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**The Ghost of Extinction: Preservation Values and
Minimum Viable Population in Wildlife Models**

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The Ghost of Extinction: Preservation Values and Minimum Viable Population in Wildlife Models

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Abstract

The inclusion of a minimum viable population in bioeconomic modeling creates at least two complications that are not resolved by using a modified logistic growth function. The first complication can be dealt with by choosing a different depensational growth function. The second complication relates to the inclusion of the *in situ* benefits of wildlife into the analysis. Knowledge about the magnitude of the *in situ* benefits provides no guide for policy about conservation management. Simply knowing that people are willing to pay a large amount each year to protect a species says nothing about whether one should manage habitat to protect or enhance the species' numbers, unless the species is in imminent danger of extinction. If willingness to pay is to be a guide, it needs to be better tied to population numbers, especially the minimum viable population.

Key words: marginal willingness to pay; endangered species and extinction; minimum viable population

JEL Category: Q20, Q24, C61

The Ghost of Extinction: Preservation Values and Minimum Viable Population in Wildlife Models

Economists have adopted Colin Clark's (1990) general framework for analyzing optimal wildlife populations and harvest levels, with one twist: they have explicitly introduced preservation benefits to say something about socially optimal populations. The logistic growth function has become the mainstay of such analyses, although when there is a threat of extinction (or more appropriately extirpation) a depensatory logistic growth function that explicitly includes a minimum viable population may be employed (Conrad, 1999). While mathematical models with the modified logistic growth function improve the richness of the policy insights, there are two problems with its use in practice. The modified logistic growth function encourages overharvesting that could lead to extinction. Further, its use in determining the socially optimal population of a species becomes exceedingly complex if *in situ* benefits of wildlife are included.

With regard to the latter, the main argument used by economists and others for preserving wildlife species is that they provide significant non-use benefits, as demonstrated by peoples' apparent willingness to pay (WTP) to preserve a variety of species (Loomis and White, 1996), and that these benefits tip most cost-benefit analyses in favor of programs that protect species. Indeed, preservation value is often the foremost determinant of an economically optimal population. However, as demonstrated in this paper, assumptions about how preservation benefits are allocated between maintaining a safe minimum viable population and increasing numbers above this minimum have a profound effect on the policy choice (Bulte and van Kooten, 1999). Although contingent valuation studies have estimated

high values for preserving species and ecosystems (Costanza et al., 1997), such information by itself may be meaningless for guiding policy related to the issue of ‘how many’ wildlife. Rather, one needs to know how peoples’ willingness to pay to protect species is allocated between preventing extinction and enhancing numbers above some ‘safe’ minimum viable population required to keep the species from going extinct. As shown in this paper, knowledge is needed not only about peoples’ *marginal* WTP, information which is generally unavailable, but also about how marginal WTP changes as the population size increases (i.e., about the functional form of marginal WTP). The informational requirements are quite demanding, and this has implications for the questions asked in contingent valuation surveys.

The objective of this paper is to improve research and policy related to wildlife management by highlighting these two problems. The focus is on wildlife species that are subject to hunting and have charismatic appeal. First, we specify a population growth function that accommodates a minimum viable population and results in realistic rates of growth. This growth function is then incorporated in an optimal control model that includes both harvest and *in situ* (non-use) benefits. Second, we develop the mathematics for modeling non-use benefits of preventing extinction by maintaining a stock just at the minimum viable population (MVP) or augmenting the stock size above MVP. Third, we derive the steady-state conditions for the optimal population size under two alternative assumptions regarding the functional form of marginal non-use benefits. Finally, we develop a numerical application of the models to the conservation of sage grouse, a harvested bird that is a species of concern in several western U.S. states, and present solutions to the models. We conclude by discussing implications of our contribution for valuation research related to the management of charismatic wildlife species.

Modeling Growth of Wildlife Species

We begin by postulating the popular Verhulst logistic function that is most-often used to describe the fecundity, mortality and growth characteristics of a fishery or charismatic wildlife population:

$$G(x(t)) = \gamma x(t) \left(1 - \frac{x(t)}{K} \right), \quad (1)$$

where x refers to fish biomass or wildlife numbers at time t , γ is the intrinsic growth rate, and K is the carrying capacity of the ecosystem. Growth function (1) is a quadratic polynomial with the characteristic that, in the absence of intervention, the population will always tend toward the ecosystem carrying capacity K , even if it is very close to zero. This is unrealistic because, for numbers below some minimum level, a species will eventually go extinct, perhaps despite intervention to prevent this.

To determine whether a species has a good chance of survival, it is necessary to take into account the possibility (as opposed to probability¹) of a population surviving under various assumptions about its habitat, reproduction, predation, legal and perhaps illegal harvests (including incidental take while hunting other species, referred to as by-catch in the fishery), genetic deterioration, and so on. To do so, we specify a growth function that includes the notion of a minimum viable population (MVP), denoted by M . The modified logistics growth function most commonly used to take into account extinction is (Clark, 1990, p.23; Conrad, 1999, p.33):²

$$G(x(t)) = \gamma x(t) \left(\frac{x(t)}{M} - 1 \right) \left(1 - \frac{x(t)}{K} \right). \quad (2)$$

Despite its use in theoretical and empirical applications (e.g., Bulte and van Kooten, 1999, 2001), this specification has some undesirable properties. We illustrate this with the aid of Figure 1, which gives the growth (panel a) and population response (panel b) of a slow-growing mammal species. As long as population exceeds MVP, harvests set equal to growth will leave the population intact.

Figure 1 highlights the first problem with the modified logistics growth function (2): if used as a basis for policy recommendations, harvest levels will be too high, perhaps dangerously so if actual growth is closer to the standard logistics growth function (1) than the modified function (2). Further, starting with a population of 15,000 animals, say, the depensatory growth function (2) results in a too rapid approach to carrying capacity of 100,000 compared to the standard logistics function. For the same intrinsic growth rate and carrying capacity, maximum growth (and thus harvest) with the logistics functional form is 2,000 animals per year, while it is 18,000 animals with function (2)!

