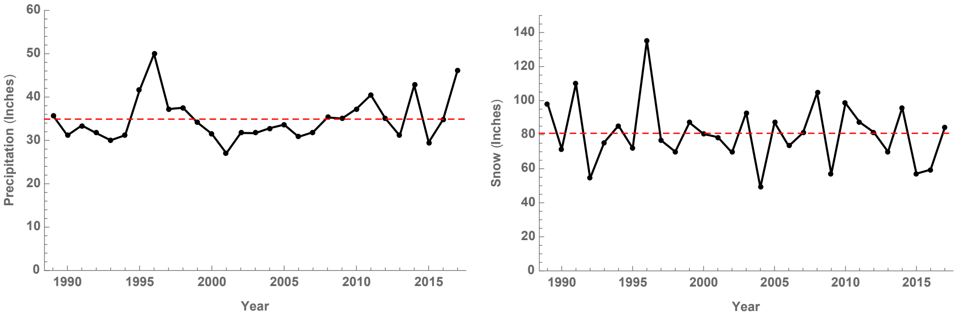


Figure 7: Number of visitors to Yellowstone and Grand Teton National Parks, over time.

In dry years, berry crop is less abundant, which tends to increase the number of grizzly bear-human conflicts (Mohr, 2018). To test this relationship, our analysis was extended to incude liquid precipitation ($PRCP$) and frozen precipitation ($SNOW$) at Yellowstone National Park stations from the National Oceanic and Atmospheric Administration (NOAA).[2] We show average annual precipitation and snowfall for these stations in Figure 8.

---

[2] NOAA climate data is from `https://www.ncdc.noaa.gov/cdo-web/search`. We used Yellowstone National Park as the search term and then narrowed down the available stations to those that had annual climate data for the desired time-period of 1989 and up. The following stations had complete data for annual precipitation: Canyon, Lewis Lake Divide, Parker Peak, Sylvan Lake, Sylvan Road, and Thumb Divide. We took an average of the annual precipitation at those six stations to create our PRECIP variable. The following stations had mostly complete data for annual snowfall: Tower Falls and Yellowstone Park Mammoth. The data for Tower Falls was missing four years of snowfall while the data for Yellowstone Park Mammoth was missing three years of snowfall. The missing years for the two stations were different, meaning there were no missing years after we averaged the annual snowfall at the two stations. Our SNOW variable is the average snowfall at these two stations.



(a) (b)

Figure 8: Average annual (a) precipitation and (b) snowfall for stations in Yellowstone National Park. The dashed line is the average value over the entire time-period.

We predict that mortality is a function of the number of grizzly bears, the number of visitors, and weather:

$$M = M(G, VISIT, PRECIP, SNOW). \tag{6}$$

This relationship is tested by estimating a negative binomial regression. The regression model is

$$M = \exp(\alpha \ln(G) + \beta_0 + \beta_1 VISIT + \beta_2 PRCP + \beta_3 SNOW), \tag{7}$$

in which M is total non-hunting grizzly bear mortality, G is the size of the grizzly bear population, and VISIT, PRCP, and SNOW are the control variables described above. The natural log of G is taken to be an exposure variable. If the coefficient α were equal to one, then doubling the number of grizzly bears would lead to a doubling of the mortality rate. Results are repoted in Table 2. In Regression (1), α is unconstrained. The coefficient is significant and greater than one, which implies that a doubling in the grizzly bear population more than doubles the rate of non-hunting mortality. In Regression (2), α is constrained to be equal to two. The coefficient estimates from this regression model are employed when solving the net growth differential equation.

	(1) MORT	(2) MORT
lnG	1.542***	2
	(0.000)	(.)
VISIT	0.000000486***	0.000000394***
	(0.000)	(0.000)
PRCP	-0.0272	-0.0266
	(0.066)	(0.072)
SNOW	0.00735	0.00814
	(0.228)	(0.156)
CONSTANT	-9.010***	-11.46***
	(0.000)	(0.000)
N	29	29

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 2: Negative binomial regressions of non-hunting mortality.

The results from Table 2 are used to parameterize the mortality equation for the convex model. The equation is[3]

$$M(G, \overline{VISIT}, \overline{PRCP}, \overline{SNOW}) = 0.0000762 \cdot G^2. \tag{8}$$

---

[3] The full derivation for the convex model is

$$\begin{aligned} M &= \exp(\hat{\alpha} \ln(G) + \hat{\beta}_0 + \hat{\beta}_1 VISIT + \hat{\beta}_2 PRCP + \hat{\beta}_3 SNOW) \\ &= \exp(2 \ln(G) - 11.46 + 0.000000394 \cdot VISIT - 0.0266 \cdot PRCP + 0.00814 \cdot SNOW) \end{aligned}$$

2.3. Modified Grizzly Bear Growth

We modify the logistic growth equation to account for the relationship between population size and non-hunting mortality

$$F(G(t)) - M(G(t)) = rG(t)\left(1 - \frac{G(t)}{K}\right) - M(G(t), VISIT, PRCP, SNOW). \tag{9}$$

For each specification of mortality, Equation (9) is analytically solved. The solution provides population projections at each instant in time (for a given initial condition and guessed r and K). The best fit values of r and K are taken as those that minimize SSE between projected and actual population estimates. Results are reported in Table 3.

Model	**r**	**K**
S	0.084	821
C	0.083	5,465

Table 3: Parameter estimates and fit of mortality trendlines.

In Figure 9, we show the growth and mortality curve for the C model. At the point where growth and mortality intersect, net growth is equal to zero. Net growth has the standard logistic appearance, but our specification allows additional richness because of the decomposition of net growth into growth and mortality.

