Optimal and Open Access Harvesting of Multi-Use Species in a Second-Best World*

Richard D. Horan[a] and Erwin H. Bulte[b]

[a]Assistant Professor, Department of Agricultural Economics
87 Agriculture Hall, Michigan State University, East Lansing, MI 48824-1039
phone: (517) 355-1301, FAX: (517) 432-1800; email: horan@msu.edu (**corresponding author**)

[b]Associate Professor, Department of Economics & CentER,
Tilburg University, P.O. Box 90153, 5000 LE Tilburg, Netherlands
e.h.bulte@kub.nl

JEL Category: Q20.

Optimal and Open Access Harvesting of Multi-Use Species in a Second-Best World

Abstract

Expansion of human populations and activities has caused increased conflicts between wildlife and humans. As a result, the distinction between resource and pest species has become blurry. We propose an economically-based classification of species based on a multi-use bioeconomic model. The classification of the steady state population of a species is shown to depend on both species' density and economic factors. We extend earlier work on multi-use (resource–pest) species by applying the theoretical model to a developing country context where property rights to wildlife are imperfectly enforced, so that second-best trade measures are often applied by the international community to promote conservation. Upon calibrating the model using data for the African elephant, we derive three further results. First, when comparing the optimal stock of a multi-use species to the open access stock, we find that the ranking in terms of abundance is ambiguous. Second, and consistent with existing literature on resource management in a second-best world, our case study supports the idea that trade bans have ambiguous effects on wildlife abundance. Third, due to a bifurcation effect characterizing the multi-use model's solution, strategic and temporary subsidizing by the North may enable them to free ride on conservation efforts of the South henceforth.

Key words: bioeconomics, elephants, management, nuisance, open access, pest, property rights, renewable resources, trade ban

Introduction

There is a growing awareness that many species cannot be classified dichotomously as either a resource that provides positive economic value (as a harvested commodity or via *in situ* conservation, e.g., fish or endangered species) or a pest/nuisance that yields negative economic value (causing damage *in situ*, e.g., insects and rodents). Instead, many 'traditional resources' are now seen as both a source of economic benefits and damages – a multi-use species (Zivin et al. 2000; Rondeau 2001).[1] Resources can turn into pests and vice versa, and often the *in situ* conservation of wild stocks yields both benefits and damages. A multi-dimensional management approach is needed to account for both of these attributes.

The African elephant (*Loxodonta africana*) is a good example. Elephant management is highly debated within the international community, with opinions divided about whether to maintain or remove the existing ban on international trade in ivory. The controversy arises, at least in part, because elephant populations represent an asset for some and a liability for others. Internationally, both the harvest (primarily, a demand for ivory) and preservation (existence values) of elephants yields economic values. At a more local level, elephants generate benefits through sales of meat and hides and also their flagship role in attracting tourists and generating revenues for the eco-tourism industry. But elephants also create considerable damage to crops and habitat, and encounters in rural areas result in some villager deaths every year. About 80% of the African elephant's range lies outside protected areas, and human-elephant conflict is increasing as the agricultural interface with elephant range expands (Hoare 1999). This conflict "has become a serious local political issue in recent years" (Hoare 1999, p.689). It is perhaps no surprise that in one survey in Cameroon, "41% of villagers polled wanted elephants moved and fenced in elsewhere. A significant minority wanted them all shot" (WWF 2000).

Several recent studies investigate the optimal management of so-called multi-use species (Rondeau 2001; Rondeau and Conrad 2002; Huffaker et al. 1992; Zivin et al. 2000). The focus on optimal wildlife management by a single planner is obviously appropriate for the case of private landowners in North America (struggling with migrating beavers or feral pigs) or local governments trying to deal with an exploding deer population. But the set-up may be less applicable to the context of developing countries where nuisance species often pose greater burdens upon farmers than in developed countries, and where property rights to many wildlife species are typically imperfectly enforced. The adverse effects of open access on wildlife conservation are well-documented for wildlife that yield only benefits. The results have inspired arguments in favor of institutional shifts from open access to sole ownership (but see de Meza and Gould 1992), although in practice institutional failure and excessive poaching typically triggers second-best conservation measures by the international community (e.g., the CITES trade ban on ivory). Open access situations have yet to be explored for wildlife that create both resource benefits and nuisance costs.

The present analysis focuses on the developing country context to extend earlier research in several ways. The paper is divided into two major sections. First, we consider optimal management by a single planner, expanding on prior work by developing an economic classification for species. We find that a species' classification can change over time with changes in species density. Moreover, different types of classifications relate to different types of equilibria, and also different types of dynamics that could affect policy choices. The planner's problem is also used as a point of comparison for the case of open access, which we develop in the second part of the analysis. The open access model involves two stakeholder groups with different incentives for harvesting wildlife: hunters, who hunt for commodities, and landowners, who may also hunt to reduce nuisance damage. Without landowners, we find a lack of property rights might enhance conservation relative to the social optimum. When landowners are added to the mix, a lack of property rights biases the results in the other direction and overharvesting is a more likely outcome. The conflicting incentives facing the groups have implications for the development and timing of conservation policies. For instance, we investigate a ban on the trade of wildlife commodities and find ambiguous impacts on wildlife conservation and welfare, depending on the institutional context and also the timing of the policy -- that is, the timing of the trade ban may matter for the final outcome. We also find that strategic and temporary subsidizing by the North, made possible by a bifurcation, may enable them to free ride on conservation efforts of the South henceforth.

As a motivating example, we analyze management and open access harvesting of the African elephant. Our study expands on prior analyses of elephant management (e.g., Bulte and van Kooten 1999, Barbier et al. 1990, Milner-Gulland and Leader-Williams 1992, Swanson 1994) by investigating how resource and nuisance values create conflicting incentives among multiple stakeholders, and how this affects optimal and open access dynamics and associated management options.

Biological and economic foundations

We begin by developing the necessary biological and economic foundations for analyzing the social planner's problem and the open access scenario associated with a country hosting medium-large elephant populations, such as Zambia or Kenya. The *in situ* stock of elephants, x, grows according to

$$\dot{x} = g(x) - h. \tag{1}$$

where $g(x)$ represents dendity-dependent growth of the stock ($g(0) = g(X) = 0$; $g_x(0) = \gamma$; $g_{xx} < 0$, where X is the carrying capacity and γ is the intrinsic growth rate) and h represents harvests.

Two types of economic values are associated with the *in situ* stock. The first value, denoted $U(x)$ ($U_x > 0; U_{xx} \leq 0$), represents tourism benefits from recreational activities such as elephant watching.[2] The second stock-dependent value is the economic damage created by the stock: $Z(x)$ ($Z_x > 0; Z_{xx} \geq 0$). These damages include agricultural and habitat damage as well as human mortalities. Brown (2000, p. 879) refers to elephants as a six ton locusts that each eat over 300 pounds of food per day, and he mentions that elephants killed 500 people in Zimbabwe in a recent seven-year period.