To address such ‘unrealistic’ growth, we specify the following growth function due to Boukal and Berec (2002):³

$$G(x(t)) = \gamma x(t) \left(\frac{x(t) - M}{x(t) + M} \right) \left(1 - \frac{x(t)}{K} \right). \quad (3)$$

The population response for this specification is much closer to that of standard logistic growth, with annual growth peaking at 1,636 animals (Figure 1a). Policy based on growth function (3) is less likely to lead to potential overharvesting.

To address the second problem, that of determining optimal population and harvest levels when *in situ* benefits are included and there exists the possibility of extinction, a model of wildlife management and exploitation is first required.

An Optimal Control Model for Wildlife Species

The benefits that society gets from protecting a wildlife species can be grouped into two general categories. Some receive benefits from harvesting, and these may exceed the costs of purchasing a hunting permit, harvesting the animal (viz., expenditures on firearms, ammunition, fishing gear, boats, specialized clothing, accommodation), and getting to the hunting location. However, wildlife also provide benefits to those who observe them in the wild (non-consumptive use benefits), to citizens who benefit simply from knowing that they exist, and to society as a whole because a species contributes to overall biodiversity. Although such benefits are difficult to measure, economists can employ a variety of techniques to determine their magnitude (Loomis and White, 1996).

Assume that the authority wishes to maximize the discounted sum of net use and non-use benefits of a wildlife species over time. This is expressed mathematically as:

$$\int_0^{\infty} [p(h(t)) h(t) - c(h(t)) + B(x(t))] e^{-rt} dt, \quad (4)$$

where $p(h)h - c(h)$ is the net benefit of harvesting and/or consuming h animals at time t , and $B(x(t)) > 0$ are total non-use benefits as a function of the *in situ* population at time t . The demand function is downward sloping if harvesters can influence price, $p'(h) < 0$, while it is perfectly elastic if price is constant. Further, $c'(h) > 0$, with marginal cost upward sloping if $c''(h) > 0$ and constant if $c''(h) = 0$, both of which are possible. It is assumed that $B'(x) > 0$ and $B''(x) < 0$, implying that non-use benefits increase as the wildlife population increases, with marginal benefits positive but declining as numbers increase. Finally, r is the social discount rate.

The economic problem is to maximize (4) subject to the population dynamics:

$$\dot{x} = G(x(t)) - h(t), \quad (5)$$

where $G(x)$ is the growth function (2) or (3) if there exists a MVP. From the maximum principle, the respective optimality condition and co-state equation are (suppressing t):

$$\lambda = [p(h) + p'(h)h] - c'(h). \quad (6)$$

$$\dot{\lambda} = [r - G'(x)] \lambda - B'(x). \quad (7)$$

From (6), the shadow price λ of wildlife – the increase in the objective function from increasing the *in situ* stock by one unit – is equal to the marginal revenue from harvesting one more unit, $p(h)+p'(h)h$, minus the marginal cost, $c'(h)$. Differentiating both sides of (6) by t gives $\dot{\lambda}$, which can be substituted along with λ into (7) to get, after rearranging,

$$\dot{h} = \frac{[r - G'(x)][p'(h)h + p(h) - c'(h)] - B'(x)}{p''(h)h - c''(h) + 2p'(h)}. \quad (8)$$

Equations (5) and (8) provide the dynamics of a wildlife harvesting system that takes into account *in situ* benefits of the wildlife.

In the steady-state, $\dot{x}=0$ and $\dot{h}=0$, so that (5) and (8) reduce respectively to:

$$G(x^*) = h^* \quad (9)$$

$$\frac{B'(x^*)}{p'(h^*)h^* + p(h^*) - c'(h^*)} + G'(x^*) = r, \quad (10)$$

where * indicates optimal levels of the state and control variables. Equation (9) indicates that, in the steady state, harvests should equal growth. As indicated above, if growth function (2) is

used while (3) applies, recommended optimal harvest levels are too high and the species could potentially be driven to extinction (see Figure 1a).

Equation (10) is the fundamental equation of renewable resources (Conrad, 1999, p.14). The optimal population of the wildlife species occurs when the social discount rate equals the marginal rate of substitution between leaving an animal (or unit of biomass) *in situ* and harvesting it today plus the growth rate. It is clear from (10) that an increase in the marginal *in situ* value of a species, $B'(x)$, will raise the optimal stock x^* , and that an increase in marginal harvest benefits will reduce the optimal population for a given discount rate r .

Finally, notice that, if the value of harvest is constant (say equal to p) and $c'(h)=c$ also constant, then $\lambda=p-c$ and (10) reduces to the simpler form $B'(x^*)/(p-c) + G'(x^*) = r$, which is used for convenience in the numerical analysis below.

Modeling Non-use Benefits

Contingent valuation surveys generally elicit willingness to pay for public programs that prevent a species from going extinct, or that increase population numbers by 50 or 100 percent above current levels (Loomis and Larson, 1994; Loomis and White, 1996). Data on *marginal* WTP are not normally available, and contingent valuation surveys do not usually distinguish between programs that are meant to keep a species from going extinct and those that increase numbers beyond some 'safe' population (MVP). We demonstrate that such a distinction is crucial for determining socially optimal populations of a wildlife species, and thereby the management strategies to be pursued. It is also important in terms of the information to be collected in a contingent valuation framework.