We substitute in the average number of visitors and the average annual values of precipitation and snow over the entire time-period. Average visitation is 5,697,278. Average annual precipitation is 34.9 inches while average annual snowfall is 80.8 inches; these averages are shown as the dashed lines in Figure 7. Plugging in these average values:

$$\begin{aligned}
&= \exp(2\ln(G) - 11.46 + 0.000000394 \cdot \overline{VISIT} - 0.0266 \cdot \overline{PRCP} + 0.00814 \cdot \overline{SNOW}) \\
&= \exp(2\ln(G) - 11.46 + 0.000000394 \cdot 5,697,278 - 0.0266 \cdot 34.9 + 0.00814 \cdot 80.8) \\
&= 0.0000762 \cdot G^2.
\end{aligned}$$

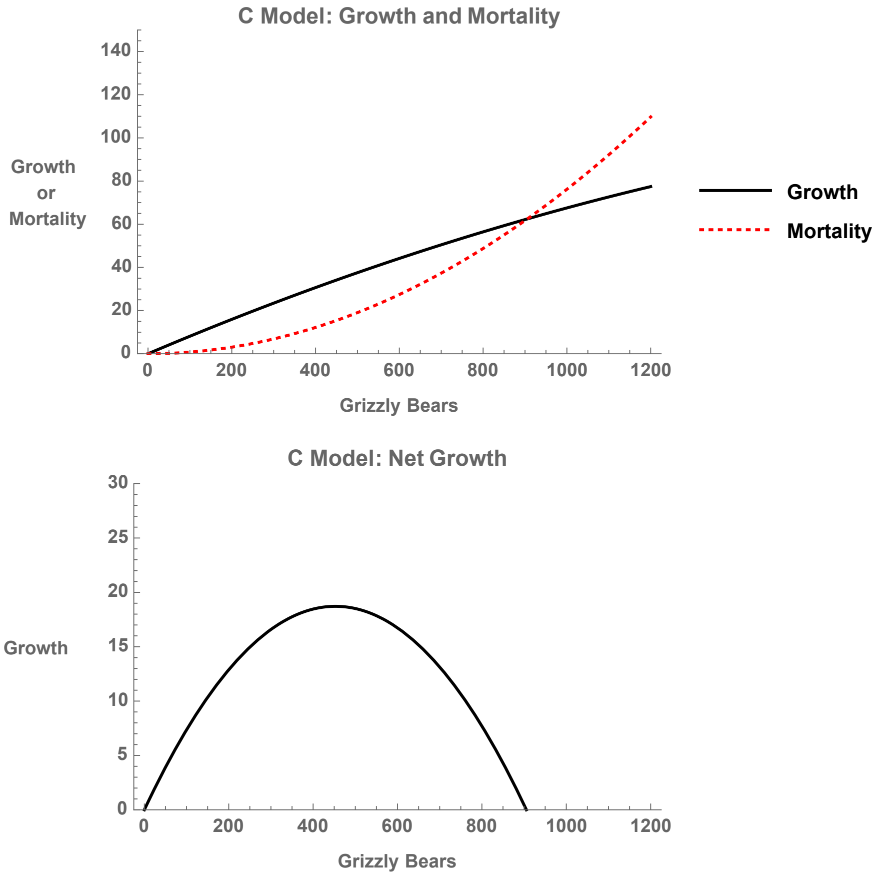
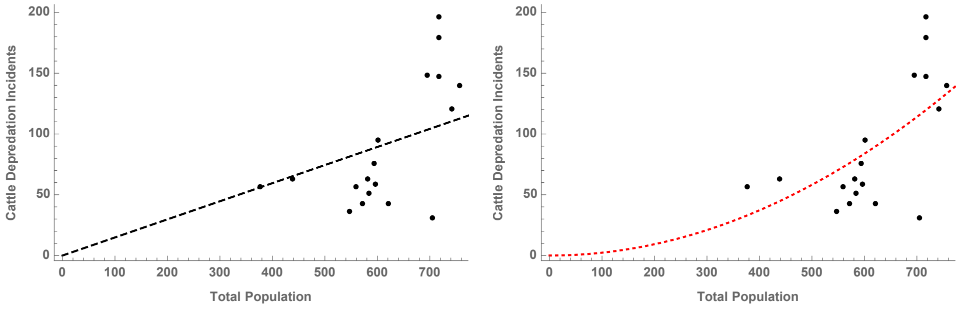


Figure 9: Growth and mortality curves for the C model.

2.4. Economic Background

Grizzly bears are an obvious example of a multi-use resource. Multi-use species, such as feral pigs in Zivin et al. (2000), urban white-tailed deer in Rondeau (2001), African elephants in Horan and Bulte (2004), and Scandinavian moose in Skonhoft and Olaussen (2005) and Olaussen and Skonhoft (2011) should be managed such that stock marginal damages are equated with stock marginal benefits. This typically requires specifying more linkages between the species and humans than the typical bioeconomic model.

There are many economic damages associated with grizzly bears. For example, there are damages to ranchers through grizzly bear-livestock depredation incidents, as well as damages to outdoor enthusiasts and hunters through occasional human injury or death incidents. The IGBST includes data on livestock depredation and human injury incidents in the human-grizzly bear conflict sections of their annual reports. The data shows that, just as there is a relationship between population size and non-hunting mortality, there is a relationship between population size and the number of damage incidents. In Figure 10, we show that there is a relationship between grizzly bear population size and the number of cattle depredation incidents, L.