Demand for harvests is given by the inverse demand, $p(h)$ ($p_h < 0$). Define $\hat{h}$ as the harvest level that satiates demand, i.e., $p(\hat{h}) = 0$. Without nuisance damages, $h > \hat{h}$ is never optimal; $h > \hat{h}$ may be optimal if the benefits of nuisance reduction are large enough. Of course, demand is not likely to be satiated in the case of legalized trade because we're only dealing with one of many countries. But demand could be satiated under a trade ban as the demand for elephant products (mainly meats and hides in this case) would only be defined within the producing country. Harvesting costs are defined by the standard cost function $c(h,x)$ ($c_h > 0$; $c_x, c_{hx} < 0$; $c_{hh}, c_{xx} \geq 0$).[3] Given this specification, social net benefits are defined as $SNB = \int p(h)dh - c(h,x) + U(x) - Z(x)$.[4]

Socially optimal management under a trade ban

We begin by examining the socially optimal management of African elephants within a single country by an international agency, assuming perfect (and costless) enforcement of property rights and of the CITES ban on the international trade of ivory.[5] Later, we relax the assumption of enforceable property rights and consider open access, so that we can compare these two extremes. The problem faced by the social planner is

$$\begin{gathered}\underset{h}{Max} \int_0^{\infty} \left(\int_0^h p(h)dh - c(h,x) + U(x) - Z(x) \right) e^{-rt} dt \\ s.t. \quad \dot{x} = g(x) - h; \; x(0) = x_0\end{gathered} \tag{2}$$

where r is a constant discount rate. The current-value Hamiltonian associated with (2) is

$$H = \int_0^h p(h)dh - c(h,x) + U(x) - Z(x) + \lambda\left[g(x) - h\right] \tag{3}$$

where λ is the co-state variable. The necessary conditions for an interior solution are equation (1) and

$$p(h) - c_h = \lambda \tag{4}$$

$$\dot{\lambda} = r\lambda + c_x - U_x + Z_x - \lambda g_x \tag{5}$$

Conditions (4) and (5) are fairly standard. But unlike most bioeconomic applications, λ may be positive or negative (Zivin et al. 2000; Rondeau 2001): harvesting may represent a rent-generating activity or a costly activity mainly for damage control. The ambiguous sign of λ may result in a non-convex Hamiltonian, in which case we cannot assume sufficiency away a priori as in standard renewable resource models.[6] If multiple equilibria arise, the various candidates need to be considered on a one-by-one basis to determine which one maximizes payoffs, as is consistent with the approach of Tahvonnen and Salo (1996) and Huffaker and Wilen (1989). The sufficiency conditions will hold for such solutions, although this can only be verified numerically. We therefore do not present sufficiency conditions here but instead refer the reader to standard references for these conditions (e.g., Leonard and Van Long 1992; Seierstad and Sydsaeter 1987).

Steady states and species classifications

Interior steady states are found by setting $\dot{x} = \dot{\lambda} = 0$ in equations (1) and (5), given that $\lambda = p(h) - c_h$

$$h = g(x) \tag{6}$$

$$r = g_x + \frac{-c_x + U_x - Z_x}{p - c_h} = g_x + \frac{\phi}{\lambda} \tag{7}$$

Because of the potential non-convexities described above, multiple equilibrium candidates may satisfy (6) and (7) (see Rondeau 2001; Skiba 1978; Tahvonen and Salo 1996; Huffaker and Wilen 1989; and Mäler et al. 2000). Which candidate is optimally pursued may depend critically on initial stock levels. We analyze a non-convex case numerically below.

The RHS of (7) is the adjusted rate of return from holding elephants *in situ*. The term g_x is the *in situ* base rate of return, as a result of x being a reproducible asset (liability). The term $\Phi = \phi/\lambda$ accounts for additional costs and benefits from letting the asset (liability) grow. This term reflects several tradeoffs that give rise to the classifications in Table 1, formalizing some of the concepts raised by Rondeau (2001).

[Insert Table 1 about here]

The tradeoffs in Table 1, which are defined at the margin, vary along two dimensions. The first dimension (row entries) is the sign of the *ex situ* marginal net benefits. When $\lambda>0$, elephants are harvested as a resource or commodity (class I or class II). Alternatively, elephants are are harvested as a nuisance or pest when $\lambda<0$ (class III or IV). The second dimension (column entries) is the sign of the *in situ* marginal net benefits. When $\phi>0$, there are conservation incentives at the margin and elephants are an *in situ* asset (class I or class III). Alternatively, elephants are an *in situ* liability (class II or IV) when $\phi<0$, as there are marginal incentives to deplete the stock. Thus, a species could simultaneously be both a commodity and a liability, or both a nuisance and an asset. For instance, in the commodity/liability case (class II), harvests create rents while keeping the stock in check so that the liability does not get worse. However, it is not worthwhile to harvest more of the stock and turn the liability into an asset: the gains in terms of reduced liability do not outweigh the loss of rents that would arise from a lower price and greater marginal harvesting costs. A similar story holds for the nuisance/asset case (class III), where large harvests prevent the asset from becoming a liability.

How do these tradeoffs and resulting species classifications translate into optimal stock levels? Regardless of classification, a larger value of Φ implies a larger steady state stock: given r, a larger Φ implies a smaller g_x, which is consistent with larger equilibrium stocks (recall that $g_{xx}<0$). For a particular value of r, class II or III steady state stocks must therefore be smaller than class I or IV steady state stocks (in particular, when $\Phi<0$ so that $0<r<g_x$, the steady state stock is less than the stock that maximizes g, or the maximum sustainable yield level (MSYL)). In other words, for commodity equilibria, liability stocks are smaller than asset stocks. The reverse is true for nuisance equilibria.

Finally, the growth function and discount rate may restrict the equilibrium species class: classes II and III are not feasible when $r>\gamma$ as Φ must be positive by equation (7). Class II does not emerge because it is less costly in this instance to turn the liability into an asset. The larger is r relative to γ, the more beneficial it is to harvest the stock as a commodity and invest the rents elsewhere. This reduces x along with damages, and the stock becomes an asset. Class III does not emerge when $r > \gamma$ because it becomes more costly to invest in nuisance control; the stock grows and class IV emerges.