The problem is illustrated with the aid of Figure 2. Let α ($0 \leq \alpha \leq 1$) be the proportion

of total WTP that respondents to a contingent valuation survey would (if asked) allocate to keep a species from going extinct, with the remainder to increase numbers above minimum viable population (see Fisher, 1988, 1996). In the figure, total non-use benefits (denoted T) are arbitrarily divided between those required to prevent the species going extinct, αT , and those associated with increases in population beyond MVP, $(1-\alpha)T$. Over the population interval $(0, M)$, infra-marginal changes in non-use benefits occur and average benefit is given by α , but marginal WTP, $B'(x)$, does not exist because any Δx such that $x+\Delta x < M$ will not prevent the species from going extinct. $B'(x)$ exists only for $x \geq M$. Let $B'(M^+) = m$ be the marginal *in situ* value of the species at its minimum viable population.

Researchers will have to choose a functional form for $B'(x)$, perhaps collecting the required information for choosing a functional form using a contingent valuation device. Before doing so, however, it might be relevant to ask whether functional form even matters. Whatever functional form is chosen, two conditions must be satisfied. First, the total amount that people are willing to pay to prevent extinction must be at least equal to the area under $B'(x)$ to $x=M$:

$$\alpha T \geq \int_0^M B'(x) dx. \quad (11)$$

Thus, α is an endogenous variable that is chosen to be as small as possible to satisfy (11). However, if $\alpha=1$ and condition (11) are not satisfied, the optimal population is zero – people are unwilling to pay enough to secure the species. Second, once the species' survival is ensured, remaining WTP determines the optimal population of the species. Thus,

$$\int_{M^+}^{x-M} B'(k)dk = (1-\alpha)T, \quad (12)$$

where $(1-\alpha)T$ is the expressed total WTP for increasing numbers above MVP.

Consider first the case where $B(x) = b \ln x$, so that $B'(x) = b/x, \forall x > 0$. From (11), we find that $b = \frac{\alpha T}{\ln M}$. As noted, however, the marginal benefit function only affects optimal numbers of a species beyond minimum viable population M . It is only relevant up to M in determining whether or not the species is worth protecting from extinction, whether there will be M members or none. Let m be the infra-marginal value of the species, or the marginal value of protecting the first member above M . Then, $m = b, \forall 0 < x \leq M$. Further, we can write the relevant marginal benefit function as:

$$B'(x) = b/(x - M) = \frac{\alpha T}{(x - M) \ln M}, \forall x > M. \quad (13)$$

Notice that $B'(x)$ depends on three parameters (T, M and α), although, from (12), one can derive $\frac{\alpha \ln(x - M)}{\ln M} = 1$. Then (13) can be rewritten so that it depends only on T and M :

$$B'(x) = \frac{T}{(x - M) \ln(x - M)}, \forall x > M. \quad (14)$$

Next consider a quadratic total benefit or WTP function. Assume $B'(x) = q - s x, \forall x \geq 0$, where q is the intercept of the marginal benefit function when $x=0$ and $-s$ ($s > 0$) is the slope of the line (see Figure 2). Assuming equality in equation (11), we find for the linear marginal benefit function (summing the triangle and rectangle in Figure 2), $q = 2\alpha T/M - 2m + M$.

Then,

$$B'(x) = 2\alpha T/M + M - 2m - s x, \forall x \geq 0. \quad (15)$$

From (15), $B'(x=M) = m = 2\alpha T/M + M - 2m - s M$, which, upon rearranging yields $s =$

$\frac{2\alpha T}{M^2} - \frac{3m}{M} + 1$. The relevant marginal benefit function is then:

$$B'(x) = m - s(x - M) = m - \left(\frac{2\alpha T}{M^2} - \frac{3m}{M} + 1 \right) (x - M), \forall x \geq M. \quad (16)$$

Notice that the marginal benefit function based on the quadratic benefit function has four parameters to be determined (T , M , α , and m or q , since $q = 2\alpha T/M - 2m + M$). The quadratic benefit function is presented in Figure 2. Suppose a represents the average WTP to preserve the species. It also follows that $B'(M) = m < a$ as indicated in the figure.⁴

The Optimal Population and Harvest Level

The marginal growth function (3) is given by:

$$G'(x) = \frac{\gamma(1-x/K)}{x+M} \left(\frac{x^2 + 2xM - M^2}{x+M} - \frac{x(x-M)}{K(1-x/K)} \right). \quad (17)$$

Now substitute (17) and the marginal benefit function from (14) into the fundamental equation of renewable resources (10), and let x^* denote the socially optimal population:

$$\frac{T}{(p-c)(x^*-M)\ln(x^*-M)} + \frac{\gamma(1-x^*/K)}{x^*+M} \left(\frac{x^{*2} + 2x^*M - M^2}{x^*+M} - \frac{x^*(x^*-M)}{K(1-x^*/K)} \right) = r, \quad x^* > M \quad (18)$$

Likewise, we can substitute the marginal benefit function from (16) to obtain:

$$m/(p-c) - \left(\frac{2\alpha T}{M^2} - \frac{3m}{M} + 1 \right) (x^* - M)/(p-c) + \frac{\gamma(1-x^*/K)}{x^*+M} \left(\frac{x^{*2} + 2xM - M^2}{x^*+M} - \frac{x^*(x^*-M)}{K(1-x^*/K)} \right) = r, \quad x^* \geq M \quad (19)$$

Expressions (18) and (19) cannot be solved analytically for x^* , even if growth function (2) were specified in place of (3).⁵ Nonetheless, several propositions can be demonstrated intuitively. Suppose $x(t) \geq M, \forall t$, implies survival of the species. Then:

PROPOSITION 1: x^ depends crucially on MVP and the total WTP (denoted T) of citizens for numbers of the species at or beyond MVP.*

Clearly Proposition 1 holds because marginal benefits are a function of at least M and T , as indicated in equations (14) and (16), as well as the slope of the marginal benefit function and the allocation of total WTP in the case of quadratic benefits. Upon modifying results (5) through (8) for the additional inequality constraint (11) that holds in every period, the associated phase-plane diagram in population-harvest (x, h) space is provided in Figure 3 (see Leonard and Van Long, 1992, pp.198-218). It is straightforward and shows that, if constraint (11) is binding, harvest falls to zero and population gravitates to M . Since equilibrium at M is unstable, species numbers will grow and the optimal harvest path (I in the figure) will either take the system to a saddle-point equilibrium or, more likely, drive the population eventually back to the binding constraint at M where h will again be forced to zero.

