Resource or Nuisance?
Managing African Elephants as a Multi-use Species*

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Abstract

Increasing human interference with natural systems causes us to re-think our perception of wildlife species and the economic choices society makes with regards to their management. Accordingly, we generalize existing 'bioeconomic' models by proposing an economically-based classification of species. The theoretical model is applied to the case of African elephant management. We demonstrate that the classification of the steady state population of a species depends on both species' density and economic factors. Our main results are threefold. First, we demonstrate the classification-dependent possibility of multiple equilibria and perverse comparative statics for multi-use species. Second, upon comparing the optimal stock of a multi-use species to the stock under an open access regime, we find that the ranking in terms of abundance is ambiguous. Finally, and consistent with existing literature on resource management in a second-best world, our case study supports the idea that trade measures have ambiguous effects on wildlife abundance under open access.

Key words: renewable resources, pest, nuisance, management, trade measures, exotic species, property rights, elephants, bioeconomics

1. Introduction

Increasing human interference with natural systems causes us to re-think our perception of wildlife species and the economic choices society makes with regards to their management. Conventionally, economic analyses make management recommendations that are based on a one-dimensional point of view, as a species is classified dichotomously as either a (conventional) resource that provides positive economic value (either as a harvested commodity or via *in situ* conservation, e.g., fish or endangered species) or a pest or nuisance that yields negative economic value (as *in situ* populations cause damages, e.g., insects, rodents, and weeds). This is not surprising given that conventional resources and nuisance species are typically viewed as separate entities. But this perception is changing. Increasingly, species that have traditionally been viewed as a resource are now seen as both a source of economic benefits and damages. Thus, a multi-dimensional approach to management, that accounts for both of these attributes, is required.

At least three factors may contribute to the changing perspectives for many species. First, as human development continues to exploit and alter ecosystems, predator-prey relations having little economic impact in pristine ecosystems are now seen as a source of economic damage. For instance, while whales are valued both as a commodity and as a conservable resource [9], they are also a source of damage to fishermen who must compete with them for commercially valuable fish [12]. This problem has become more pervasive as recent conservation efforts have increased whale populations.

Second, as human encroachment diminishes wildlife habitats, economic damages caused by wildlife may increase. For example, habitat for animals such as 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 [5]. 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.

Third, increases in world trade have been accompanied by increases in the artificial introduction of species into non-native environments.[1] 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 [16],[2] and can also damage economic activities more directly. For example, the U.S. Fish and Wildlife Service estimates that, over the next decade, zebra mussels may cause as much as $5 billion in damages to U.S. and Canadian industry, utilities, ships, and fisheries in the Great Lakes Region [21].

Smith [27] was the first to suggest a conventional resource could also be a nuisance, although he did not pursue this insight in any detail. More recently, Zivin, Heuth, and Zilberman [31] explore the management of so-called multi-use species for the case of a private landowner whose crops are damaged by feral pigs. Focusing on steady states in the private optimum, that paper demonstrates the management regime (i.e., landowners shoot the pigs and/or sell permits to hunters to shoot the pigs on private lands) primarily determines whether the species is a resource or a pest. But many interesting features of the multi-use model remain unexplored, such as the possibility that a species may optimally be a pest at one point in time and a resource at other times, depending on the species' abundance. We find this changing economic perception has significant consequences for management.

In this paper, we analyze both the socially optimal management of a multi-use renewable resource and open access outcomes, using the African elephant (*Loxodonta africana*) as a motivating example (although the results will apply to other multi-use species such as whales, deer, moose, and wild pigs). Elephant management is a highly debated topic within the international community, with

opinions divided about whether trade in ivory should be banned or legalized. Part of the controversy may be explained by recognizing that an elephant population may represent an asset for some countries and a liability for others. Internationally, there are economic values associated with both the harvest (a demand for ivory, meat and hides) and preservation (existence values) of elephants. At the regional level, the demand for elephant products consists mainly of meat and hides. In addition, elephant stocks play a flagship role in attracting tourists and generating revenues for the eco-tourism industry [23]. Finally, elephants may create considerable damage to crops and habitat, and encounters with people living in rural areas result in the death of some villagers every year. According to Hoare [15], about 80% of the African elephant's range lies outside protected areas, and human-elephant conflict appears to be increasing as the agricultural interface with elephant range expands. The resolution of this conflict "has become a serious local political issue in recent years" [15, p.689]. It is perhaps no surprise, therefore, that in one survey in Cameroon, "41% of villagers polled wanted elephants moved and fenced in elsewhere. A significant minority wanted them all shot" [30].

The analysis is used to develop a comprehensive, economic classification of multi-use species, and the outcomes are contrasted with those of conventional resource and pest models. Whereas species classification in prior research is based largely on management regime, our classification system is based primarily on species density (and economic factors). Because species density changes over time, so too can species classification change over time. Moreover, these multiple classifications can lead to multiple equilibria. Finally, we find that "optimal" steady state stocks may be greater or smaller than those occurring under a regime without property rights, and demonstrate that the effect of trade measures on wildlife conservation and welfare is ambiguous, depending on the institutional context.

2. Socially Optimal Management of Multi-Use Species: African Elephants

We begin by examining the socially optimal management of multi-use species, in the context of the African elephant. Denote the *in situ* population (stock) of elephants by x. Left alone, the stock grows according to the logistic function $g(x) = \gamma x(1-x/X)$, where X is the environmental carrying capacity and γ is the intrinsic growth rate. Harvests are denoted by h. Thus, population dynamics are defined by[3]

$$\dot{x} = \gamma x(1 - x/X) - h. \tag{1}$$

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 existence benefits (i.e., benefits associated with the utility people derive from a healthy stock, and not from harvesting, see e.g., [13]) or tourism benefits from recreational activities such as elephant watching. $U(x)$ is concave, indicating that marginal values would be larger for stocks that are closer to extinction [11]. In what follows, $U(x) = \beta\ln(x)$.

The second stock-dependent value is the economic damage created by the stock. In principal, economic damages depend on the ecological and behavioral responses to the physical damages [13]. For example, the welfare effects of a pest that threatens an 'open access resource' (where rents have been dissipated by excessive entry) may be limited [20]. In cases such as crop losses, damages would depend on farmer responses, including any preventative actions taken. Because damages may take a variety of forms depending on the situation, we simplify the analysis by assuming damage is proportional to the stock: $Z(x)=\alpha x$. Such an approach can offer important insights without the complexities that arise in multi-species and/or multi-sector models.[4]

Demand for harvests is given by the downward sloping inverse demand, $p = a - bh_c$, where $a>0$ and $b>0$ are parameters and h_c denotes harvests that are sold at a positive price (i.e., $h_c < a/b$). Harvests in excess of a/b would not be optimal in a conventional resource management (CRM) model, but may

optimally occur if the benefits of nuisance reduction are large enough. In conventional pest management (CPM) models, the harvest is not valued for any positive harvest level (i.e., a=b=0).