Optimal elephant management when trade is banned

We return to the case of elephant management because elephants are an excellent example to illustrate the key tradeoffs that matter in this context. The steady states are examined numerically by adopting the functional forms and parameter values used by Bulte and van Kooten (1999). Let $U(x) = \beta\ln(x)$, $Z(x)=\alpha x$, and $c(h,x) = ch/(qx)$, where $c/q = 692{,}300$, $\beta=2.6\times10^6$, $\alpha = 165$, $\gamma=0.067$ and $X=300{,}000$.[7] This specification is to a certain extent appropriate for countries with medium-large elephant populations like Zambia or Kenya, although it is best to consider this to be a numerical example rather than a rigorous case study. Bulte and van Kooten's demand function is for international trade in ivory, but this has been banned since 1989. Instead, meat, hides and ivory may only be traded in regional markets. Data is unavailable to calibrate demand under the trade ban; however, Barnes (1996) notes that elephant prices are less than average harvesting costs when harvests exceed a few thousand. Given this observation, we adopt the following specification: $p(h)=a-bh$, where $a= 1000$ and $b=0.8$.[8]

[Insert Table 2 about here]

The interior steady states are presented in Table 2. Three optimality candidates arise for each discount rate: the *commodity equilibrium* is a saddle with elephants being harvested as a commodity (class I or II, depending on the discount rate); the *unstable equilibrium* is either an unstable focus or an unstable, improper node with elephants being harvested as a nuisance; and the *nuisance equilibrium* is a saddle with nuisance harvests. The stability of each equilibrium has been calculated using the eigenvalues of the linearized dynamic system (see Conrad and Clark 1987). Below, we investigate the dynamics of the model in greater detail to determine which candidates are actually optimal. Before doing this, however, notice a few results from Table 2. First, steady state stocks are much smaller than levels that would occur in the absence of damages (i.e., when α=0). For example, when r=0.1 and α=0, there is a unique steady state stock of about 272,000 elephants (compared to 15,382 for the commodity equilibrium and 254,980 for the nuisance equilibrium in Table 2). Second, note that an increase in r reduces class I stocks (as in conventional resource models, because these stocks are a biological asset and r is the opportunity cost of leaving this asset *in situ*) but increases class IV stocks. Class IV stocks are larger for larger values of r because these stocks are a biological liability and r is the cost of devoting resources to divest this liability.

Optimal elephant management: identifying optimal equilibria

With multiple optimality candidates, transition paths indicate which steady states are indeed optimal and how they can be achieved given an initial stock level. The dynamics of the model are determined jointly by equation (1) and an expression for dh/dt, which is obtained by differentiating (4) with respect to time. For ease of notation, we adopt general functional specifications but maintain the features of the numerical specification defined above (e.g., c_{hh}=0, $c_{hx}h = c_x$, and $Z_{xx} = 0$) to derive

$$\dot{h} = [(r - g_x)(p - c_h) - U_x + Z_x + c_{hx}g(x)]/p_h \qquad (8)$$

The multiple optimality candidates arise because the $\dot{h} = 0$ isocline is not monotonic due to the changing sign of λ (see also Rondeau 2001; Tahvonen and Salo 1996; and Huffaker and Wilen 1989).

[Insert Figure 1 about here]

The phase plane associated with r=0.1 is presented in Figure 1. The curve λ=0 divides nuisance and commodity harvests: λ<0 for harvests above the λ=0 curve, and λ>0 for harvests below the λ=0 curve. Thus, the λ=0 curve divides the phase plane into subregions (distinct from isosectors) having different species classifications. Subregions are labeled according to the species classification in that subregion. Although Table 1 is defined for the steady state, the classifications may be extended for other combinations of *x* and *h* by incorporating the capital gain/loss term $\dot{\lambda}$ into the *in situ* marginal net benefits, or simply by obtaining the signs of $\lambda = p - c_h$ and $r - g_x$ for different combinations.

The isoclines in Figure 1 intersect three times in accordance with the three optimality candidates in Table 1.[9] Only the two saddles are actually candidates for optimality (Tahvonnen and Salo 1996; Huffaker and Wilen 1989). The initial stock determines which saddle should be pursued. Using the Runge-Kutta method (see Conrad and Clark 1987), we find the separatrix leading to the commodity equilibrium (path A) should be followed whenever $x_0 < x_0^L$=72,831. Path A highlights the result that elephants are optimally harvested as a nuisance/liability (class IV) for some time before becoming a commodity/asset (class I). Thus, it may be necessary to temporarily subsidize harvests before switching to quotas or taxes, depending on the incentives facing private decision-makers.

The separatrix leading to the nuisance equilibrium (path B) should be followed whenever $x_0 > x_0^U$=72,838 (which is the unstable equilibrium). Although the nuisance equilibrium yields negative net benefits, path B is socially preferred in this case because the costs of harvesting the stock down to the commodity equilibrium are too great. Finally, when $x_0^L \le x_0 \le x_0^U$, path A and path B are both options. Within this range, there exists a value x^* such that path A should be chosen when $x_0 < x^*$ and path B should be chosen when $x_0 > x^*$ (Tahvonen and Salo 1996; Huffaker and Wilen 1989).

[Insert Figure 2 about here]

The phase plane for *r*=0.05<γ is presented in Figure 2, which is labeled in the same manner as Figure 1. Now, the $\dot{h} = 0$ isocline has a vertical asymptote at the value of *x* that solves $\mathrm{r} = g_x$ (the dotted line at *x*=38,060). Below the curve λ=0, the asymptote separates species classes I and II. Above the curve λ=0, the asymptote separates classes III and IV. Unlike conventional bioeconomic models, changing the discount rate thus affects the qualitative features of the phase plane for a multi-use species, including the optimal approach dynamics as we describe next.

As in Figure 1, the isoclines intersect to create three interior steady states, or candidates for optimality. The commodity and nuisance saddles could be approached along path A and path B, respectively. But in contrast to Figure 1, either path A or path B could be followed for initial stock values in excess of x_0^L=144,346 elephants. Tahvonen and Salo (1996) and Huffaker and Wilen (1989) show that the monotonic path A is globally optimal in such instances. The difference between these results and those of Figure 1 are due to the differences in discount rates used. The smaller the discount rate, the larger the present value of future damages. Hence, society is better off by harvesting more nuisance elephants today to reduce future costs. For initial stock levels below the commodity steady state level, elephants are optimally harvested as a class II species. For all other initial stock levels, elephants may optimally be harvested as either a class II, III, or IV species.