It is obvious that M is determining if the optimal solution is $x^* \geq M$ – the value of x^* depends on the value of the minimum viable population as is evident from (18) or (19). Likewise, M is determining for any solution $x^* < M$ because it implies extinction is optimal. In this case, T is clearly too small even if $\alpha=1$ (so α has no influence). If $x^* > M$, the optimal solution will depend on $(1-\alpha)T$, with x^* increasing as $(1-\alpha)T$ increases.

PROPOSITION 2: If harvest of the species is ruled out and $T \geq B(M)$, then x^ equals the carrying capacity K .*

Without loss of generality, suppose there are no harvest benefits. Clearly, if people are only interested in ensuring that the population of a wildlife species does not fall below a safe minimum standard (which we take here to be the minimum viable population), and they are willing to pay what is required, then $B(x=M)=T$ (i.e., $\alpha=1$). All WTP is assigned to ensuring species survival (the area under $B'(x)$ in Figure 2 is zero). Yet, the steady-state population is $x^*=K$ and not $x^*=M$. From Figure 3, in the absence of harvests, $x \geq M$ implies that the population will gravitate to the carrying capacity K (as indicated by II but governed by $G(x)$).

This assumes, of course, that the cost of maintaining the species at some level above MVP at any time t does not exceed T . For species that depend on the preservation of large areas of habitat, the opportunity cost of land may simply be too high to preserve the species. This happened in the case of the once-plentiful bison that roamed the Great Plains of North America. The bison was doomed because the land was much more valuable in cattle than bison production, even if the bison could somehow have been domesticated (Anderson and Hill, 2004, pp.94-102). However, for many species that have existence value this is unlikely the case – the MVP is much smaller than extant populations (e.g., elephants, grizzly bears), the critical habitat is relatively distinct and easy to protect (e.g., woodland caribou in northern Canada), and/or the habitat is not all that valuable in other uses (e.g., sage grouse in Nevada). Hence, this possibility can be ruled out in general.

PROPOSITION 3.1: If there are no in situ benefits and there are no harvest benefits, $x^>0$ only if there is a cost to driving population below M (eradication) and the species is able to survive on its own account.*

PROPOSITION 3.2: If there are no in situ benefits, for many species of wildlife it is better to permit harvesting than not, because this will raise their numbers above the safe minimum standard required to keep them from going extinct.

Proposition 3.1 is obvious: If there is no desire to keep a species from going extinct, no effort will be made to protect it and, in this model, the species will go extinct unless it somehow survives despite neglect (or possibly as the result of policies that inadvertently protect the species).

Proposition 3.2 is often disputed by animal rights' activists. Note that $G(x^*=M) = 0$, so that $h^*=0$ in a steady state. Thus, if there exist harvest benefits so that $h^*>0$, then $x^*>M$ even if $B(x=M)=T$. As long as the population is not about to be extirpated, x^* exceeds M even if society is unwilling to pay to keep the species from going extinct. However, if people are only interested in paying to keep a species from going extinct, then, by permitting harvests, x^* is less than it would be in the case of no harvest because, according to Proposition 2, the inherent population dynamics of the depensational growth function would take the species to its carrying capacity rather than to M . In this sense, animal rights activists may be correct.

In the next sections, we demonstrate some of these results numerically. Our main objective is, however, to illustrate the importance of correctly specifying the non-use benefit function. It is not enough to collect information on total WTP. Rather, information is required about marginal WTP and the form of the marginal WTP function.

Numerical Application to the Conservation of Sage Grouse

Previous research using non-market benefits to determine the optimal numbers of a species has generally assumed a specific functional form for marginal benefits (usually linear), total benefits over some range, and assumptions about the intercept or slope parameter. For

example, Loomis and Larson (1994) found that households were on average willing to pay approximately US\$17 for a 50% increase in the gray whale population given an initial stock of some 20,000 animals, while they would be WTP \$19 to increase the gray whale population to about 40,000 animals. The slope of $B'(x)$ falls from 0.0017 to 0.00095 to 0.0002, indicating that a logarithmic total benefit function would be most appropriate. Bulte and van Kooten (1999) nonetheless employed a linear marginal WTP function, $B'(x)=q-sx$, and assumed that $B'(x)$ was zero at the extant population. Then, given total WTP, one of q or s could be derived from T and the value of the other parameter. To take into account the minimum viable population, the researchers simply lowered the value of WTP and re-calculated the marginal benefit function as if it started at the MVP. The foregoing derivations indicate that this is likely to result in errors about the socially optimal level of charismatic species to preserve.

Our approach is to solve equations (18) or (19) for x^* given assumptions about T , M , γ , K , p and c , and, for the case of the linear $B'(x)$ function, m and α . This allows for a direct comparison of economically optimal population sizes as determined by a linear *versus* nonlinear functional form for $B'(x)$.

Parameter Values

Our numerical application is to the greater sage grouse (*Centrocercus urophasianus*), a bird species whose current range is found primarily in Colorado, Idaho, Montana, Nevada, Oregon, Utah and Wyoming (Neel, 2001). Biologists have been concerned with the plight of the greater sage grouse since the early 1900s. Experts estimate that populations have declined by 69 to 99 percent from historic pre-European settlement to today (Deibert, 2004), with declines in the Western States having averaged some 30 percent over the past several decades (Bureau of Land Management, 2000).