Harvesting costs are defined in accordance with the standard Gordon-Shaefer model, $c(h,x) = ch/(qx)$, where c is the cost per unit of harvesting effort and q is the catchability coefficient of the Schaefer production function. In addition to these regular harvesting costs, it may be costly to dispose of harvested nuisance animals (when $h \geq a/b$) 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 always the least cost approach. Given this specification, social net benefits are consumer's surplus, plus firm-quasi rents, plus tourism values, less damages i.e., $SNB=\int p(h)dh - c(h,x) + U(x) - Z(x) = ah - (b/2)h^2 - ch/(qx) + \beta\ln(x) - \alpha x$.[5]

2.1. Necessary Conditions for Optimal Management

The problem faced by the social planner is given by

$$\underset{h}{Max} \int_0^\infty \left(\int_0^h p(h)dh - c(h,x) + U(x) - Z(x) \right) e^{-rt} dt \qquad (2)$$

$$s.t. \quad \dot{x} = g(x) - h$$

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

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

where λ is the co-state variable. The necessary conditions for an interior solution can be written as

$$p(h) - c_h \leq \lambda \qquad (4a)$$

$$h[p(h) - c_h - \lambda] = 0 \qquad (4b)$$

$$\dot{\lambda} = r\lambda + c_x - U_x + Z_x - \lambda g_x \qquad (5)$$

and equation (1) again. Conditions (4a), (4b), and (5) are standard for CRM models (except for the term Z_x in (5)) and CPM models (except for the term $p(h)$ in (4a,b) and the term U_x in (5)).

Condition (5) can be rewritten as

$$\frac{\dot{\lambda} - c_x + U_x - Z_x}{r - g_x} = \lambda \qquad (6)$$

Taken together, conditions (4a,b) and (6) illustrate several tradeoffs that influence the sign of λ. First is the tradeoff in conditions (4a,b) involving the *ex situ* marginal benefits and marginal costs of harvesting. Second is the tradeoff in equation (6) involving the *in situ* benefits and costs from increases in the stock at the margin. Such tradeoffs do not influence the sign of λ in CRM and CPM models. In CRM models, λ>0 because the elephant stock is a source of future benefits and current period harvests reduce the stock that will be available for future use. In CPM models, λ<0: harvesting creates social benefits because the resource will be unavailable to create future damages (see also [27, p. 745]). Another way to think about this is the following. Clark [7] shows that a conventional resource stock is a biological asset and there is value from investing in this asset (λ>0). In contrast, a nuisance stock is a biological liability and there is value from divesting this liability (λ<0). The sign of λ is ambiguous in the present case since elephants exhibit qualities of both an asset and a liability.

The two types of tradeoffs described above can be used to distinguish between six different cases that vary along two dimensions. First, elephants may produce *in situ* benefits that outweigh *in situ* costs ($\dot{\lambda} - c_x + U_x - Z_x > 0$), or they may produce *in situ* costs that outweigh *in situ* benefits ($\dot{\lambda} - c_x + U_x - Z_x < 0$). Second, harvesting may represent a rent-generating activity ($p - c_h = \lambda > 0$), a costly activity mainly undertaken as damage control ($p - c_h = \lambda < 0$), or an activity that is too costly

to be economic ($p - c_h < \lambda$). Using some admittedly arbitrary phrasing, this gives rise to the classifications used in Table 1, each of which ultimately depends on the current stock density.

[Insert Table 1 about here]

Species of class I, II, or V, in which λ>0, are referred to as commodity species. In contrast, species of class III, IV, or VI, in which λ<0, are referred to a nuisance species or pests. The condition $r > g_x$ must be satisfied for class I and class IV to occur so that *in situ* and *ex situ* net benefits remain balanced at the margin. The reverse is true for class II and class III species. Logistic growth may restrict the species classification. The condition $r<g_x$ can be written as $x<(\gamma\text{-}r)X/(2\gamma)$, which means that $x<0$ when $r>\gamma$. Thus, classes II and III are not feasible when $r>\gamma$, but any outcome is possible when $r<\gamma$. Finally, classes V and VI represent situations in which *in situ* net benefits outweigh any *ex situ* net benefits at the margin. Accordingly, harvests optimally do not occur in these situations.

2.2 The Socially Optimal Steady State

The equations that define interior steady states are determined by plugging the solution to λ from (4a) into equation (5), and by setting $\dot{x} = \dot{\lambda} = 0$ in equations (1) and (5):

$$h=g(x) \tag{7}$$

$$r = g_x + \frac{-c_x + U_x - Z_x}{p - c_h} = g_x + \Phi \tag{8}$$

The solution to (7)-(8) may not be unique, as it is well-established that models with stock-dependent costs and benefits can exhibit multiple equilibria (e.g., [18], [19], [22]). We examine such a case below.

The RHS of (8) is the adjusted rate of return from holding the resource (liability) *in situ*. The term g_x represents the *in situ* base rate of return, as a result of the stock being a reproducible asset

(liability). The term Φ, often referred to as the stock term, is an adjustment that accounts for additional costs and benefits from letting the resource asset (liability) grow. In CRM models, Φ>0 since λ>0 and $Z_x = 0$. Thus, in CRM models, $r > g_x$, and the steady state involves a class I species. In contrast, large damages cause Φ<0 for a class II steady state so that $r < g_x$ in this case (and hence, g_x>0 for r>0, which implies that the steady state stock is less than the stock that maximizes g, or the maximum sustainable yield level (MSYL)). Thus, Φ could be positive or negative for a commodity species, depending on its classification (density). Φ could also be positive or negative for a nuisance species (Φ<0 for class III species and Φ>0 for class IV species). Regardless of species 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). Accordingly, for a particular value of r and specification for g, class II or III steady state stocks must be smaller than class I or IV steady state stocks.

We examine the steady states numerically by adopting the parameter values used by Bulte and van Kooten [5], which are to a certain extent appropriate for countries with medium-large elephant populations like Zambia or Kenya: c/q = 692,300, β=2.6×10^6, α = 165, γ=0.067 and X=300,000.[6] In addition, we consider two scenarios that influence demand, $p(h)$. In the first scenario, denoted 'legalized trade', international trade in ivory is allowed and ivory proceeds dominate the revenues from culling elephants. Demand in this case is $p(h)$=6397-0.044h. In the second scenario, denoted 'trade ban', international trade in ivory and other elephant products is banned (as is the case with the post 1989 CITES ban). Meat, hides and ivory may be traded in regional markets, but the benefits of harvesting are much smaller than before. The trade ban scenario is consistent with the problem of a regional planner who determines optimal management given an exogenous ban. Data is unavailable to calibrate demand in the trade ban case; however, Barnes [2] notes that elephant prices are less than

average harvesting costs when harvests exceed a few thousand. We therefore consider a demand specification for the trade ban scenario that is consistent with this observation: $p(h)$=1000-0.8h.