Optimal elephant management when the trade ban is lifted

To conclude our discussion of optimal management, consider the combined effects of species class and the trade ban on elephant conservation. This is accomplished by comparing the results derived in the previous section with optimal management under conditions of legalized trade. Applying the legal-trade demand function used by Bulte and van Kooten (1999), $p=6397 - 0.04h$, optimal steady states under a legalized trade scenario are a unique saddle with elephants harvested as a commodity (22,044 elephants when $r=0.05$ [class II]; 6,765 elephants when $r=0.1$ [Class I]).[10] Consistent with Bulte and van Kooten (1999), the trade ban increases commodity equilibrium stocks under larger discount rates (e.g., $r>\gamma=0.067$, such that elephants are a class I species under legalized trade) and decreases commodity equilibrium stocks under lower discount rates ($r<\gamma$). Our results provide further insights into why the latter result occurs. Elephants are harvested as a class II species under legalized trade with $r<\gamma$. At the margin, there is an incentive to deplete the stock (because the *in situ* benefits are negative) when the price is reduced (as occurs under the trade ban). The stock is therefore culled to a lower level of abundance after the trade ban is implemented. Thus, a conservation policy such as a trade ban may optimally have the opposite effect than what is intended, depending on the species classification. Indeed, a trade ban reduces the optimal commodity equilibrium stock by almost 27% when r=0.05, from 22,044 elephants to 16,156 elephants.

But what was not previously recognized is that the effect (on wildlife stocks and welfare) of implementing a trade ban may depend on *when* the ban is implemented. Timing matters for sufficiently high discount rates ($r>\gamma$) because both the commodity and nuisance equilibria under a trade ban are locally optimal, depending on the initial stock level. Timing does not matter when discount rates are sufficiently low because a global optimum emerges in such cases. If discount rates are sufficiently high, then conservationists may prefer that a trade ban is introduced early enough that regional governments may prefer to pursue the nuisance (large-stock) equilibrium. Note this outcome is consistent with negative social welfare in range states. Indeed, Anderson and Blackhurst (1992, p.42) state "Conservationists have been prepared to insist on a ban on raw ivory trade in large part because they have not been required to compensate the losers", the African range states. In other words, the (wealthy) developed countries free ride on the conservation efforts of the (poor) developing countries.

Open access exploitation

Property rights to elephants are hard to enforce as these animals range over extensive areas, moving between public and private lands and even crossing borders. How do the results described above compare to outcomes arising from free entry in harvesting the species? In conventional open access models, entry (exit) in the harvesting industry occurs as long as profits are positive (negative), so that equilibrium rents are dissipated. A standard assumption in these models is that competition and free entry remove incentives for individuals to consider how their harvesting decisions affect future stocks (Gordon 1954). The conventional result is over-depletion of resource stocks. The logical corollary of this result is that an institutional shift from open access to sole ownership will enhance the scope for conservation. In this section we explore whether this is true or not for the case of a species that can be a resource or a nuisance. To this end, we compare harvesting equilibria of the government to those obtained under open access.

In the present case, some individuals have additional incentives to harvest: in addition to reaping the benefits (if any) of selling harvests in commodity markets they also may benefit from reduced nuisance – both now and in the future. For example, peasants may shoot elephants because they want to sell the ivory, but also because they want to prevent an elephant from entering their fields and destroying their crops. To the extent that damages are exclusive to these landowners, they will have incentives to consider how their harvesting decisions affect future stocks, and hence future damages. Landowners are the claimants of future damages and this claim will not be competed away (unlike with hunters, where competition reduces their claim on future harvesting benefits).

Without loss, consider two types of individuals.[11] First are hunters, indexed by j, who value harvests as a commodity and are not damaged by elephants. Elephants are not confined, so hunters may harvest on public lands (and possibly on private lands) and thus can enter and exit freely.[12] The second type of individuals are landowners, indexed by i, who are damaged by elephant stocks and may therefore value harvests both as a commodity and as a method of pest reduction. Landowners also face free entry/exit into harvesting, but they cannot freely reduce the damage burden placed upon them.

As described above, only landowners have incentives to consider the future. Thus, the model is to some extent a hybrid of conventional open access models (Gordon 1954) and rational expectations models (Berck and Perloff 1984). Consider the dynamic problem faced by individual landowners, noting that any rents that arise will instantaneously dissipate due to entry of hunters (i.e., $p - c/(qx) \leq 0$). This could emerge as an equilibrium, in which case hunters and landowners would be indifferent about harvesting at current levels as neither would have an incentive to harvest any more or less. For simplicity, we model an open-loop Nash equilibrium in which each landowner chooses harvests to maximize his/her net benefits, taking others' harvest decisions as given. Assume that all hunters and landowners face the same harvest cost functions, $c_i(h_i, x) = ch_i/(qx)$ (where h_i is the *i*th individual's harvest), and harvest price – as landowners could sell meat and hides from culled animals. Damages are spread evenly over the *N* landowners, i.e., $Z_i(x) = Z(x)/N = \alpha x/N$. Finally, assume that landowners reap a portion of tourism values, $U_i(x) = \zeta\beta\ln(x)/N$, where $\zeta<1$ since some tourism takes place on public lands.

Given this specification, each landowner *i* takes *p* as given and maximizes

$$\begin{aligned} NB_i &= \int_0^\infty [ph_i - ch_i/(qx) + \zeta\beta\ln(x)/N - \alpha x/N]e^{-rt}dt \\ &s.t. \quad \dot{x} = g(x) - h, \quad and \quad p - c/(qx) \leq 0 \end{aligned} \tag{9}$$

where $h = \sum_i h_i + \sum_j h_j$. The necessary conditions associated with the linear control problem (9) are

$$p - c/(qx) \overset{>}{\underset{<}{=}} \mu_i \qquad \forall i \tag{10}$$

$$\dot{\mu}_i = r\mu_i - ch_i/(qx^2) - \zeta\beta/(xN) + \alpha/N - \mu_i g_x - \rho_i c/(qx^2) \quad \forall i \tag{11}$$

$$p - c/(qx) \leq 0 \;\; ; \;\; \rho_i[p - c/(qx)] = 0 \qquad \forall i \tag{12}$$

where $p=p(h)$, μ_i is the co-state variable from landowner *i*'s (as opposed to the planner's) perspective, and ρ_i is the Lagrange multiplier associated with the rent dissipation constraint. Consider the singular solution in which condition (10) holds as an equality. When the zero profit condition is binding ($\rho_i \neq 0$), then conditions (12) and (10) imply $\mu_i = 0$. When the constraint is non-binding (i.e., $\rho_i=0$), then $\mu_i<0$ and condition (11) differs from its socially optimal counterpart (condition (5)) as individual landowners may not care about damages to neighbors and tourism benefits are not fully accounted for.[13]

Steady States

Two types of steady state equilibria may arise depending on the sign of μ_i. If μ_i=0, then elephants are a commodity as hunters have entered freely until profits are dissipated. Thus, the first type of equilibrium, which we denote the zero profit equilibrium, involving hunters and possibly landowners, and is characterized by condition (6) and the zero profit condition $p = c/(qx)$. These are the standard equilibrium conditions in conventional open access models (Berck and Perloff 1984). Note that, in contrast to most open access models, there are multiple steady state candidates associated with the zero profit condition. This is not due to nuisance damages, but rather the endogenous price and stock-dependent harvest costs as the zero profit curve $p(h)$-$c/(qx)$=0 intersects the $\dot{x} = 0$ isocline in three places.