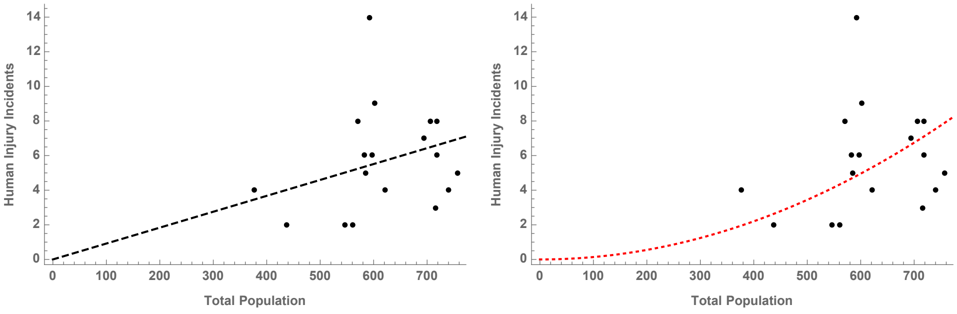
(a) (b)

Figure 10: Relationship between grizzly bear total population size and cattle livestock depredation incidents with: (a) linear trendline, (b) convex trendline.

A negative binomial regression is again used model to estimate the number of annual cattle depredation incidents as a function of grizzly bears, visitation, and weather. The estimation finds

$$L = L(G, \overline{VISIT}, \overline{PRECIP}, \overline{SNOW}) \approx 0.108 \cdot G. \tag{10}$$

In Figure 11, we show that there is a relationship between grizzly bear population size and the number of human injury incidents, I.



(a) (b)

Figure 11: Relationship between grizzly bear total population size and human injury incidents with: (a) linear trendline, (b) convex trendline.

In a similar fashion, a negative binomial regression mode is employed to estimate the number of annual human injuries as a function of grizzly bears, visitation, and weather. We find

$$I = I(G, \overline{VISIT}, \overline{PRECIP}, \overline{SNOW}) \approx 0.009 \cdot G. \tag{11}$$

While there is existing data on the economic damages associated with grizzly bears, the data on the economic benefits associated with grizzly bears is sparse. Swanson et al. (1994) categorize different types of values associated with the grizzly bear population in the Yellowstone Recovery Zone, including use, option, existence, and bequest values. Richardson et al. (2014) conducted a stated preference survey in Yellowstone National Park to estimate how much visitors would be willing to pay, in the form of increased park entrance fees, to keep bears along park roads.

Just as grizzly bear population size influences the number of economic damage incidents, we assume that the population size would impact the benefits gained from grizzly bear viewings. First, it is important to note that there are different possible types of grizzly bear viewings. Roadside viewers (e.g., tourists who visit Yellowstone or Grand Teton National Park) have a probability of seeing a grizzly bear along a park road. These encounters are typically safe, so we assume that roadside viewers have a positive willingness to pay to increase the probability of such encounters. Outdoor enthusiasts and big-game hunters, on the other hand, have a probability of seeing a grizzly bear in the backcountry. Some experienced outdoor enthusiasts and big-game hunters may be willing to pay a positive amount to increase the probability of such encounters, but it is also possible that some of them may be willing to pay to decrease the probability of such encounters. For example, while some might find it thrilling or natural to see grizzly bears in the backcountry, others might hope to avoid such sightings on account of a desire to stay safe. We do not claim to know whether, on average, outdoor enthusiasts and big-game hunters would be willing to pay to increase or decrease the probability of such encounters, so we drop these types of grizzly bear viewers from our model.

We assume that the probability of seeing a grizzly bear along a park road, P, is a function of the number of grizzly bears, such that an increase in the number of grizzly bears leads to an increase in the probability of a sighting, at a decreasing rate, i.e. a concave specification

$$P(G) = 1 - e^{-\lambda G}, \tag{12}$$

in which λ is a parameter. λ is calibrated following the assumptions that at a population size of 100 grizzly bears, roadside viewers have a 5% probability of a sighting; at a population size of 700 grizzly bears, they have a 30% chance of a sighting. These two data points are used to calculate the λ that minimizes the SSE between predicted and actual probabilities of sighting. In Figure 12, we show a plot of the relationship between grizzly bear population size and probability of a sighting along a park road.

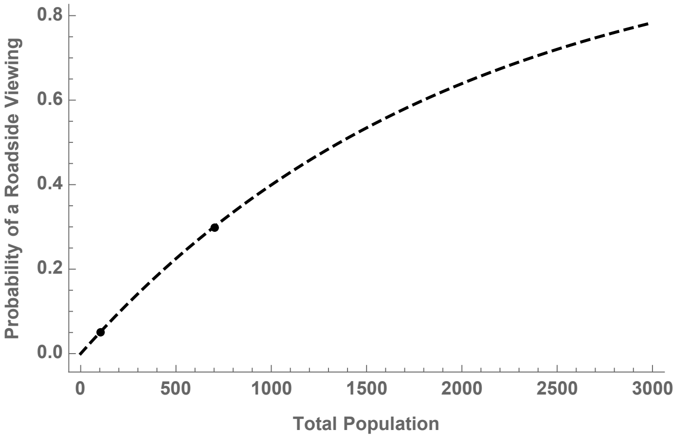


Figure 12: How the probability of seeing a grizzly bear along a park road changes as the population size changes.

Table 4 presents a summary of the economic parameters and some functional forms used in Section 3. In the model we utilize linear rancher damages, linear human injury damages, and concave probability of a grizzly bear sighting in the construction of a bioeconomic model of grizzly bear management.