[Insert Table 2 about here]

The interior steady states for the two trade scenarios are presented in Table 2. First, consider the legalized trade scenario. For each discount rate, the steady state is unique and a saddle, and elephants are harvested as a commodity (recall $\lambda>0$ for classes I and II). Steady state species classifications are the same as in CRM models (class I) when $r>\gamma=0.067$, which as indicated above is required, but elephants are a class II species when r=0.05 (as we discuss below, these classifications may not be constant along transition paths). Steady state stock levels are significantly smaller than levels that would occur in the absence of damages (i.e., when $\alpha=0$). For example, the optimal stock with r=0.1 and $\alpha=0$ is just over 11,000 elephants (compared to 6,765 in Table 2).

Next, upon comparing the "optimal stocks" with and without the nuisance effect to the current populations in Zambia and Kenya (32,500 and 25,000 elephants, respectively, see [24]), it is clear that current stocks are still sub-optimally abundant. Thus, despite significant depletion of elephant populations in the recent past and considerable international attention to prevent further reductions, it would be optimal to draw down stocks if trade in ivory is resumed.

Three steady state equilibria arise under the trade ban (Table 2), which we classify as follows: the *commodity equilibrium* is a saddle with elephants being harvested as a commodity (class I or II); 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 nuisance equilibrium yields *negative* net benefits due to harvesting and disposal costs (for each value of r, $h>a/b$=1,250, indicating substantial disposal costs are incurred), and significant damages resulting from

the large *in situ* population. The nuisance equilibrium is preferred to the carrying capacity equilibrium (i.e., corner solution with h=0 and x=X) due to the extensive damages that occur when x=X. As with the legalized trade scenario, steady state stocks when α=0 are much larger than those reported in Table 2. For example, the steady state stock level when r=0.1 and α=0 is about 272,000 elephants (compared to 15,382 for the commodity equilibrium and 254,980 for the nuisance equilibrium in Table 2).

If there were no disposal costs, then p=0 after demand is satiated, no matter how many more elephants are harvested. The commodity equilibria (in both trade scenarios) are unaffected by this change in model specification. However, the other two steady states in the trade ban case vanish.

The impact of a trade ban on the planner's problem is found by comparing the legalized trade equilibrium with the commodity equilibrium under a trade ban. Steady state stock levels and harvests are smaller (larger) under legalized trade than under the trade ban for larger (smaller) discount rates. For smaller discount rates, elephants are harvested as a class II species so that, at the margin, there is an incentive to deplete the stock (because the *in situ* benefits are negative). Therefore, as the *ex situ* benefits are reduced (due to a smaller price under the trade ban), the stock is culled to a lower level of abundance. These differences in stock and harvest levels also imply differences in steady state welfare. The trade ban reduces welfare when r = 0.1 or r= 0.05, but increases welfare when r=0.15.[7]

[Insert Table 3 about here]

2.3 Comparative statics

We calculated the comparative statics for each of the steady states presented in Table 2 and found the results depend on species class and equilibrium stability properties. The comparative statics are presented in Table 3 in accordance with these findings. Results are only consistent across one row: the impact of changes in X are invariant to species class or stability property. Comparison of the results for Class I and Class II species indicates important differences even for two types of commodity

species. The differences lie in the effect of increases in demand (due to an increase in *a* or a decrease in *b*). An increase in demand decreases the steady state stock for a class I species, while the reverse is true for a class II species. For class I species, increased demand promotes more harvests in the short term. For class II species, increased demand provides incentives to increase future harvesting (recall that x<MSYL for class II species, so steady state values of x and h move together), which enables society to better tolerate future damages. 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 stock by almost 27% when r=0.05 (Table 2).

The comparative statics of the saddle equilibrium for a class IV species are also interesting. The only difference between the comparative statics of this equilibrium and those of a class I species is the impact of the stock to changes in r. An increase in r reduces class I stocks since these stocks are a biological asset and r is the opportunity cost of leaving this asset *in situ*. In contrast, an increase in r increases class IV stocks since these stocks are a biological liability and r is the cost of devoting resources to divest this liability. This result can be seen in Table 2 for non-marginal changes in r.

2.4 Transition Dynamics

The transition to the steady state is important for two reasons. First, species classification may optimally change over time. One policy implication is that it may be optimal to subsidize harvests in some periods but tax them in others. Second, with multiple equilibria, transition paths indicate how the various equilibria can be achieved. The dynamics of the model are determined jointly by equation (1) and the following equation which is obtained by differentiating (4a) with respect to time (assuming it is satisfied as an equality; note that c_{hh}=0) and substituting in expressions (1) and (5)

$$\dot{h} = \frac{(r - g_x)(p - c_h) + c_x - U_x + Z_x + c_{hx}(g(x) - h)}{p_h} \qquad (9)$$

The properties of the dynamic system defined by equations (1) and (9) may vary depending on the species class. To illustrate, consider the slope of the $\dot{h}=0$ isocline ($Z_{xx}=0$)

$$\frac{dh}{dx}=\frac{(r-2g_x)c_{hx}+g_{xx}(p-c_h)-c_{xx}+U_{xx}}{(r-g_x)p_h} \tag{10}$$

From equation (10), the slope of the $\dot{h}=0$ isocline is ambiguous. Two factors in particular that affect this ambiguity are the sign and magnitude of λ, and also the sign of the term $(r-g_x)$. In contrast, the signs of λ and the term $(r-g_x)$ are not ambiguous in CRM models in which damages are not a factor.

If λ>0 and $(r-g_x)>0$ (class I) (and assuming, realistically for most values of *x*, that the first term in the numerator of (10) is sufficiently small), then the slope of the $\dot{h}=0$ isocline is positive and the equilibrium is a saddle as is standard in the literature [7]. If λ>0 and $(r-g_x)<0$ (class II), then the $\dot{h}=0$ isocline is negatively sloped with the type of equilibrium and its stability depending on the model specification. The slope *dh/dx* is ambiguous when λ<0 (classes III and IV).

The $\dot{h}=0$ isocline need not be monotonic – particularly if classification changes over time as species abundance changes. For example, suppose the stock is optimally a class II species in some periods and a class I species in others. As this transition occurs, g_x approaches *r* and $|dh/dx|\rightarrow\infty$. Thus, classifications that change over time may be consistent with asymptotic phase planes and multiple equilibria. We use the numerical specification described above to analyze these features in more detail.

[Insert Figure 1 about here]

The phase plane associated with *r*=0.1 is presented in Figure 1 for the legalized trade scenario. This is a conventional phase plane for renewable resources [7], with the exception of the curve labeled Θ (which is barely distinguishable from the *h* axis): λ is negative for harvest levels to the left of Θ and positive for harvests to the right of Θ. Thus, elephants are not likely to be harvested as a nuisance

species (classes III or IV) in the legalized trade case due to the high ivory prices on international markets. The steady state is at the intersection of the isoclines at point *E*.