The second type of equilibrium, denoted a nuisance equilibrium, occurs when μ_i<0 and ρ_i=0 (i.e., nuisance harvesting). In this case, profits from sales are negative: all hunters have exited and only landowners harvest elephants, doing so as pest control. From condition (10) and given identical landowners, it is clear that $\mu_i = \mu_j = \mu \;\; \forall i,j$. The equilibrium conditions in this case are therefore given by (6) and

$$p - \frac{c}{qx} = \frac{ch/(x^2N) + \zeta\beta/(xN) - \alpha/N}{r - g_x} \qquad \forall i \qquad (13)$$

This condition reduces to the zero profit condition as $N \to \infty$: damages are spread out over too many individuals, and hence no single landowner will choose to incur the costs of harvesting elephants as a nuisance in order to reduce damages that are largely incurred by others – hunting would be a pure public good in this case. However, for finite *N*, some harvesting will be done by landowners as a means of pest control.

Given this discussion, the first open access result is that multiple steady states are possible.

Unlike the case of optimal management, however, multiple steady states may arise for two distinct reasons. Separate conditions define the zero profit and nuisance equilibria: (a) condition (6) and the zero profit condition if the solution involves hunters and landowners hunting elephants as a commodity, and (b) conditions (6) and (13) if the solution involves just landowners hunting to avoid damage. Equilibria (a) and (b) may each have one or more solutions. But the particular solution(s) that are ultimately pursued depend on the dynamics of the system, to which we now turn.

Open access elephant harvesting: dynamics

Applying the numerical model from above, open access equilibrium candidates are presented in Table 3 for the case of ζ=0.3 and r = 0.1, and for two values of N: N=1 and N=100. The phase planes can be analyzed to determine which candidates will be pursued. The phase plane for N=1 is illustrated in Figure 3. Figure 3 looks similar to Figure 1, although an important difference is that the λ=0 curve, labeled as π=0 in Figure 3, now represents the zero profit locus along which hunters would harvest elephants (at least, in the absence of competition by landowners).[14] The π=0 curve intersects the $\dot{x} = 0$ curve in three places, indicating three zero profit equilibria – two of which are stable and one which is unstable (in the absence of landowner actions). One stable equilibrium (equilibrium 1) occurs at a lower stock level than any of the socially optimal stocks listed in Table 2, as might be expected under open access. The other stable equilibrium (equilibrium 3) occurs at a larger stock level than any of the socially optimal stocks in Table 2. This clearly contrasts with models not having a nuisance component: hunters harvest too few animals because they are not responsible for spillover damages caused by migrating wildlife and disregard the benefits of culling for local landowners. Thus, a lack of property rights may enhance conservation, at least in the absence of any landowner actions.

[Insert Table 3 and Figure 3 about here]

But where the stock ultimately stabilizes does depend on the actions of landowners. The $\dot{h} = 0$

isocline in Figure 3 looks similar to its counterpart in Figure 1, except that it only intersects the $\dot{x} = 0$ isocline twice. A third intersection would have occurred in the absence of the zero profit constraint, but with that constraint in place the $\dot{h} = 0$ isocline "ends" (i.e., is cut off) where it meets the π=0 curve (because outcomes below this curve would generate positive profits which, by assumption, are instantaneously dissipated by hunters' entry). The combination of hunters and landowners therefore alters the dynamics as previously described for the social optimum. For initial stock levels in excess of 82,700 elephants (equilibrium 5), the landowner harvests elephants as a nuisance (so that hunters do not enter) along a saddle path that leads to the nuisance equilibrium (equilibrium 5). Note the open access nuisance equilibrium stock is smaller than that of the social optimum (because the landowner does not reap all tourism benefits) and also the stock that hunters would have pursued in the absence of landowners (because, unlike hunters, the landowner does take into account nuisance damages). For initial stocks slightly below 82,700 elephants, the landowner harvests elephants as a nuisance (again, crowding out hunters) along a saddle path *until* the zero profit threshold is reached. At this point, hunters enter and diminish the stock to the zero profit equilibrium 1, which is at a lower stock level than the landowner would have pursued (this other stock is not reported in Table 3 since it is not a solution given the zero profit constraint). Note that the approximate threshold of 82,700 elephants (determining whether the system ends up in the small-stock zero profit equilibria or in the abundant-stock nuisance equilibria) is greater than that in the social optimum. Relative to the social optimum, fewer initial stock levels will lead to a nuisance (large-stock) equilibrium and more will lead to the commodity equilibrium under open access. Hence, while there are incentives to conserve when landowners do not hunt, there are incentives to over harvest when landowners do hunt.

To consider some of the conflicting interests that may arise between landowners/hunters, local governments, and the international community, suppose the system is headed for the (low-stock) zero profit equilibrium 1. The local government might have an incentive in this case to tax harvests or subsidize conservation efforts to increase the stock. But depending on the current stock level, the government might not want to pursue the (high-stock) nuisance equilibria, instead determining the (low-stock) commodity equilibria from Table 2 is socially optimal. The international community, however, might prefer a larger stock level because it gets the transboundary benefits associated with thicker stocks but none of the damages. In this case, the multiple equilibria in the open access case give rise to an interesting policy solution for international governments – one that may allow them to free ride on the conservation efforts of others.

The international community (possibly other nations but more likely an NGO) could *temporarily* subsidize landowners (not hunters) to increase stock levels through a subsidy of the form sx, where s is the per unit subsidy rate. Essentially, the subsidy would increase the range of initial stock values for which landowners would be willing to allow the stock to grow. In terms of figure 3, the subsidy would flatten the northwest hump of the $dh/dt=0$ isocline so that it no longer intersects the $dx/dt=0$ isocline at the commodity and unstable equilibria -- the subsidy creates a bifurcation. As a result, landowners always have incentives to allow the stock to grow (although hunters become a limiting factor in this case).[15] Once the stock is increased past the approximate threshold of 82,700 elephants, the subsidy could be removed and landowners and hunters would pursue the nuisance equilibria on their own. Local governments would also find it beneficial to encourage increased conservation at this point. Hence, NGOs and/or others can take advantage of a bifurcation that allows them to pursue large stocks while only incurring a fraction of the costs.[16] Of course, this strategy only works when $r > \gamma$ for the landowner. Otherwise, the phase plane is similar to figure 2 and a (low stock) global optimum emerges. Hence, for small private discount rates, a permanent subsidy would be needed to encourage conservation.

Now suppose N>1. Table 3 present results for the case of N = 100, although we find that all cases for which N>1 are qualitatively similar. The phase plane (not presented) is analogous to Figure 2, although as above the dynamics are now altered due to the zero profit curve. Landowners in this case do not account for the full cost savings and tourism benefits that arise from a larger stock. As a result, they no longer pursue the nuisance equilibrium (equilibrium 7). Instead, they pursue a commodity equilibrium (i.e., such as the one that arises in Figure 2 in the absence of the zero profit constraint), but they never reach it because hunters emerge first and drive the stock down further to the zero profit equilibrium 1.