Parameter/ Function	**Value/ Functional Form**
$\overline{VISIT}$	5,697,278 visitors
$\overline{PRCP}$	34.9 in.
$\overline{SNOW}$	80.8 in.
δ	0.02
p, k	\$1,950
r_m	0.3
r_s	0.2
c_m	\$5,000
c_s	\$5,000
c_r	\$245,530/33.08
c_i	\$5,000
V	AvgVISIT
wtp_V	\$0.5
$P(G)$	$1 - e^{-\lambda G}$
λ	0.0005
G_0	718 grizzly bears

Table 4: Economic parameter estimates.

3. Model

The first component of the North American Model of Wildlife Conservation is that "wildlife resources are a public trust" that should be "held in trust for the benefit of present and future generations" (Organ et al., 2012). When managing a wildlife population such as grizzly bears, a representative state wildlife agency should take all user groups who are influenced by grizzly bears into account. We thus model a representative state wildlife agency that maximizes social net benefits. We define social net benefits, NSB, as the difference between benefits, B, and costs, C:

$$NSB = B - C, \tag{13}$$

in which benefits include agency net revenue, grizzly bear hunter welfare, and grizzly bear viewer welfare, and costs include those related to management damages, rancher damages, and medical damages.

Benefits. The agency receives revenue by selling grizzly bear hunting licenses, h, at license price p. The cost to the agency of issuing these licenses is a function of the number of licenses sold and is given by $c_A(h)$. Agency net revenue, N_A, is equal to agency revenue minus cost:

$$N_A(h) = ph - c_A(h). \tag{14}$$

To simplify the analysis, we assume that the cost of issuing licenses is negligible. Grizzly bear hunters' obtain welfare from the completion of a successful hunt equal to

$$\mathrm{wtp}_H + m - c_H - p$$

in which wtp_H is the hunter's willingness to pay to go on the hunting trip, m is the meat value associated with a grizzly bear kill, c_H are the hunter's trip and supply costs, and p is the license price. Combined, all hunters obtain welfare, W_H, such that

$$W_H(h) = (\mathrm{wtp}_H + m - c_H - p)h = (\mathrm{wtp}_H + m - c_H)h - ph = kh - ph, \tag{15}$$

in which k is a lumped parameter that represents an individual hunter's "kill value," or the net of their willingness to pay for a hunt plus meat value minus costs of the hunting trip and supplies. In Equation (15), we are assuming that the total number of grizzly bear hunters is given by the number of grizzly bear hunting licenses issued, h. This amounts to assuming that every licensed grizzly bear hunter actually goes on a hunt and successfully harvests a grizzly bear. The odds of drawing a grizzly bear tag will likely be very low, so it is reasonable to assume that licensed hunters will do what they can to ensure they have a successful hunt. We assume that

$$k \geq p, \tag{16}$$

otherwise a hunter would not choose to purchase a hunting license and go on a hunt.

The welfare of all grizzly bear viewers, W_V, is equal to the sum of roadside viewer welfare, W_J, outdoor enthusiast viewer welfare, W_O, and big-game hunter viewer welfare, W_G, or

$$W_V = W_J + W_O + W_G. \tag{17}$$

As discussed in Section 2.4, outdoor enthusiast viewer welfare and big-game hunter viewer welfare are omitted so that

$$W_V(G) = W_J(G) = J \cdot \mathrm{wtp}_J \cdot P(G), \tag{18}$$

in which J is the total number of roadside viewers and wtp_J is a roadside viewer's willingness to pay to increase the probability of a grizzly bear sighting, P, by one percent. As also discussed in Section 2.4, the probability of a grizzly bear sighting is a concave function of the size of the grizzly bear population.

Costs. The agency incurs costs from management damages, D_A, each time it must make a management removal or conduct an investigation after a self-defense kill of a problem grizzly bear. From Figure 5, we know that management removals and self-defense kills are the two main drivers of human-caused non-hunting mortality. As shown in Figure 4, human-caused non-hunting mortality is in turn the main driver of total non-hunting mortality. Management removals are a ratio, r_m, of non-hunting mortality incidents while self-defense kills are a ratio, r_s, of non-hunting mortality incidents, or

$$D_A(G) = r_m M(G) c_m + r_s M(G) c_s = M(G)(r_m c_m + r_s c_s), \tag{19}$$

in which c_m and c_s are the costs to the agency per management removal and self-defense investigation, respectively.

The cost of rancher damages, D_R, depends on the number of cattle depredation incidents, $L(G)$. As shown in Section 2.4, the number of cattle depredation incidents is a linear function of the total grizzly bear population

$$D_R(G) = c_R L(G), \tag{20}$$

in which c_R is the cost per rancher damage incident.

The cost of medical damages from human injuries, D_i, depends on the number of human injury incidents, $I(G)$. As shown in Section 2.4, the number of human injury incidents is a linear function of the total grizzly bear population

$$D_i(G) = c_i I(G), \tag{21}$$

in which c_i is the medical cost per human injury incident.

Combining all terms, we find

$$\begin{aligned}NSB(h,G) &= N_A(h) - D_A(G) + W_H(h) + W_J(G) - D_R(G) - D_i(G)\\ &= -M(G)(r_m c_m + r_s c_s) + kh + \mathrm{wtp}_J P(G)J - c_R L(G) - c_i I(G).\end{aligned} \tag{22}$$

The agency knows that if it issues h licenses, h grizzly bears will be harvested. Thus, net grizzly bear growth is

$$\dot{G} = F(G) - M(G) - h = rG\left(1 - \frac{G}{K}\right) - 0.0000762G^2 - h. \tag{23}$$

The agency maximizes net social benefits over time by choosing the optimal number of licenses to issue in each time period, subject to the following: the dynamic constraint in Equation (23), that there is a maximum number of licenses ($h^{\max}$) that can be issued, that grizzly bear stock size must be greater than or equal to zero, and that the initial grizzly bear stock size is G_0. The problem facing the agency, with time subscripts suppressed, is to maximize the net present value of managing grizzly bears, or

$$\max_h \int_0^\infty NSB(h,G)e^{-\delta t}dt \tag{24}$$

subject to

$$\begin{aligned}&\dot{G} = F(G) - M(G) - h,\\ &0 \le h(t) \le h^{\max},\\ &G \ge 0,\end{aligned}$$

and

$$G(0) = G_0.$$

In the agency's problem, δ is the discount rate that represents the rate of return on alternative investments in society.