[Insert Figure 2 about here]

Now consider the trade ban scenario for r=0.1, illustrated in Figure 2. The figure is divided into four alphabetic isosectors: region A lies below both isoclines; region B lies above the $\dot{x}=0$ isocline and below the $\dot{h}=0$ isocline; region C lies above both isoclines; and region D lies below the $\dot{x}=0$ isocline and above the $\dot{h}=0$ isocline. Regions having the same alphabetic label exhibit similar dynamic properties (e.g., phase arrows point in the same directions in all regions labeled 'A'). As in Figure 1, the curve Θ divides nuisance and commodity harvests: λ is negative for harvest levels above Θ and positive for harvests below Θ. Thus, Θ divides each major region A-D into subregions having different species classifications (e.g., region AIV indicates the part of region A involving species class IV). Note that the curve Θ approaches a/b= 1,250 asymptotically from below. Thus, for a wide range of stocks, nuisance harvesting ($\lambda<0$) almost always coincides with $p<0$.

There are two important differences between Figures 1 and 2. First, the isoclines in Figure 2 intersect in three places (as opposed to once in Figure 1), indicating three steady states.[8] The small stock (commodity) equilibrium and the large stock (nuisance) equilibrium are both saddles, while the other (unstable) equilibrium is an unstable focus. As both the commodity and nuisance equilibria satisfy the conditions for an optimal solution, the initial stock determines which saddle should be chosen by the social planner (see [25], [28]). Note that the commodity equilibria is not attainable from large initial stock levels. For instance, harvests must occur in region CIV to deplete the stock from large levels, but region BIV (which contains the saddle path) is not generally attainable from region CIV. Similarly, the nuisance equilibrium is not attainable from small initial stock levels. Thus,

"history" at least partially determines future elephant abundance and the success of conservation policies.[9]

The second difference between Figures 1 and 2 is that the saddle path to the commodity equilibrium (from stocks to the right of the equilibrium) involves harvesting elephants as a 'pure' nuisance for some time. Thus, for society to approach the commodity equilibrium, it may be necessary to temporarily subsidize harvests before switching to quotas or taxes. This result occurs because the curve Θ intersects the $\dot{x}=0$ isocline in Figure 2 (but not in Figure 1), at a stock level of 19,989 elephants. For initial stock levels in the neighborhood of 19,989 elephants, the transition to the steady state is likely to involve only class I species (regions DI or BI). For larger initial stock levels, harvesting would initially involve a class IV species (regions BIV or CIV). This is because $p<0$ when $h>1{,}250$ elephants, which is required in order to deplete the stock to a level such that harvesting in region BI is optimal.

[Insert Figure 3 about here]

Finally, consider the trade ban case with $r=0.05<\gamma$. The associated phase plane is presented in Figure 3. (To conserve space, the phase plane for the ivory trade scenario with $r=0.05$ is not presented; however, the results are qualitatively similar to those in Figure 3 in terms of the asymptote.) Figure 3 is labeled in the same manner as Figures 1 and 2, although this figure is significantly more complex. 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 Θ, the asymptote separates species classes I and II. Above the curve Θ, the asymptote separates species classes III and IV. The asymptote results from a singularity, similar to those that create bang-bang solutions in linear control problems – but with two important differences. In a linear control problem, a discontinuous jump in the control variable (h) is optimal and the steady state occurs at the singularity. In contrast, a discontinuous jump is not necessary in the present model

when $r=g_x$, and the steady state does not occur at the singularity. Instead, the singularity represents a change in the economic forces that drive harvest decisions. Specifically, regions having a particular alphabetic label exhibit different dynamics depending on which side of the asymptote they are located.

For initial stock levels below the 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. Thus, as above, it may be optimal to subsidize harvesting en route to the steady state. Note that, unlike Figure 2, it may be optimal to approach the commodity equilibrium from large initial stock values (i.e., it is possible to enter region BIV from region CIV). This is because the smaller discount rate in this case reduces the opportunity cost of nuisance harvests. Finally, elephants are never harvested as a class I species under a trade ban when r=0.05.[10]

Suppose now that there are no disposal costs. In this case, p=0 after demand is satiated, no matter how many more elephants are harvested. Accordingly, the dynamics in the trade ban case are significantly altered.[11] Harvests in regions III or IV occur at a zero price, and the problem essentially takes the form of a linear control problem in these regions. Thus, we have a bang-bang solution at harvest levels above Θ (for most stock levels). Nuisance harvests will occur as quickly as possible, until the stock is diminished to levels at which it becomes optimal to harvest elephants as a commodity.

3. Open Access Exploitation and Multi-Use Species

Steady states arising from an optimal solution to resource management are often compared to steady states arising from open access situations in which property rights for a species are either not defined or enforced, such that free entry occurs. In conventional open access models, entry (exit) in the harvesting industry will occur 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 [14].

The open access multi-use model is slightly more complex as individuals have an additional incentive 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 related future damages. This is because landowners are the claimants of future damages since they will continue to own their land in the future, and this claim will not be competed away (unlike with hunters, where competition reduces their claim on future benefits).

It is necessary to specify who may harvest elephants and who suffers damage in the open access model. Without loss of generality, consider two types of individuals. 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 can value harvests both as a commodity and as a method of pest reduction. Landowners are also free to enter and 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 [14] and rational expectations models [3]. Because of this asymmetric treatment of the future, we begin with the dynamic problem faced by individual landowners, but impose the additional constraint that any rents that may arise will instantaneously dissipate due to entry of hunters. We model an open-loop Nash equilibrium in which

each landowner chooses harvests to maximize his/her net benefits (which do not include non-use values), taking others' harvest decisions as given. For simplicity, assume that all hunters and landowners face the same harvest cost functions, $c_i(h_i,x) = ch_i/(qx)$ (hence $\partial c_i/\partial h_i = \partial c_k/\partial h_k \ \forall i,k$). The rent dissipation constraint can then be written as $p - c/(qx) \leq 0$. Given this specification, each landowner i maximizes

$$NB_i = \int_0^\infty [ph_i - c_i(h_i,x) - Z_i(x)]e^{-rt}dt \qquad (12)$$
$$s.t. \quad \dot{x} = g(x) - h, \quad and \quad p - c/(qx) \leq 0$$

where $h = \sum_i h_i + \sum_j h_j$, and $c_i(\cdot)$ and $Z_i(\cdot)$ are the landowner's individual harvesting cost and damage functions, respectively. Individuals take p as given, although p will be influenced by aggregate harvests h. Disposal of nuisance harvests may or may not be an issue in the open access case. It could be an issue if elephants are killed on private lands and if non-disposal creates disutility for landowners.