Note that the policy solution of a temporary stock subsidy, as described above for the case of N=1, does not work when N>1: society is doomed to a low stock unless a government is willing to provide a permanent subsidy. Thus, provided that private discount rates are sufficiently large, it is to an NGO's advantage to encourage cooperation among landowners. If landowners can be encouraged to operate as a single entity (so essentially N=1), then NGOs can take advantage of a bifurcation and offer short term payments. If either of these conditions is violated (i.e., there are multiple non-cooperating landowners or cooperating landowners who apply a low discount rate), then permanent subsidies are needed to promote conservation in equilibrium.

The impact of the ivory trade ban under open access

Earlier we explored the impact of a trade ban on conservation when elephants were being managed optimally. What is the impact when there is imperfect enforcement so that open access emerges? Open access under legalized trade can be shown to result in a single equilibrium at a very low stock level (108 elephants). Both stable equilibrium stock levels under the trade ban are larger, indicating that the trade ban generally promotes conservation under an open access regime. However, the particular equilibrium that is approached after the trade ban is implemented depends on the stock value at the time of implementation. Thus, as above, the timing of the trade ban matters for both elephant stocks and welfare levels.

Discussion and concluding remarks

As human populations and activities continue to expand and (direct and indirect) interaction with wildlife is increased, more and more species are being discovered to exhibit both resource and nuisance attributes. In this paper a multi-use bioeconomic model was used to develop an economically-based classification of species. The classification depends on both species' density and economic factors, and it can change over time as these features change. Multiple equilibria may emerge in conjunction with the various classifications, and it may be possible to approach any one of these depending on the initial state of the system, the management regime adopted, and the timing of management decisions.

To gain additional insight we developed a numerical example of elephant management. The results shed some light on the ongoing and heated international discussions (e.g., CITES) on the best strategy to deal with this large mammal. An important finding is that the classification of elephants is determined by their (local) level of abundance (which varies greatly over Africa; see Said et al. 1995). Different steady state classifications are possible, and different types may be distinguished along the transition dynamics towards steady states. It is therefore easy to understand why international discussions on the ivory trade ban have proven to be difficult, as have discussions focusing on many other species whose management is debated in the international arena (whales, tigers, bears, etc.). While talking about one biological species, delegates from different countries are actually discussing the fate of different "types" of animals who may be hunted for different reasons by many different types of people (e.g., poachers, landowners who suffer nuisance damages), depending on the property rights regimes in place. Thus, it would be difficult to agree on a single management tool (such as the trade ban) since a single tool is insufficient for managing a plethora of "types" of animals. Rather, conservation instruments should be evaluated at the country or regional level and they should be regularly updated as animal densities change.

The potential for multiple equilibria highlights the importance of history in conservation, particularly the timing of conservation policies, as early efforts will to a large degree determine in which equilibrium the system comes to rest. Significant conservation efforts by the international community in early periods, for example, might put range states on a trajectory towards a high-abundance stable steady state. An interesting policy implication is that the international community may only have to offer short-term incentives for conservation, after which it may become optimal for local managers to pursue conservation on their own. The temporary incentives ensure that the system proceeds on a trajectory towards an abundant wildlife stock until a time at which the system is no longer in danger of flipping to a low abundance steady state. In contrast, low or zero conservation efforts early on could trigger a trajectory towards a low-abundance steady state. Once on a low-abundance trajectory it may become too expensive to switch to an alternative trajectory that encourages conservation.

References

Anderson, K. and R. Blackhurst. *The Greening of World Trade Issues,* Hertfordshire: Harvester Wheatsheaf, 1992.

Barbier, E., J. Burgess, T. Swanson and D. Pearce. *Elephants, Economics and Ivory*. London: Earthscan Publications, 1990.

Barnes, J.J. "Changes in the Economic Use Value of Elephant in Botswana: The Effect of International Trade Prohibition." *Ecological Economics* 18(1996): 215-230.

Berck, P. and J. Perloff. "An Open Access Fishery with Rational Expectations." *Econometrica* 52 (1984): 489-506.

Brander, J. and M.S. Taylor. "International Trade and Open Access Renewable Resources: The Small

Open Economy Case." *Canadian Journal of Economics* 30(1997): 526-552.

Brown, G. "Renewable Natural Resource Management and Use Without Markets." *Journal of Economic Literature* 38: 875-914.

Bulte, E.H. and G.C. van Kooten. "Economics of Antipoaching Enforcement and the Ivory Trade Ban." *American Journal of Agricultural Economics* 81(1999): 453-466.

Bulte, E.H., R.D. Horan, and J.F. Shogren, “Elephants: Comment.” *American Economic Review*, In press.

Carlton, J.T. *Introduced Species in U.S. Coastal Waters: Environmental Impacts and Management Priorities*, Arlington, VA: Pew Oceans Commisison, 2001.

Coase, R.H. "The Problem of Social Cost." *J. Law Econom.*, III (1960): 1-44.

Conrad, J.W. and C.W. Clark, *Natural Resource Economics: Notes and Problems,* New York: Cambridge University Press, 1987.

de Meza, D. and J.R. Gould, "The Social Efficiency of Private Decisions to Enforce Property Rights." *Journal of Political Economy* 100(1992): 561-580.

Flaaten, O. and K. Stollery. "The Economic Costs of Predation." *Environmental and Resource Economics* 8(1996): 75-95.

Freeman III, A.M. *The Measurement of Environmental and Resource Values: Theory and Method*, Washington, DC: Resources for the Future, 1993.

Gordon, H.S. "The Economic Theory of a Common Property Resource: The Fishery." *Journal of Political Economy* 62(1954): 124-142.

Hoare, R.E. "Determinants of Human-Elephant Conflict in a Land Use Mosaic." *Journal of Applied Ecology* 36 (1999): 689-700.

Holmes, B. "Day of the Sparrow." *New Scientist* 27(1988): 2-35.

Horan, R.D. and J.S. Shortle. “Optimal Management of Multiple Renewable Resource Stocks: An Application to Minke Whales.” *Environmental and Resource Economics* 13(1999): 435-458.

Huffaker, R.G. and J.E. Wilen. "Dynamics of Optimal Stocking in Plant/Herbivore Systems." *Natural Resource Modeling,* 3(1989): 553-573.

Huffaker, R.G., M.G. Bhat and S.M. Lenhart. "Optimal Trapping Strategies for Diffusing Nuisance Beaver Populations." *Natural Resource Modeling*, 6(1992): 71-97.