We focus specifically on estimating the economically optimal stock of the greater sage grouse in northeastern Nevada's Elko County. We focus on this geographic area because we have collected and examined an unusually extensive amount of data (grouse counts, hunting levels, etc.) on the species in this region (van Kooten et al., 2007). The sage grouse has been the focus of a substantial amount of attention in Nevada, including formation of a Governor's Task Force on Sage Grouse in 2000 (Neel, 2001).

The first parameter to be specified is T , the total WTP for non-use values of the sage grouse. There is little available information regarding the *in situ* value of this species. Loomis and White (1996) provide estimates of households' willingness to pay to preserve various threatened and endangered species, with WTP varying from several dollars to almost \$100 per household annually for well-known species such as spotted owl or steelhead salmon. For the sage grouse, we use a baseline value of \$15 per household, and conduct sensitivity analysis around that. There are about 5.5 million households in the seven states that encompass the majority of the current range of the sage grouse (U.S. Census Bureau), so that non-use benefits may be estimated at about \$81.9 million. This value applies to all sage grouse over its range in these states, rather than solely to sage grouse in Elko County, Nevada. Based on a map of sage grouse range (Neel, 2001, p.6), assume that 5% of the range is found in Elko County, and that we can examine this area in isolation as a microcosm of the entire sagebrush ecosystem. Therefore, we use \$4 million as the baseline value for T .

The minimum viable population of sage grouse in Elko County is not known. Most biologists are unwilling to speculate regarding minimum viable populations in general, with $MVP \approx 2,000$ for large mammals sometimes considered a rule of thumb (see Soulé, 1987). We use a conservative baseline value of 3,000 for this parameter, but also examine results for a

lower value of MVP=1,000. Biological parameters (γ and K) for the bioeconomic model are chosen using data specifically for Elko County (van Kooten et al., 2007): The intrinsic growth rate is $\gamma=1.72$ and carrying capacity (K) is approximately 100,000 birds. Baseline values for the parameters p and c are \$80 and \$25, respectively, and are based on Nevada information.

Two additional parameters (α and m) come into play in the model using quadratic-based $B(x)$, linear $B'(x)$, as shown in (19). As $0 \leq \alpha \leq 1$, we use $\alpha=0.49$ as the baseline value. Consider the implications for m as α is varied. As α approaches unity, all of T is devoted to preservation (rather than augmenting x above M) and the average benefit (a) of preserving the species would approach T/M (approximately \$1300 for our baseline parameter values) and m would approach zero. However, as α declines below unity, the non-use value of the first animal beyond M , denoted m , increases. We assume $m=\$400$ in the baseline, and conduct sensitivity analysis about both m and α .

Numerical Results

Table 1 provides economically optimal populations x^* based on the logarithmic benefit function (so $B'(x)$ is nonlinear), obtained by solving (18). For the baseline parameter values, x^* is between 50,000 and 60,000 birds. The optimal solution is relatively insensitive to changes in the values of the minimum viable population (M), total WTP (T), population growth (γ) and harvest benefits ($p-c$), but quite sensitive to changes in the value of the carrying capacity (K).

Economically optimal populations x^* based on the quadratic benefit function, with linear $B'(x)$, are obtained by solving (19) and are provided in Table 2. The results stand in stark contrast to those derived using the nonlinear marginal non-use benefit function. Rather

than x^* ranging between 50,000 and 60,000 birds, the socially optimal population is only slightly more than MVP. That is, optimal stock size is at levels just high enough to maintain the species, and this holds for both $M=3,000$ and $M=1,000$, even though carrying capacity is estimated to be two orders of magnitude higher than MVP. In addition, x^* is quite insensitive to variations in K ($\frac{1}{2} \times K$ and $2 \times K$), in contrast to high sensitivity to K under nonlinear $B'(x)$. The solution is also reasonably insensitive to changes in every other parameter in the model except MVP, the stock size below which the population is not viable. The impact of changing the allocation of total WTP between ‘preventing the species from going extinct’ and ‘additional numbers above MVP’ (i.e., varying α) is interesting. As the proportion of total WTP allocated to prevent extinction increases, socially optimal sage grouse numbers do fall (as predicted in the propositions above) toward the MVP level. However, the fall is not dramatic in this case, since x^* lies above but reasonably close to the MVP regardless of the value of α .⁶

Conclusions

A significant number of valuation studies have utilized stated preference methods to estimate society’s total WTP to preserve sensitive wildlife species. While providing useful insights into the values people assign to wildlife in general, the information provided by most such studies turns out not to be very useful for policy analysis. In this study, we illustrated this using a general bioeconomic model for charismatic wildlife that includes the notion of a minimum viable population, and hunting and preservation values. The results illustrate that the socially desirable population of sage grouse depends crucially on (i) the minimum viable population, (ii) the ecosystem carrying capacity for sage grouse, and, most importantly, (iii) the functional

form of the marginal non-use benefits function. These are important findings because all three of these factors tend to be quite uncertain.

In particular, generally almost nothing is known about the form of the marginal preservation benefit function for any charismatic wildlife species. This is due mostly to the fact that nonmarket valuation studies most often focus on total values, or at best the values for a large defined change in the quantity of the resource, rather than detailed information on *changes in marginal benefits* as resource quantity is varied. For the case of charismatic wildlife species, research that focuses on the form of marginal preservation benefits becomes extremely complex, especially when minimum viable population is introduced as a factor. At the same time, our results indicate just how important it is to know something about this functional form. Calculated optimal wildlife populations vary by over an order of magnitude depending on whether a linear or nonlinear marginal preservation benefit function is specified.