The optimization problem follows from the associated current-value Hamiltonian, H, given by

$$\begin{aligned}H = &- M(G)(r_m c_m + r_s c_s) + kh + \mathrm{wtp}_J P(G)J - c_R L(G) - c_i I(G)\\ &+ \mu\left[F(G) - M(G) - h\right],\end{aligned} \tag{25}$$

in which μ is the shadow price. The shadow price can be interpreted as the value of an additional grizzly bear in the wild.

The optimal program follows from a simultaneous solution of three conditions:

$$\frac{\partial H}{\partial h} = k - \mu \lesseqgtr 0, \tag{26}$$
$$\dot{G} = F(G) - M(G) - h, \tag{27}$$

and

$$\dot{\mu} = \delta\mu - \frac{\partial H}{\partial G}. \tag{28}$$

The first condition provides a rule to determine the optimal number of licenses to issue, by a comparison of what a grizzly bear in the wild is worth (the shadow value) to the kill value. Because the Hamiltonian is linear in licenses, we find that licenses either ought to be set at zero, at a signular value between the lower and upper bound, or at the maximum possible number:

$$h(t) = \begin{cases} h^* = 0 & \text{if } \mu(t) > k, \\ h^* \in [0, h^{\max}] & \text{if } \mu(t) = k, \\ h^* = h^{\max} & \text{if } \mu(t) < k. \end{cases} \tag{29}$$

If the value of a grizzly bear in the wild exceeds the kill value ($\mu(t) > k$), then it is optimal for there to be no hunting program. In this case, the second condition, Equation (27), provides a differential equation for the grizzly population while the third condition, Equation (28), provides a differential equation governing the evolution of the value of grizzly bears in the wild. While only numerical solutions are possible, the steady state grizzly bear population and shadow value for this case can be calculated as

$$\begin{aligned} G_{h^*=0} =& \frac{rK}{r + m_2 K} \\ \mu_{h^*=0} =& \frac{1}{F'(G_{h^*=0}) - M'(G_{h^*=0}) - \delta}[(c_m r_m + c_s r_s)M'(G_{h^*=0}) \\ & - J\text{wtp}_J P'(G_{h^*=0}) + c_R L'(G_{h^*=0}) + ciI'(G_{h^*=0})] \end{aligned}$$

In contrast, if the value of a wild grizzly bear does not exceed the kill value, a hunting program may be optimal, as set at the maximum possible rate or at some intermediate level (the singular solution). In the case that the kill value is greater than the value of a wild grizzly bear ($k > \mu(t)$), licenses ought to be set at the maximum level, with the second condition, Equation (27), becoming

$$\dot{G} = F(G_{h^*=\max}) - M(G_{h^*=\max}) - h^{\max}$$

and governing the evolution of the population. The third condition, Equation (28), evaluated as the grizzly bear population changes over time, provides a differential equation for the shadow value in this case.

However, we are most interested in the singular solution, which occurs when the value of a grizzly bear in the wild just equals the kill value ($\mu(t) = k$). In this case, as k is a constant, the value of a grizzly bear in the wild is also constant over time. By combining this with the third condition, Equation (28), and rearranging, we find a rule governing the singular solution of grizzly bears:

$$\begin{aligned}\delta = \overbrace{F'(G) - M'(G)}^{\text{marginal growth}} + \frac{1}{k}\Big\{ \qquad & \overbrace{J\mathrm{wtp}_J P'(G)}^{\text{marginal non-consumptive benefits}} \\ \underbrace{-(c_m r_m + c_s r_s)M'(G)}_{\text{marginal management costs}} \quad & \underbrace{-c_R L'(G)}_{\text{marginal livestock costs}} \\ \underbrace{-c_i I'(G)}_{\text{marginal injury costs}} \quad \Big\}. & \end{aligned} \tag{30}$$

Equation (30) is a natural asset equilibrium condition that provides the agency with a rule to determine the grizzly stock in the case that the value of a grizzly bear in the wild just equals the kill value. The intuition of the rule is simple - grizzly bears ought to be managed as natural assets that are competitive with other assets in the economy. They are competitive when the rate of return from holding an additional grizzly bear in the wild (conserving) just equals the rate of return the agency could earn from harvesting (exploiting) a grizzly bear and investing the proceeds. The market rate of return is the discount rate, δ, on the left-hand side (LHS) of Equation (30). The rate of return from holding an additional grizzly bear in the wild is given by the right-hand side (RHS) of the equation, summarized as the sum of five terms. An additional grizzly bear generates some marginal growth, which can be positive, zero, or negative, depending on the existing size of the stock. The grizzly bear also results in some marginal non-consumptive benefits: an additional grizzly bear has a positive effect on the probability of grizzly bears that are seen. The remaining terms on the RHS are all marginal costs associated with an additional grizzly bear in the wild: marginal costs of management kills and self-defense kills, marginal costs from cattle depredation incidents, and marginal cost from human injuries. The equilibrium stock of grizzly bears is determined by the stock that just brings the LHS of Equation (30) into balance with the RHS. The rule implicitly defines the singular grizzly bear stock, G^*, as a function of the parameters.