Karp, L. and D. Newberry. "Intertemporal Consistency Issues in Depletable Resources", Chapter 19 in: *Handbook of Natural Resources and Energy Economics* vol. III. A.V. Kneese and J.L. Sweeney (eds), pp881-934, North Holland: Amsterdam, 1993.

Kremer, M. and C. Morcom. "Elephants" *American Economic Review* 90(2000): 212-234.

Leonard, D., and N. Van Long. *Optimal Control Theory and Static Optimization in Economics*, Cambridge: Cambridge University Press, 1992.

Mäler, K.-G., A. Xepapadeas, and A. de Zeeuw. "The Economics of Shallow Lakes." Working paper, Center for Economic Research, Tilburg University, The Netherlands.

Michigan Department of Environmental Quality (MDEQ). *Nonindigenous Aquatic Nuisance Species State Management Plan: A Strategy to Confront Their Spread in Michigan*. http://www.deq.state.mi.us/ogl/plan.html, (Downloaded October 25, 2001).

Millner-Gulland, E.J. and N. Leader-Williams. "A Model of Incentives for the Illegal Exploitation of Black Rhinos and Elephants: Poaching Pays in Luangwa Valley, Zambia." *Journal of Applied Ecology*, 29 (1992): 388-401.

Rondeau, D. "Along the Way Back from the Brink." *Journal of Environmental Economics and Management* 42(2001): 156-182.

Rondeau, D. and J. Conrad. "Managing Urban Deer." *American Journal of Agricultural Economics*, (2002), In Press.

Said, M., R,N. Chunge, G.C. Craig, C.R. Thouless, R.F.W. Barnes and H.T. Dublin. *African Elephant Database 1995*. Occasional paper of the IUCN Species Survival Commission no. 11, Gland, Switzerland: IUCN, 1995.

Seierstad, A., and K. Sydsaeter, *Optimal Control Theory with Economic Applications*, New York: North-Holland, 1987.

Skiba, A.K. "Optimal Growth with a Convex-Concave Production Function." *Econometrica* 46 (1978): 527-539.

Smith, F., G.C. Daily and P.R. Ehrlich. "Human Population Dynamics and Biodiversity Loss." *The Economics and Ecology of Biodiversity Decline*. T.M. Swanson, ed. Cambridge: Cambridge University Press, 1995.

Swanson T.M. "The Economics of Extinction Revisited and Revised: A Generalised Framework for the Analysis of the Problems of Endangered Species and Biodiversity Losses." *Oxford Economic Papers*, 46 (1994): 800-821.

Tahvonen, O. and S. Salo. "Nonconvexities in Optimal Pollution Accumulation." *Journal of Environmental Economics and Management*, 31(1996): 160-177

World Wildlife Fund (WWF). *Elephants in the Balance: Conserving Africa's Elephants*, www.panda.org/resources/publications/species/elephants/index.html, 2000.

Zivin, J., B.M. Hueth and D. Zilberman. "Managing a Multi-Use Resource: The Case of Feral Pig Management in California Rangeland." *Journal of Environmental Economics and Management* 39(2000): 189-204.

Table 1. A classification of marginal animal species (for interior solutions).

ex situ marginal net benefits	*in situ* marginal net benefits	
	$-c_x + U_x - Z_x = \phi > 0$	$-c_x + U_x - Z_x = \phi < 0$
$p - c_h = \lambda \geq 0$	I. commodity/asset[a]	II. commodity/liability[b]
$p - c_h = \lambda < 0$	III. nuisance/asset[b]	IV. nuisance/liability[a]

Notes: [a]Requires $r > g_x$. [b]Requires $r < g_x$.

Table 2. Steady state optimality candidates under a trade ban.

Discount Rate	Steady State Outcomes	Commodity Equilibrium	Unstable Equilibrium	Nuisance Equilibrium
$r = 0.05$	Stock	16,156	147,037	234,206
	Harvest	1,024	5,023	3,441
	Social net benefits (annual $ in millions)	23.09	1.58	-7.8
	Species class	II	IV	IV
	Equilibrium Type	Saddle	Unstable focus	Saddle
$r = 0.1$	Stock	15,382	72,838	254,980
	Harvest	978	3,695	2,564
	Social net benefits (annual $ in millions)	23.08	15.29	-9.78
	Species class	I	IV	IV
	Equilibrium Type	Saddle	Unstable focus	Saddle
$r = 0.15$	Stock	14,311	43,815	262,163
	Harvest	913	2,507	2,215
	Social net benefits (annual $ in millions)	23.05	20.51	-10.57
	Species class	I	IV	IV
	Equilibrium Type	Saddle	Unstable, improper node	Saddle

Table 3. Open access optimality and zero profit candidates under a trade ban.

Steady State Equilibrium Candidates	Equilibrium Type	Steady State Stock	Steady State Harvest	Social Net Benefits (annual $ in millions)
Hunter/Landowner Equilibria (*N*=1)[a]				
1. Zero profit*	Stable	7,200	48	16.99
2. Zero profit	Unstable	19,200	1,205	23.06
3. Zero profit	Stable	280,075	1,246	-12.98
4. Nuisance	Unstable	82,700	4,013	13.33
5. Nuisance*	Saddle	253,500	1,258	-9.63
Hunter/Landowner Equilibria (*N*=100)[a]				
Zero Profit Equilbria 1-3 as described above				
6. Nuisance	Unstable	19,874	1,243	23.04
7. Nuisance	Saddle	279,844	1,260	-12.94

Note: [a] The three zero profit equilibria correspond to the three equilibria that would arise with hunters but no landowners. The * indicates which equilibria may actually be pursued. For the case of *N*=100, only the zero profit equilibrium 1 will be pursued.

Endnotes

1. At least four factors may contribute to the changing perspectives for many species. (1) As human development exploits and alters ecosystems, predator-prey relations having little economic impact in pristine ecosystems are now seen as a source of economic damage. For instance, whales are valued both as a commodity and as a conservable resource (Horan and Shortle 1999), but they are also a source of damage to fishermen who must compete with them for commercially valuable fish (Flaaten and Stollery 1996) -- a problem that has become more pervasive in recent years due to conservation efforts that have increased whale populations. (2) As human encroachment diminishes wildlife habitats, economic damages caused by wildlife may increase. For example, habitat for deer and elephants has been significantly altered over the past century. With diminished natural food sources and with traditional migration routes blocked by development, these animals increasingly invade agricultural lands in search of food and water, creating damages as they eat and trample crops and forage. Deer and moose are also increasingly responsible for auto accidents in North America and Northern Europe as road and highway expansions have encroached upon and divided their habitat. (3) Increases in world trade have been accompanied by increases in the artificial introduction of species into non-native environments (Carlton 2001). While a species may be of value in its native habitat, it is often viewed as a pest in non-native habitats. Without natural predators to curtail population growth, non-native or exotic species can out-compete native species for food and habitat. Exotics are increasingly considered a major factor in biodiversity loss (Holmes 1998), and can also damage economic activities more directly. (4) Related to the second and third factors, there are increasing efforts to re-introduce species that were previously locally extinct (Rondeau 2001), such as wolves, grizzlies, and beavers. Obvious conflicts may arise between humans and these sorts of animals, particularly in locations that have adapted to their absence. For instance, farmers who increased land areas devoted to crops and livestock after a local extinction occurred may be more vulnerable than ever to species re-introductions.