In general, we view use of the nonlinear marginal benefit function as more realistic and resulting in more accurate estimates of x^* , and the sensitivity analysis results are better behaved under nonlinear $B'(x)$ as well. In addition, use of a linear $B'(x)$ results in optimal population sizes barely above the MVP. This leaves little room for error in the event the MVP is not well-known, which is the normal case. The fact that linear marginal non-use benefits may be inappropriate should not be surprising given some CVM studies' findings of highly nonlinear preferences. For example, Desvousges et al. (1992) found that the average WTP to protect 2,000 birds from perishing in oil spills was as great as the WTP for protecting 20,000 or even 200,000 birds. Such a finding is consistent with a logarithmic-based total benefit function.

An additional implication is that knowledge about the size of *total* non-use benefits does little or nothing for guiding policy about conservation management. The results of this paper show that sensitivity of x^* to the total non-use value of the species to society is small, and in fact very small when compared to the extreme sensitivity of x^* to the functional form of $B'(x)$. This in turn implies that simply knowing that people are willing to pay a large amount of money each year to protect a species says little about whether one should increase efforts to protect or enhance the species' numbers, unless the species is in imminent danger of extinction. Rather, policymakers need information on the safe minimum viable population, carrying capacity, and the marginal WTP function – that is, the parameters that determine the impact on economic values of marginal changes in charismatic wildlife numbers. Both economic and biological research in this direction appears sorely lacking.

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End Notes

¹ It is beyond the scope of the current paper to model uncertainty and meta-populations (local extinction and ‘replenishment’ from elsewhere). See van Kooten and Bulte (2000, pp.211-215) for a discussion of these issues.

² This function exhibits what in fisheries is referred to as depensational growth. It is a population-level phenomenon related to spawner-recruitment, unlike the Allee effect that shows up as a lower per capita growth rate at low population levels (Boukal and Berec 2002).

³ Boukal and Berec (2002) also demonstrate that the discrete-time and continuous-time versions of growth models can exhibit quite different population dynamics.

⁴ The proof is as follows: Given $B'(x) = q - sx$, then, from (11), $\alpha T = M(q - \frac{1}{2} s M)$. Thus, $a =$

$$\alpha T/M = q - \frac{1}{2} s M = \frac{T + 0.5s(M^2 + x^2)}{(M + x)} - \frac{1}{2} s M = [T + \frac{1}{2}sx(x-M)]/(M+x). \text{ Now, } m = (T - s$$

$$M^2)/2M. \text{ Therefore, } a-m = \frac{T(M - x) + sM(M^2 + x^2)}{(M + x)} > 0, \text{ since } s, M, T > 0 \text{ and } M > x \text{ in the}$$

relevant range; thus, $a > m$.

⁵ Using Maple 10, it is possible to derive expressions for x^* , but the resulting expressions are extremely complex. For the simple population dynamics given by equation (2), it is possible to derive an expression for $\frac{\partial x^*}{\partial \alpha}$, but it is impossible to sign.

⁶ To our knowledge, Bulte and van Kooten (1999) are the only others to allocate WTP between ‘extinction prevention’ and ‘additional numbers’, using the case of minke whales in the Atlantic. They set $\alpha = \frac{1}{2}$, so that, from (15), $B'(x) = m + (m^2/T) \times M - (m^2/T)x$. [Proof: Since

$$\int_M^{x^*} B'(x) dx = \frac{1}{2} T, \text{ then } \frac{1}{2}m(x^* - M) = \frac{1}{2} T \text{ (see Figure 2). Then } x^* = T/m + M, \text{ which when}$$

$$\text{substituted into (16) gives } s = \frac{T + 2mM}{T^2 - M^2}. \text{ Substituting } s \text{ into (15) and rearranging gives the}$$

desired result.] In determining their optimal populations, however, Bulte and van Kooten (1999) used $B'(x) = m - (m^2/T)x$ [proof is similar], a subtle but important difference that results

in lower estimates of x^* than would be provided here.

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Table 1: Optimum Sage Grouse Populations, Elko County, NV: Sensitivity Analysis for
Results from Logarithmic Non-use Benefit Function, Nonlinear $B'(x)$

Total WTP (T) and Minimum Viable Population (MVP)	Scenario						
	Baseline ^a	$\frac{1}{2} \times (p-c)$	$2 \times (p-c)$	$\frac{1}{2} \times K$	$2 \times K$	$\frac{1}{2} \times \gamma$	$2 \times \gamma$
<i>MVP = 3,000</i>							
\$2 million	53,199	55,014	52,236	28,817	101,788	53,657	52,955
\$4 million	55,014	58,301	53,199	30,597	103,582	57,018	53,903
\$8 million	58,301	63,936	55,014	33,605	106,982	62,748	55,694
<i>MVP = 1,000</i>							
\$2 million	51,445	53,238	50,496	27,193	99,931	51,890	51,209
\$4 million	53,238	56,491	51,445	28,915	101,718	55,216	52,144
\$8 million	56,491	62,084	53,238	31,855	105,106	60,901	53,913

^a Baseline parameter values: T=\$4 million, $K=100,000$, $(p-c)=\$55.00$, $\gamma=1.72$, $r=0.05$.