Assuming an interior solution, the necessary conditions associated with (12) are

$$p - \partial c_i/\partial h_i = \lambda_i \qquad \forall i \qquad (13)$$

$$\dot{\lambda}_i = r\lambda_i + \partial c_i/\partial x + \partial Z_i/\partial x - \lambda_i g_x - \rho_i \partial^2 c_i/(\partial h_i \partial x) \quad \forall i \qquad (14)$$

where p=$p(h)$, λ_i is the co-state variable, reflecting the shadow price from the private rather than social planner's perspective, and ρ_i is the Lagrange multiplier associated with the rent dissipation constraint (ρ_i<0 when the constraint binds). Note ρ_i<0 along with (13) implies $\lambda_i = 0$. Even when the constraint is non-binding (i.e., ρ_i=0), conditions (13) and (14) differ from those characterizing the social optimum as λ_i generally differs for each landowner (individual landowners may not care about damages to neighbors)[13], tourism benefits are not accounted for[14], and hunters are not part of the solution.

3.1 Open access steady states: nuisance and commodity harvesting in equilibrium

Consider the open access steady state equilibria. Two types of equilibria may arise depending on the sign of λ_i. If λ_i=0, then elephants are a commodity as hunters have entered freely until profits are dissipated (so that ρ_i<0). Thus, the first type of equilibrium involves both hunters and landowners and is characterized by condition (7) and the zero profit condition $ph = c(h,x)$. These are the standard equilibrium conditions in conventional open access models [3].

The second type of equilibrium occurs when λ_i<0 and ρ_i=0 (i.e., nuisance harvesting, see [27, p.745]). In this case, profits from sales are negative. In these steady states, hunters have all exited and only landowners harvest elephants, doing so as pest control. The equilibrium conditions in this case are given by (7) and

$$p - \frac{\partial c_i}{\partial h_i} = \frac{-\partial c_i/\partial x - \partial Z_i/\partial x}{r - g_x} \qquad \forall i \tag{15}$$

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 reasons. Separate conditions define the commodity and nuisance equilibria (i.e., the conditions depend on if the solution involves hunters and landowners or just landowners), and both sets may have a solution. Also, each set of conditions may have multiple solutions. For example, steady state profits may be negative when stocks are "sufficiently small" (so that harvesting costs are high) and also when stocks are "sufficiently close" to MSYL (with *p* depressed due to a large supply). Nuisance equilibria may therefore occur at both low and intermediate population densities. This is illustrated in the next section.

3.2 Open Access Equilibria and Comparison with Optimal Management

The second open access result is that open access stocks may be greater than optimal stocks. The nuisance aspect thus adds a dimension to the property rights theme that is traditionally at the heart of

resource economics (e.g., [29]). In conventional open access models, individuals have no incentive to "invest" in the resource by leaving a unit *in situ* to enhance productivity and future harvesting potential. Such foresighted actions are not rewarded as somebody else will respond by harvesting that unit. For the multi-use model, however, an offsetting effect exists as it is socially optimal to "invest" both in future harvesting *and* in reducing future nuisance damage. Under open access conditions, no individual is willing to make socially efficient investments in reducing future damage. Thus, in addition to the well-known issue of "*who has the right to reap future benefits*?" of investing in resource stocks, we now face the question "*who is responsible for future damages*?" If property rights are not defined in ways that assign both individual rights to benefits and individual responsibility, then these issues are left unresolved and investment decisions of rational individuals are affected along one or both dimensions. Hence, open access stocks of multi-use species may be too large relative to optimal levels.

The open access equilibria are provided in Table 4 for the case of r=0.1. Elephants are harvested as a commodity (by both hunters and landowners) when ivory trade is legal, and thus the open access steady state in this case is invariant to r. As might be expected, elephants are significantly over-harvested in this situation (compare to Table 2), to the point where it is only sustainable to harvest seven elephants annually. Even so, steady state social net benefits remain somewhat large due to the benefits from tourism (an artefact of the current specification no doubt) and minimal damages.

[Insert Table 4 about here]

Now consider the trade ban case (Table 4). For the reasons described above, we find multiple commodity equilibria (in which hunters and landowners harvest elephants and the zero profit condition applies) and multiple nuisance equilibria (in which only landowners harvest and profits are negative). One commodity equilibrium is conditionally stable and yields positive net benefits, while the other commodity equilibrium is stable and yields negative net benefits (both to society and to farmers due

to the high damage costs they incur). Although the stable equilibrium yields negative net benefits, farmers are unable to further reduce the stock from this equilibrium due to the fungibility of harvesting effort. If farmers increase their own effort, they will crowd out the effort of poachers. Thus, the investment required to significantly deplete the stock from this point is too great.

Both of the commodity equilibria exhibit stock levels well in excess of optimal levels (Table 2). This clearly contrasts with conventional open access models: landowners and hunters harvest too few animals because they are not responsible for spillover damages caused by migrating wildlife and disregard the benefits of culling for neighboring landowners. Thus, a lack of property rights enhances conservation.[15]

Elephants may also be harvested as a nuisance in the trade ban scenario – so that only landowners hunt the species and where the equilibrium is described by (7) and (15).[16] Two interior nuisance equilibria arise (although the equilibria with *x*=66,873 only arises in the presence of disposal costs). One equilibrium (*x*=126) is conditionally stable, while the other is an unstable focus. Thus, nuisance harvesting may stabilize at the smaller stock level. However, since the landowner's profits from harvests are negative at this equilibrium and since damages still occur even at low stocks, the landowner may do better to pursue an extinction strategy (a corner solution, instead of the interior solutions reported in Table 4). Clark [6] shows extinction could be optimal in a profit maximization framework in which the stock is harvested as a resource, and it should not be surprising that extinction may also arise in a multi-use framework with landowners minimizing the costs of nuisance harvesting.

A final result of open access harvesting of multi-use species is also evident from Table 4, and is related to the effect of trade measures (the ivory trade ban) on abundance and economic welfare. Consider the welfare and stock impacts of a trade ban when an open access situation prevails. Anderson & Blackhurst [1, 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 the present analysis. In other words, the (wealthy) developed countries free ride on the conservation efforts of the (poor) developing countries. Clearly, this statement may be overly pessimistic as the impact on steady state welfare and stock levels is ambiguous. Under open access, the trade ban may enhance welfare (at least; in the steady state). This empirical result is consistent with theoretical work on resource management in a second-best context [4].

Of course, a trade ban could also have detrimental effects – for both welfare and stock levels. The ultimate impacts of a trade ban depend on whether elephants are harvested as a commodity or as a nuisance, and which particular equilibrium is approached. Because the outcome depends entirely on initial stock values, the impact depends on the stock levels when the trade ban is introduced. Thus, history matters. A trade ban imposed at the wrong time could result in extinction, which is a devastating, unintended consequence – particularly since the legalized trade equilibrium is stable.