2. The function $U(x)$ could also include non-use existence benefits (see e.g., Freeman 1993), and the effect of $U(x)$ is the same as if U was an existence value. We do not model existence values in the numerical example to follow because there is little data available on these values and because these values would be largely external to countries such as Zambia or Kenya. They are presumably much larger at the international level, but even so marginal existence values may be small when the stock is in no danger of extinction.

3. In addition to these regular harvesting costs, it may be costly to dispose of harvested nuisance animals for which there is no demand (i.e., $h \geq \hat{h}$), or there may be social disutility (cost) from not disposing of them. For instance, suppose 10,000 nuisance elephants are culled. Disposal costs are likely to be significant, as is the disutility associated with 10,000 rotting carcases. Generally, three disposal options exist: (i) no disposal (natural decomposition), (ii) physical disposal (e.g., cremation), and (iii) paying those having a negative marginal utility of consumption (such that $p(h)<0$) to consume the harvested animals. Disposal costs are the least cost combination of these options, and for simplicity we assume the third option is the least cost approach.

4. We do not consider issues associated with ivory storage, although this is not an issue assuming the trade ban remains in effect. See Kremer and Morcom (2000) and Bulte et al. (in press) for discussions of storage issues in the case of legalized ivory trade.

5. In the present model it is equivalent to think of the social planner as a national wildlife agency since demand is defined at the country level under a trade ban and since we are not modeling existence values, which would largely be external to African range states. If we were considering existence values, then the international and domestic social planners would choose different resource allocations unless there was some mechanism in place for local governments to capture non-use existence values. Also note that the planner takes the trade ban to be exogenous, which is probably the case when considering only a single country. According to the African Elephant Database (Said et al. 1995), some 25 African countries have at least 1000 elephants and therefore across-the-board CITES trade bans are likely more affected by developments in all countries than by management decisions in a single country. But more generally the existence of a trade ban is not independent of either international non-use values or the degree to which access is regulated among all nations that host elephant populations. We are grateful to a referee for pointing this out.

6. The Hamiltonian can be non-convex for other reasons besides the shadow value. For instance, Tahvonen and Salo (1996) analyze the case of a non-convex damage function. $Z(x)$ could also be non-convex in reality, with marginal damages at first increasing and then decreasing as some maximum level of damages are approached. However, elephants are known for killing people in addition to crops (Brown 2000), and so the assumption $Z_{xx} \geq 0$ is probably reasonable for a large range of stock levels.

7. The functional forms are taken from Bulte and van Kooten (1999), although the application of the present model is quite different. They focused on management and anti-poaching enforcement issues by modeling the interaction between governments and poachers.

8. The qualitative results are unaffected under a large range of reasonable values for *a* and *b*.

9. Because of the uncertainty associated with the demand curve for the trade ban case, we explored several other demand curves. The qualitative results were the same for all cases as long as *b* is not too small. When *b* is sufficiently small, the downward sloping portion of the $\dot{h} = 0$ isocline shifts up and we get a single equilibrium. But even in that case, nuisance harvesting is optimal. With smaller discount rates, we also find asymptotic phase planes (as described below) in the single equilibrium trade ban case.

10. Market demand under a trade ban is limited to domestic demand for elephant products. Under legalized trade, market demand is given by the international demand for elephants, which includes both domestic and non-domestic willingness to pay for elephant products. Suppose domestic demand is given by $Q_D = a_D - b_D P$ and that non-domestic demand is $Q_{ND} = a_{ND} - b_{ND} P$, so that the international inverse demand is $P = (a_D + a_{ND})/(b_D + b_{ND}) - 1/(b_D + b_{ND})Q$. It is easy to verify that the international inverse demand curve should be less steeply sloped than the domestic curve. Moreover, the international choke price should be greater than the domestic choke price as long as the domestic choke price is less than the choke price in non-domestic markets.

11. Our model does not do full justice to the complex case of multiple use in Africa. As indicated by a referee, there are really three types of people who may want to shoot elephants: 1) hunters who value elephants as a commodity, and enter until profits have dissipated, 2) private landowners who care about controlling the nuisance costs of elephants (in addition to any

sellable commodities that are produced in the process of killing elephants), and 3) trophy hunters, who are typically willing to pay formidable amounts for the right to kill an elephant. We only consider poachers and landowners and ignore trophy hunting altogether. The reason is twofold. First, in terms of elephant mortality, trophy hunting is relatively unimportant. Second, to accurately model trophy hunting, one really needs a sex and age structured model, which would greatly complicate the model.

12. In Zivin, Hueth and Zilberman's (2000) feral pig model, the pigs are assumed to somehow be restricted to private lands so that landowners can charge hunters to shoot the pigs. In our model, landowners could charge fees for hunting on their land. However, we assume that public lands suitable for hunting are not scarce and so landowners have no motivation to charge for hunting on their lands (as there is no demand for this).

13. The tourism industry is not fully involved with the solution (since $\zeta<1$). However, Coase (1960) would argue that this industry might bargain with landowners and/or hunters to conserve elephants, as long as the transactions costs of these negotiations are not too great.

14. Since landowners take p as given, landowner i's problem is linear in the control variable h_i. Accordingly, it is optimal for landowners to set harvest rates at their maximum or minimum values whenever condition (10) is not satisfied as an equality, so that the singular solution is approached along the most rapid approach path. In most linear control bioeconomic models with p fixed, the singular solution results in a specific value of x. But p is endogenous at an aggregate level in the present model. The result is that the singular solution is a *path* as opposed to a *point*. Aggregate harvests, h, therefore vary over time and the $\dot{h} = 0$ isocline is well-defined along the singular path. See Conrad and Clark (1987, pp.28-30) for a brief discussion of singular paths.

15. Note that a stock-based subsidy paid to hunters would be ineffective as entry and hence harvests would only be increased by the subsidy.

16. The idea of a "temporary subsidy" only works when African range states are naïve (unsuspecting to be subjected to strategic manipulation) – otherwise they will note that the subsidy scheme is dynamically inconsistent, and will be aborted by the self-interested international community after the threshold has been crossed and the system has entered the region where trajectories lead to the high-stock equilibrium (see Karp and Newberry (1993) for more on the issue of dynamic inconsistency).