The complete solution becomes

$$h(t) = \begin{cases} h^* = 0 & \text{if } G(t) < G^*, \\ h^* \in [0, h^{\max}] & \text{if } G(t) = G^*, \\ h^* = h^{\max} & \text{if } G(t) > G^*, \end{cases} \tag{31}$$

which is an example of a most rapid approach path (Spence and Starrett, 1975).

4. Results

We present the most interesting numerical solutions to the simple (S) and convex (C) models in Figure 13.

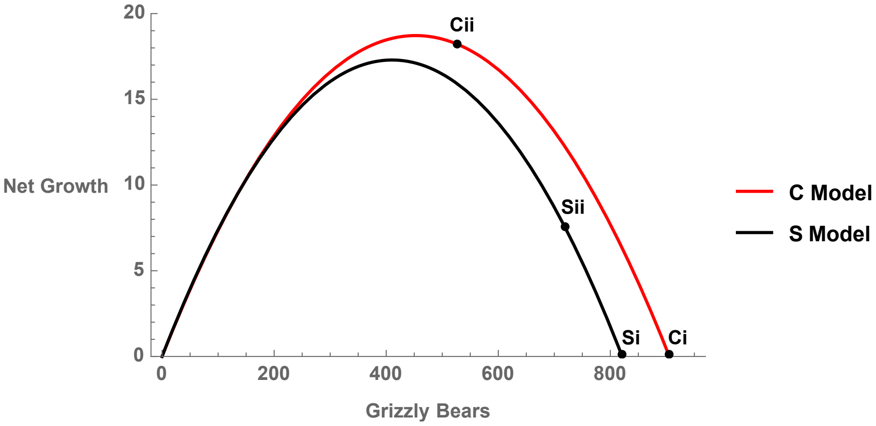


Figure 13: Solutions.

Case i - No hunting. If it is optimal for there to be no hunting program (as when $\mu(t) > k$), then the equilibrium stock in the S model (which omits non-hunting mortality) is forecasted to be less than the equilibrium stock in the C model (which accounts for non-hunting mortality). We have grizzly bear stock $G_{S_i} < G_{C_i}$. The feedback control rule for the S model in Case i is

$$h(t) = \begin{cases} h^* = 0 & \text{if } G(t) < G_{S_i}, \\ h^* = 0 & \text{if } G(t) = G_{S_i}, \\ h^* = h^{\max} & \text{if } G(t) > G_{S_i}, \end{cases} \tag{32}$$

The feedback control rule for the C model in Case i is likewise

$$h(t) = \begin{cases} h^* = 0 & \text{if } G(t) < G_{C_i}, \\ h^* = 0 & \text{if } G(t) = G_{C_i}, \\ h^* = h^{\max} & \text{if } G(t) > G_{C_i}, \end{cases} \tag{33}$$

The rules differ only if the observed stock of grizzly bears is in the interval $G_{S_i} \leq G(t) \leq G_{C_i}$. In this interval, if non-hunting mortality is ignored (as in the S model), then the feedback control rule would be to harvest (cull) at the maximum rate, in contrast to to the rule that incorporates non-hunting mortality which would be to do nothing and allow the population to naturally grow to G_{C_i}.

The implications are that in the case without a sustained hunting program, ignoring non-hunting mortality leads to an underestimate of long-run grizzly bear populations, an inaccurate accounting of the associated benefits, costs and damages associated with the species, and a management plan at high population levels (as currently observed) that would advocate reducing the population, when it ought to be allowed to expand further.

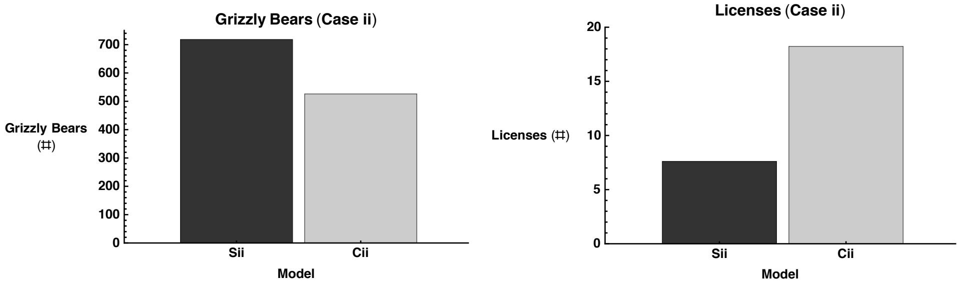
Case ii - Hunting program. If a hunting program is optimal along the singular solution (as when $\mu(t) = k$), then the equilibrium stock when mortality is omitted is forecasted to exceed that with mortality ($G_{S_{ii}} > G_{C_{ii}}$). The feedback control rule for the S model is

$$h(t) = \begin{cases} h^* = 0 & \text{if } G(t) < G_{S_{ii}}, \\ h^* = h_{S_{ii}} & \text{if } G(t) = G_{S_{ii}}, \\ h^* = h^{\max} & \text{if } G(t) > G_{S_{ii}}, \end{cases} \tag{34}$$

where singular licenses $h_{S_{ii}}$ are given by net growth at $G_{S_{ii}}$. The similar rule for the C model is

$$h(t) = \begin{cases} h^* = 0 & \text{if } G(t) < G_{C_{ii}}, \\ h^* = h_{C_{ii}} & \text{if } G(t) = G_{C_{ii}}, \\ h^* = h^{\max} & \text{if } G(t) > G_{C_{ii}}, \end{cases} \tag{35}$$