4. Discussion and Concluding Remarks

Application of the multi-use model to elephant management sheds 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 its (local) level of abundance (which varies greatly over Africa; see [24]). Different steady state classifications are possible, and different types may be distinguished along the transition dynamics towards steady states (highlighting the importance of designing flexible management instruments).

It is therefore easy to understand why international discussions on the ivory trade ban have proven to be difficult. While talking about one biological species, delegates from different countries are actually discussing the fate of different "types" of animals. 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. Since it may be reasonably expected that this is also true for many other species whose management is debated in the international arena (whales, tigers, bears etc.), it is evident that such negotiations can achieve "third best" solutions at the very best. Not only do trade measures typically target the wrong problem (e.g., [10]), it is also true that one policy will very rarely serve all conflicting purposes. The set of policy instruments would have to be expanded to deal with these issues efficiently. This insight is re-enforced by the conclusion that conservation policies may yield counter-intuitive effects, depending on the classification of species. For example, the effect of conservation policies (such as the ivory trade ban) may be counter-effective if the species to be protected represents a nuisance for some actors. Our results also highlight the importance of history in conservation, as the timing of conservation policies may be particularly important.

Finally, open access wildlife stocks may be greater than socially optimal stocks. The reason is that, in addition to the opportunity to invest in future *harvesting*, the multi-use species model recognizes that investments in future *nuisance* reductions may be optimal. Hence, the absence of property rights may promote conservation of certain endangered species. Also, a trade ban in the absence of property rights has ambiguous impacts, both on conservation and welfare levels. Consistent with prior theoretical work on resource management in a second best world (a world without property rights, for example), we find that trade restrictions may enhance welfare.

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Table 1. A classification of animal species

Short run *ex situ* net benefits	Long run *in situ* net benefits	
	$\dot{\lambda} - c_x + U_x - Z_x > 0$	$\dot{\lambda} - c_x + U_x - Z_x < 0$
$p - c_h = \lambda \geq 0$	I. 'Pure' commodity[a]	II. Depletable commodity[b]
$p - c_h = \lambda < 0$	III. Conservable nuisance[b]	IV. 'Pure' nuisance[a]
$p - c_h < \lambda \gtrless 0$	V. Preservable commodity (λ>0)	VI. Preservable nuisance (λ<0)

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

Table 2. Optimal Steady State Outcomes for African Elephants (with Disposal Costs)

Discount Rate	Steady State Outcomes	Legalized Trade p = 6397 - 0.044h	Trade Ban p = 1000 - 0.8h		
			Commodity Equilibrium	Unstable Equilibrium	Nuisance Equilibrium
r = 0.05	Stock	22,044	16,156	147,037	234,206
	Harvest	1,368	1,024	5,023	3,441
	Social net benefits (annual $ in millions)	31.04	23.09	1.58	-7.8
	Species class	II	II	IV	IV
	Equilibrium Type	Saddle	Saddle	Unstable focus	Saddle
r = 0.1	Stock	6,765	15,382	72,838	254,980
	Harvest	443	978	3,695	2,564
	Social net benefits (annual $ in millions)	24.6	23.08	15.29	-9.78
	Species class	I	I	IV	IV
	Equilibrium Type	Saddle	Saddle	Unstable focus	Saddle
r = 0.15	Stock	3,831	14,311	43,815	262,163
	Harvest	253	913	2,507	2,215
	Social net benefits (annual $ in millions)	22.39	23.05	20.51	-10.57
	Species class	I	I	IV	IV
	Equilibrium Type	Saddle	Saddle	Unstable, improper node	Saddle

Note: Steady states for the legal trade scenario and steady state 1 of the trade ban scenario are the same when there are no disposal costs. Steady states 2 and 3 of the trade ban scenario vanish without disposal costs.

Table 3. Comparative Statics

Comparative Statics	Class I	Class II	Class IV		
			Unstable focus	Unstable, improper node	Saddle
dx/da	-	+	+	-	-
dx/db	+	-	-	+	+
dx/dc	+	+	-	+	+
dx/du	+	+	-	+	+
$dx/d\alpha$	-	-	+	-	-
dx/dj	+	+	-	+	+
dx/dX	+	+	+	+	+
dx/dr	-	-	-	-	+

Note: Parameters come from the relations: $p(h) = a - bh$; $c(h,x) = ch/x$; $U(x) = u\ln(x)$; $Z(x) = \alpha x$; and $g(x) = jx(1 - x/X)$.

Table 4. Open Access Steady State Outcomes for African Elephants (r=0.1)

Trade Scenario	Steady State Equilibrium	Equilibrium Type	Steady State Stock	Steady State Harvest	Social Net Benefits (annual $ in millions)
Legalized Trade $p = 6397 - 0.044h$	Commodity	Stable focus	108	7	12.16
Trade Ban $p = 1000 - 0.8h$	Commodity	Saddle	19,200	1,205	23.06
	Commodity	Stable, improper node	280,075	1,246	-12.98
	Nuisance	Saddle	126	8	12.52
	Nuisance (with disposal costs)	Unstable focus	66,873	3,482	16.45

Note: Net benefits are defined as social net benefits ($\int pdh - c + U - Z$) and not private benefits to open access hunters and landowners.