Table 2: Optimum Sage Grouse Populations, Elko County, NV: Sensitivity Analysis for Results from Quadratic Non-use Benefit Function, Linear $B'(x)$

Total WTP (T) and Minimum Viable Population (MVP)	Scenario							
	Baseline ^a	$\frac{1}{2} \times m$	$\frac{1}{2} \times \alpha$	$2 \times \alpha$	$2 \times (p-c)$	$\frac{1}{2} \times K$	$2 \times K$	$2 \times \gamma$
<i>MVP = 3,000</i>								
\$2 million	3,550	3,242	3,636	3,433	3,613	3,547	3,552	3,616
\$4 million	3,433	3,199	3,550	3,304	3,481	3,431	3,434	3,484
\$8 million	3,304	3,147	3,433	3,190	3,337	3,303	3,305	3,338
<i>MVP = 1,000</i>								
\$2 million	1,258	1,105	1,593	1,121	1,290	1,257	1,258	1,291
\$4 million	1,121	1,057	1,258	1,058	1,134	1,121	1,121	1,135
\$8 million	1,058	1,030	1,121	1,029	1,065	1,058	1,058	1,065

^a Baseline parameter values: T=\$4 million, $K=100,000$, $(p-c)=$55.00, $\gamma=1.72$, $r=0.05$, $m=$400, $\alpha=0.49$.$$

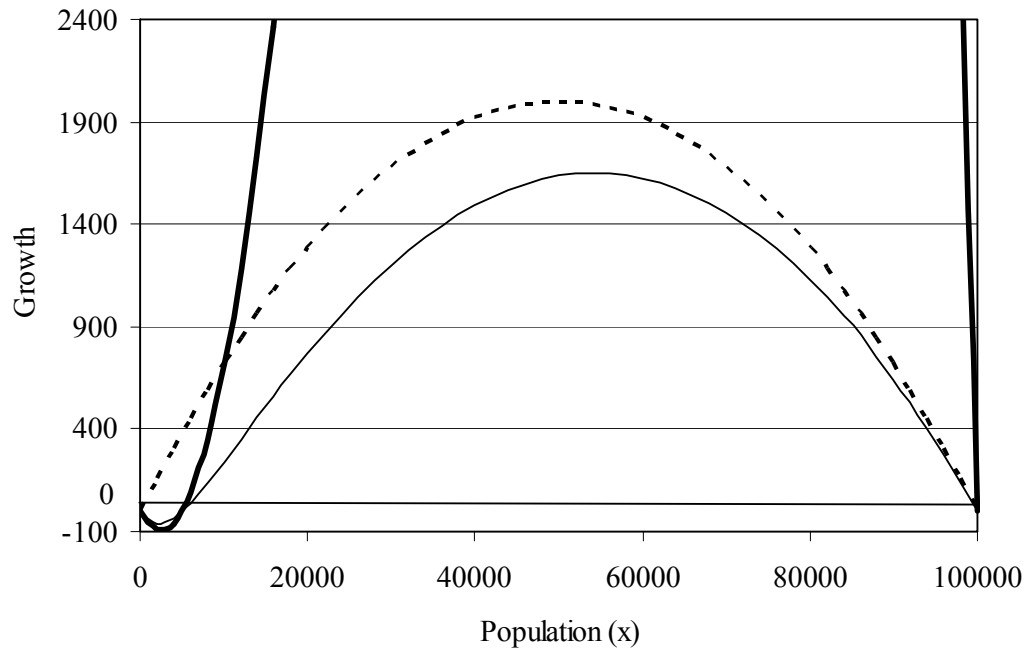


Figure 1a: Population growth for equations (1) (dashed line), (2) (thick solid line) and (3) (thin solid line), with $\gamma=0.08$, $M=5,000$ and $K=100,000$

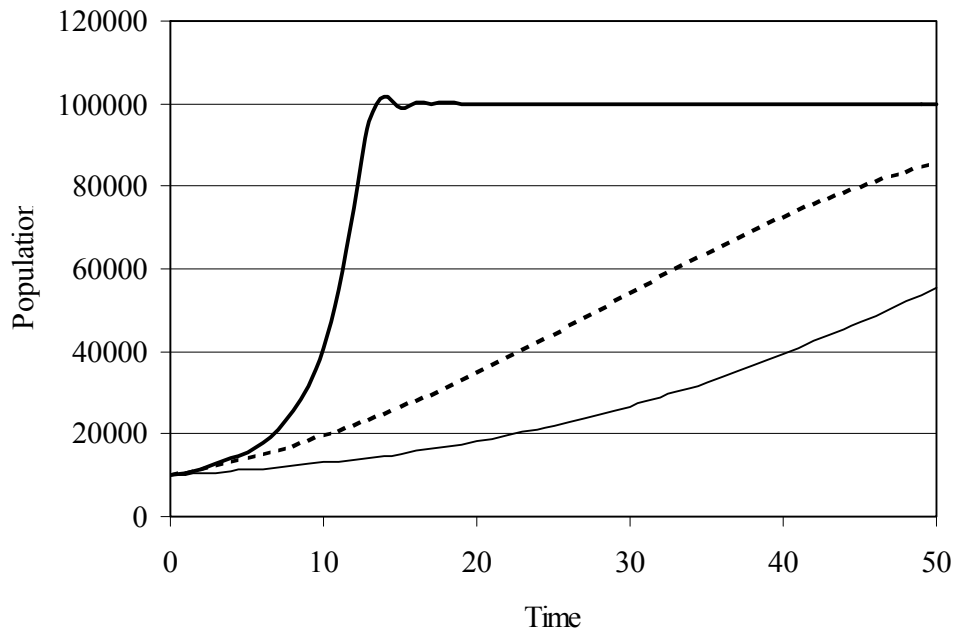


Figure 1b: Population response for growth equations (1) (dashed line), (2) (thick solid line) and (3) (thin solid line), with $\gamma=0.08$, $M=5,000$ and $K=100,000$