with net growth at $G_{C_{ii}}$ determining singular licenses $h_{C_{ii}}$. In this case of a sustained hunting program, whether non-hunting mortality is taken into account or not leads to significant differences in equilibrium grizzly bear stocks and management rules. In addition to the overshooting of the S model equilibrium over the C model equilibrium, in the interval of observed grizzly populations $G_{C_{ii}} \leq G(t) \leq G_{S_{ii}}$, the management prescriptions derived from the feedback control rules are again in direct opposition of one another. In this interval, the S model would prescribe no hunting, allowing the population to grow to $G_{S_{ii}}$, while the C model would suggest a rapid reduction of the population to $G_{C_{ii}}$. This result is completely driven by costs associated with mortality incidents incorporated in model C. Following the S model will lead to substantially more grizzly bears than the C model, fewer licenses, more non-hunting mortality and less welfare. Figure 14 compares case ii solutions.



(a) (b)

Figure 14: Comparison of Model S vs. Model C with respect to: (a) grizzly bears, (b) licenses.

In either model, an indication of the relative merits of a hunting program can be assessed by a comparison of the net social benefits at the equilibrium points associated with case i and ii. Figure 15 demonstrates the welfare gains possible in either model as the difference in net social benefits of equilibrium welfare.

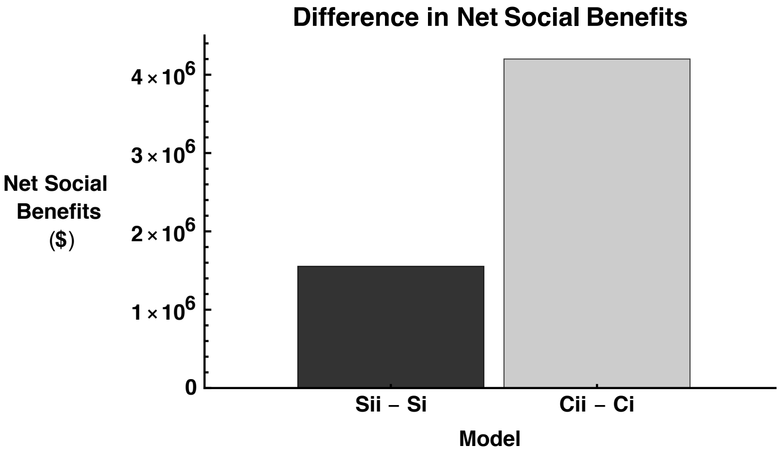


Figure 15: Comparison of net social benefits: Case i vs. Case ii.

In both models, for our parameterization, a hunting program provides substantial gains. The gains are appreciably larger in the C model, when non-hunting mortality is taken into account. In addition, under a hunting program total mortality is lower as shown in Figure 16 for model C.

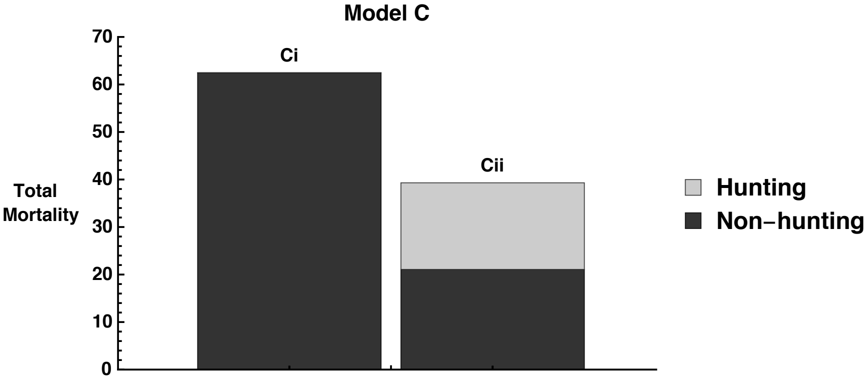


Figure 16: Effect of hunting on total mortality in Model C.

The logic is simple - at a lower number of grizzly bears with a hunting program, non-hunting mortality is low enough to more than make up for the grizzly bears that are lost to hunting.

5. Discussion

Grizzly bears are an interesting natural resource because, even in a state of the world without hunting, they are a species with high rates of non-hunting human-caused mortality. Human-caused mortality limits the growth of the grizzly bear population. High population sizes lead to a higher number of required grizzly bear culls, both in the form of management removals by an agency and self-defense kills by recreationists, ranchers, and hunters. If an agency legalizes hunting and issues licenses, the ensuing grizzly bear hunts would lower the grizzly bear population size. This would then in turn lead to lower rates of necessary non-hunting human-caused mortality. An agency can therefore use hunting licenses as a tool to control the grizzly bear population by influencing non-hunting mortality.

Our first major result is that it would be a mistake for an agency not to account for non-hunting mortality when considering optimal bioeconomic management of grizzly bears. In a state of the world in which hunting is not legal, not accounting for non-hunting human-caused mortality would cause the agency to under-predict the size of the population in equilibrium. In a state of the world in which hunting is legal (case ii) the agency would not only over-predict the size of the equilibrium population, it would also issue too few hunting licenses. Management prescriptions, out of equilibrium for high numbers of observed grizzley bears would be the opposite of what would be suggested if non-hunting mortality were taken into account.