Figure 1. Legalized Trade, $r = 0.1$

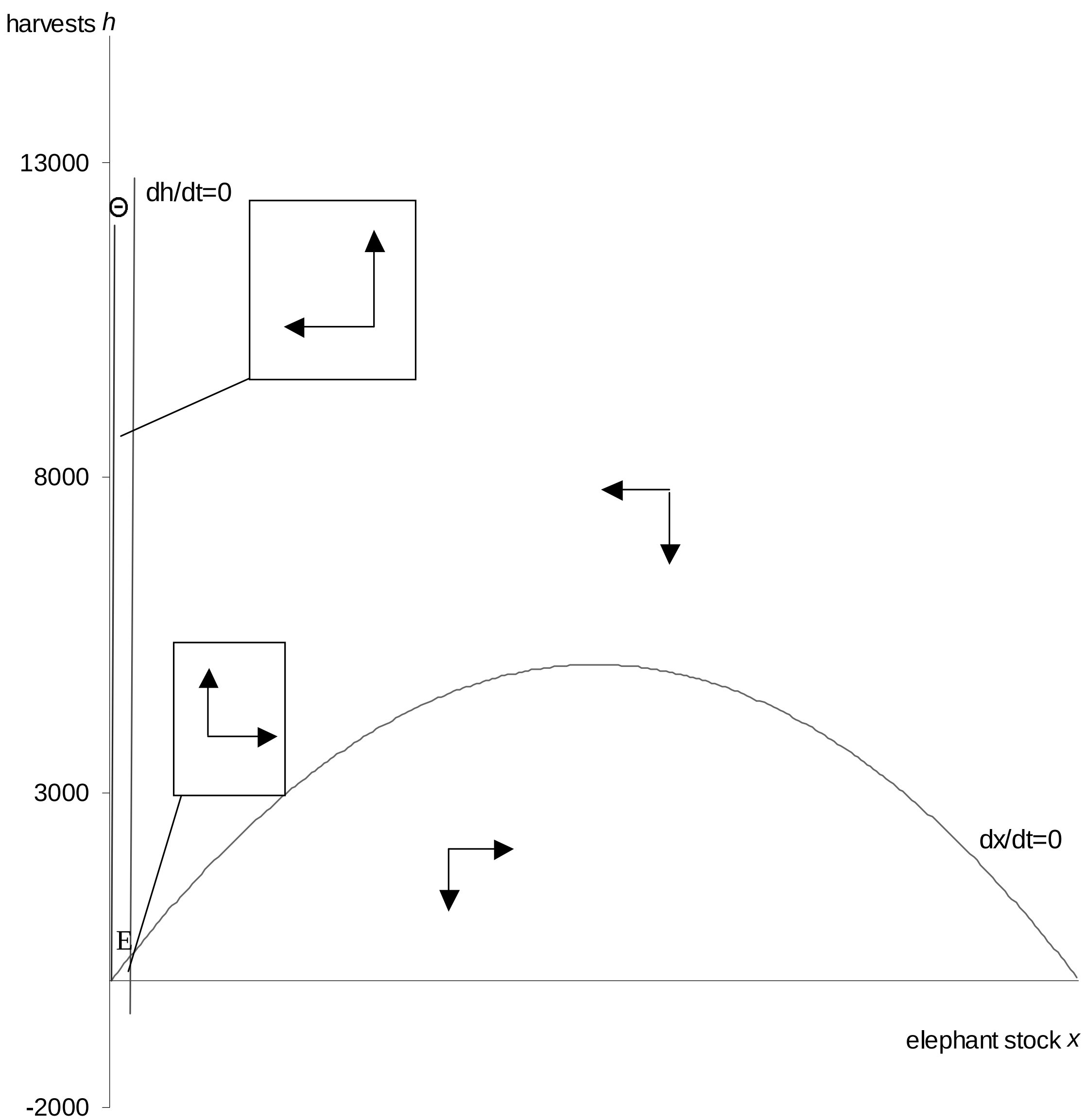


Figure 2. Trade Ban, *r*=0.1

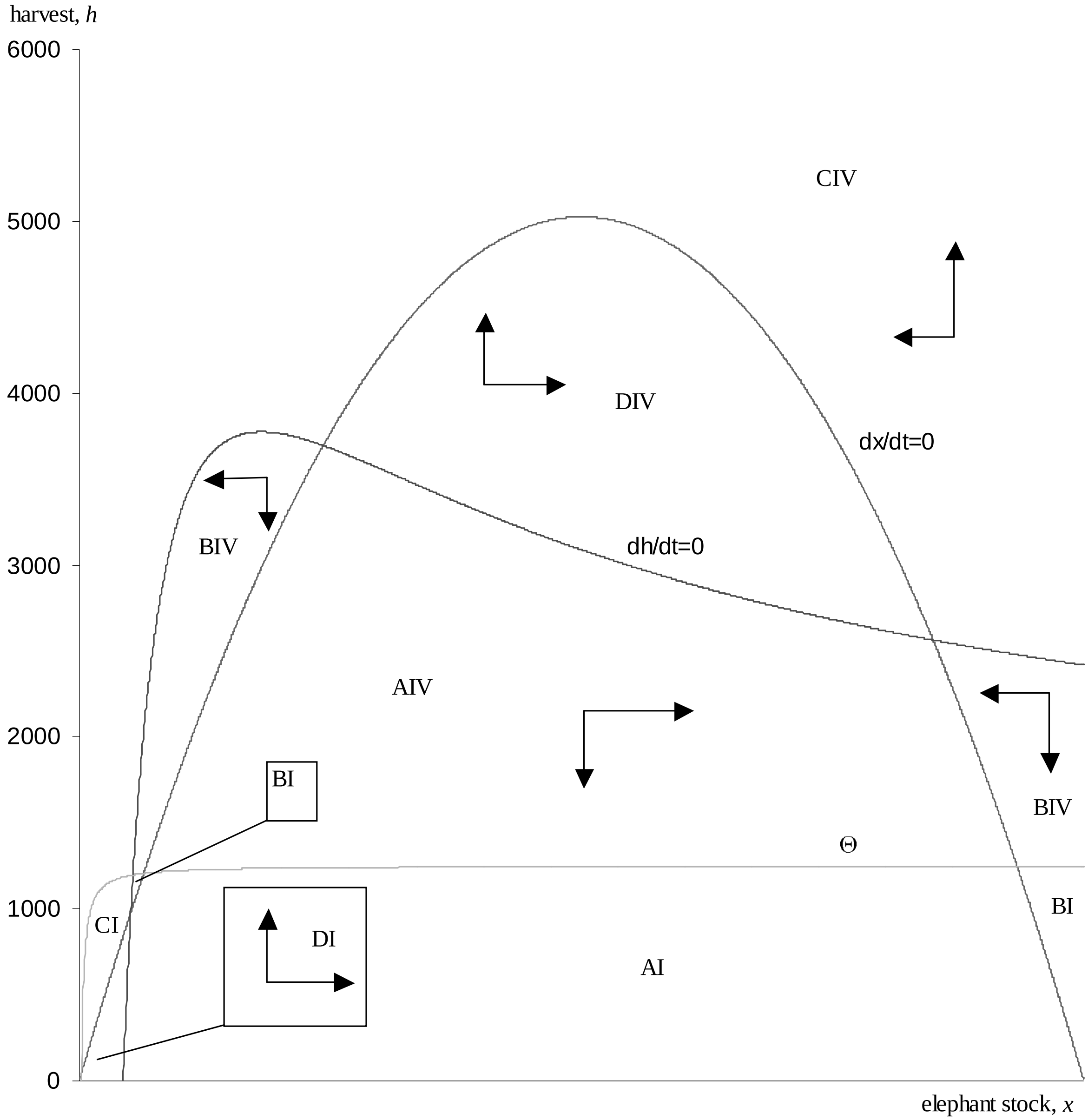
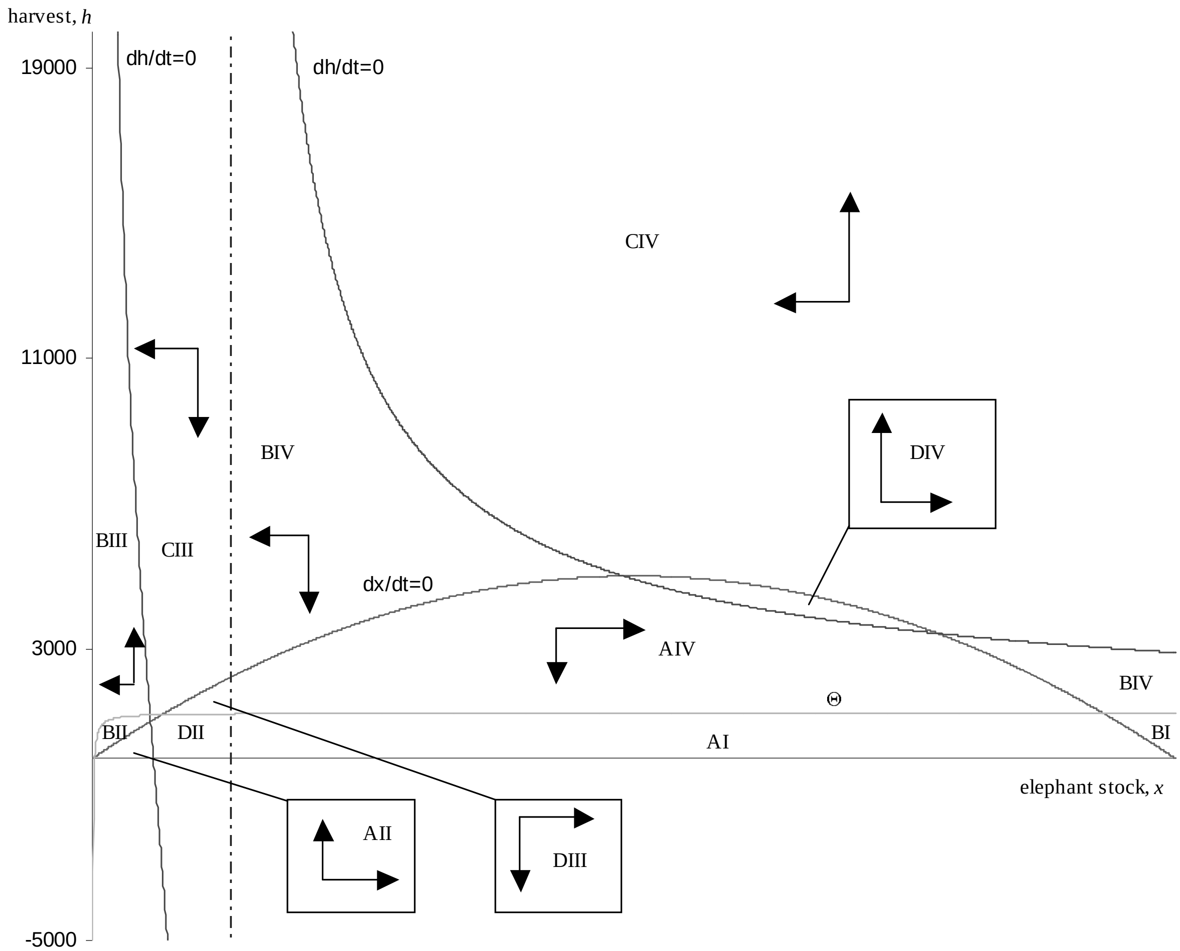