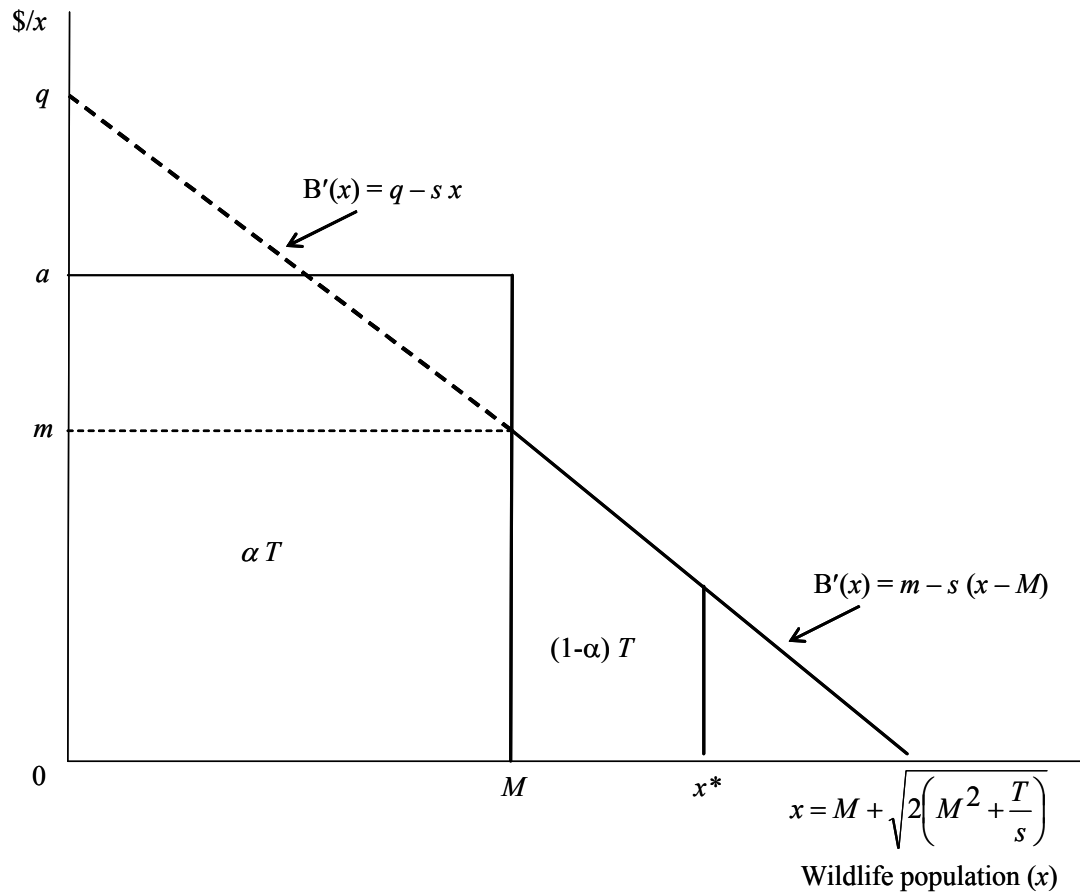


Figure 2: Marginal and total non-market benefits for protecting wildlife

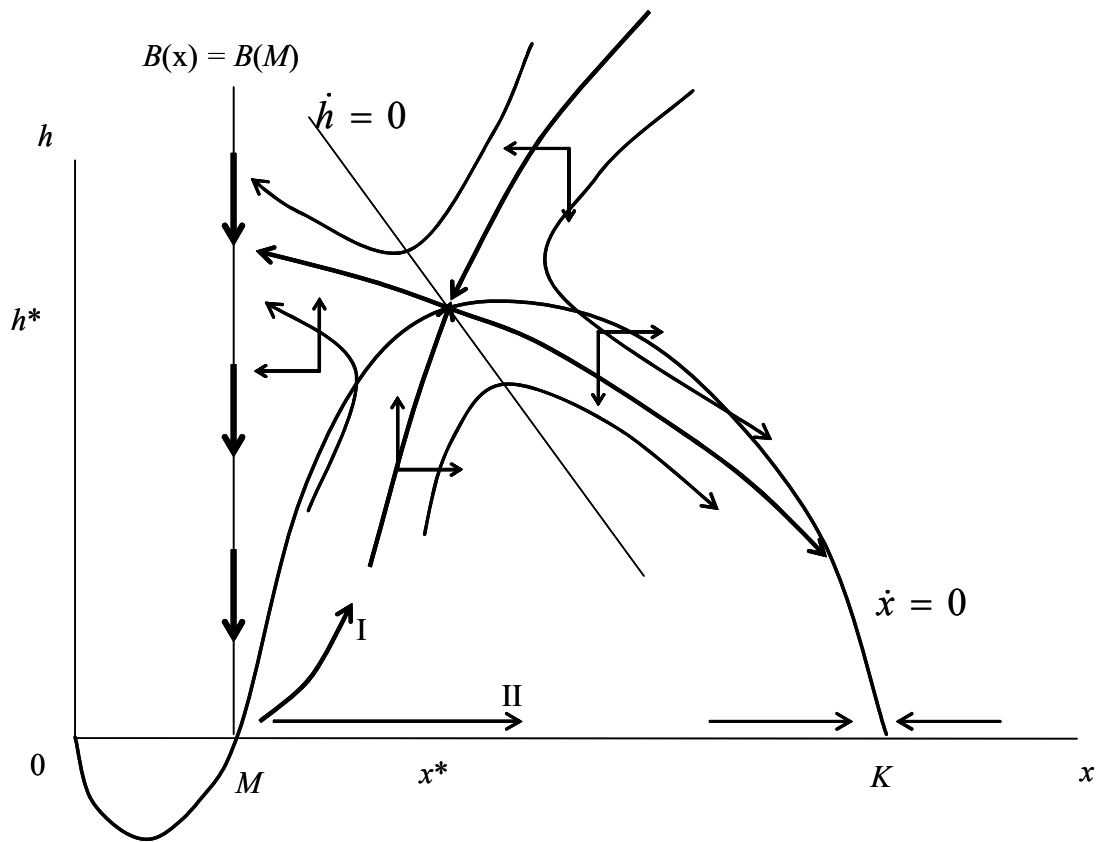


Figure 3: Phase-plane diagram for constrained dynamics