We assume that the agency of interest is one that considers all of the most important stakeholders impacted by grizzly bears. This is in tune with the North American Model of Wildlife Conservation, of which the first principle states that the government should manage wildlife for the public. Grizzly bears are a multi-use species that induce both damages and benefits, depending on the type of stakeholder considered. With respect to damages, the agency incurs costs related to both management removals and self-defense investigations. Ranchers incur monetary damage from cattle depredation incidents. Recreationists, ranchers, and hunters are at risk of being injured in human-grizzly bear conflicts. These are all economic damages that can be quantified with data. We use simple empirics to obtain the marginal effect that an additional grizzly bear in the wild has on each type of damage incident. The data shows that the number of damage incidents increases as the grizzly bear population size increases. The agency can thus use hunting as a form of damage control. When an agency issues more licenses, more grizzly bears are killed, which leaves less grizzly bears in the wild. A lower number of grizzly bears in the wild then leads to a lower number of damage incidents, which entails less monetary damage incurred by stakeholders.

Of course, there are more than just damages associated with grizzly bears. Grizzly bears are an iconic and charismatic species, and there are many people that are outraged at the prospect of grizzly bear hunts. Although there is plenty of data on economic damages, to our knowledge, there is currently no such data available for grizzly bear use values. We focus on grizzly bear sightings, and we assume that each recreationist that sees a grizzly bear values that grizzly bear sighting. We assume that recreationists see more grizzly bears the more grizzly bears there are in the wild.

We jointly account for the costs, damages and benefits in a linear optimal control model that we use to analyze the optimality of grizzly bear hunting when non-hunting human-caused mortality is taken into account. Given our estimated parameters, we find that hunting is optimal; the state of the world in which hunting occurs has a higher associated welfare than the state of the world in which hunting is banned.

References

Bjornlie, D. D., Bramblett, A. M., Cain, S. L., Coleman, T. H., Fortin-Noreus, J. K., Frey, K. L., Haroldson, M. A., Kamath, P. L., Reinertson, E. G., Robbins, C. T., Thompson, D. J., Tyers, D. B., Wilmot, K. R., Wyman, T. C., 2017. Yellowstone Grizzly Bears: Ecology and Conservation of an Icon of Wildness. Yellowstone Forever and U.S. Geological Survey.

Doak, D. F., Cutler, K., 2014. Re-evaluating evidence for past population trends and predicted dynamics of Yellowstone grizzly bears. Conservation Letters 7 (3), 312–322.

Eberhardt, L., Knight, R., 1996. How many grizzlies in Yellowstone? The Journal of wildlife management, 416–421.

Horan, R. D., Bulte, E. H., 2004. Optimal and open access harvesting of multi-use species in a second-best world. Environmental and Resource Economics 28 (3), 251–272.

Kudelska, K., March 2019. Some Wonder If A New State Bill Authorizing Grizzly Hunting May Be Illegal?
URL `\url{https://www.wyomingpublicmedia.org/post/some-wonder-if-new\\-state-bill-authorizing-grizzly-hunting-may-be-illegal\#stream/0}`

Mohr, K., October 2018. Bear Conflicts Down in Jackson Hole Area of NW Wyoming.
URL `https://www.apnews.com/682f41e230944394849c1b5362a18e06`

National Park Service, September 2018. Grizzly Bears & the Endangered Species Act.
URL `\url{https://www.nps.gov/yell/learn/nature/bearesa.htm}`

Olaussen, J. O., Skonhoft, A., 2011. A cost-benefit analysis of moose harvesting in Scandinavia. A stage structured modelling approach. Resource and Energy Economics 33 (3), 589–611.

Organ, J. F., Geist, V., Mahoney, S. P., Williams, S., Krausman, P. R., Batcheller, G. R., Decker, T. A., Carmichael, R., Nanjappa, P., Regan, R., Medellin, R. A., Cantu, R., McCabe, R. E., Craven, S., Vecellio, G. M., Decker, D. J., December 2012. The North American Model of Wildlife Conservation. Technical review, The Wildlife Society and The Boone and Crockett Club, Bethesda, Maryland, USA.

Peterson, C., March 2018. Grizzly bear hunting regulations proposed in Wyoming; rules would allow up to 24 bears to be killed in historic hunt. Casper Star Tribune.

Richardson, L., Rosen, T., Gunther, K., Schwartz, C., 2014. The economics of roadside bear viewing. Journal of environmental management 140, 102–110.

Rondeau, D., 2001. Along the way back from the brink. Journal of Environmental Economics and Management 42 (2), 156–182.

Skonhoft, A., Olaussen, J. O., 2005. Managing a migratory species that is both a value and a pest. Land Economics 81 (1), 34–50.

Spence, M., Starrett, D., 1975. Most rapid approach paths in accumulation problems. International Economic Review, 388–403.

Swanson, C. S., McCollum, D. W., Maj, M., 1994. Insights into the economic value of grizzly bears in the yellowstone recovery zone. Bears: Their Biology and Management, 575–582.

U.S. Fish and Wildlife Service, March 2016. Federal Register/Vol. 81, No. 48/Friday, March 11, 2016/Proposed Rules.
URL `\url{https://www.fws.gov/policy/library/2016/2016-05167.html}`

van Manen, F. T., Haroldson, M. A., Karabensh, B. E., 2018. Yellowstone Grizzly Bear Investigations: 2017 Annual Report of the Interagency Grizzly Bear Study Team. Annual report, U.S. Geological Survey.

Wilkinson, T., July 2018. Jane Goodall Joins Wyoming Protestors in Buying Up Grizzly Hunt Tickets. National Geographic.

Wyoming Game & Fish Department, August 2018. Chapter 68: Grizzly Bear Hunting Seasons - Emergency Rule.

Zivin, J., Hueth, B. M., Zilberman, D., 2000. Managing a multiple-use resource: the case of feral pig management in California rangeland. Journal of Environmental Economics and Management 39 (2), 189–204.