Figure 3. Trade Ban, r=0.05



Endnotes

1. Exotics may be introduced accidentally, as when species are inadvertently transported in the ballast water of commercial shipping vessels, or they may be purposeful in an effort to, for example, boost production (e.g., the Nile perch in Africa) or control other pest species (e.g., salmon in the Great Lakes to control alewife). In any case, introductions are thought to be growing worldwide. In the Great Lakes alone, at least 145 non-indigenous aquatic species have been introduced since the 1830's, with one-third being introduced during the past thirty years – likely in response to increased shipping in the St. Lawrence Seaway [21].

2. Historical data suggest at least 23% of the 486 documented extinctions since 1600 are due to the introduction of foreign species and diseases [26].

3. This equation of motion will be a simplification for those species for which a metapopulation with migration between separate subpopulations is more apt. For example, local extermination of rats may not be feasible as the vacant ecological niche will quick be filled by "entry" from adjacent populations.

4. Empirical data from Africa and India indicate that close to 80% of the crop raids were perpetrated by male groups or lone males (Sukumar 1990, Hoare 1999). The observation of opportunistic feeding forays of a segment of the male elephant population has spurred the hypothesis that males and females follow different behavioral strategies, where risk taking by males is "rewarded"--maximizes reproductive success through better nutrition. The model developed in the text is based on biomass and does not distinguish between different sexes, and therefore does not capture these intricacies of behavioral ecology.

5. The functional forms we adopt are taken from Bulte and van Kooten [5], although the application of the present model is quite different. They focused on management and enforcement issues associated with banning the international trade in ivory, and modeled the interaction between government and poachers. Finally, we do not consider issues associated with ivory storage. See Kremer and Morcom [17] for a discussion of storage issues.

6. The function $U(x)$ is defined as the net benefits from tourism in Bulte and van Kooten's [5] model. The effect of this function is the same as if U was an existence value. There are likely to be existence values for elephants that would be in addition to U, although these values would be largely external to regions such as Zambia or Kenya and data to compute existence values was unavailable.

7. Obviously the net present value of benefits along the optimal approach path may be greater for the legalized trade case than for the trade ban scenario (providing an incentive to further "mine" the elephant stock).

8. 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.

9. An interesting feature of the unstable equilibrium is that its qualitative features change as r is increased. Specifically, the equilibrium is an unstable focus at smaller discount rates and is an unstable, improper node at larger discount rates. This is in contrast to CRM models as the type of equilibrium in those models is unaffected by changes in r.

10. For the trade ban case, the commodity steady states reported in Table 2 and illustrated in Figures 2 and 3 would not be approachable in CRM models if initial stock levels are in excess of 19,989. That is because the large harvest levels required for a depletion strategy in this range would result in $p \leq 0$. In a CRM model, $p \leq 0$ would never be optimal because that would imply $\lambda < 0$. Accordingly, a CRM steady state must lie on the portion of the $\dot{x} = 0$ isocline that borders regions AI and BI (in Figures 2 or 3) if it is to be approachable from any initial stock (with r=0.05 and α=0, the steady state stock is about 282,000 elephants).

11. The phase plane under legalized trade will also be affected, but not in ways that are likely to influence optimal approach paths.

12. In Zivin, Hueth and Zilberman's [31] 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. With imperfectly elastic demand for commodities and supply of factors, individual farmers may even benefit when a nuisance species damages neighboring crop fields.

14. The tourism industry is not involved with the solution. However, Coase [8] would argue that this industry might bargain with landowners to conserve elephants and prevent a nuisance equilibrium from arising (and possibly with hunters as well in the commodity equilibrium), as long as the transactions costs of these negotiations are not too great.

15. Note that we obtain this result even though landowners do not include non-use values (recreation values) in their decision-making process (but these values are included in the computation of net benefits reported in Table 4) under the open access regime and include them for the socially optimal outcome!

16. The nuisance equilibria results in Table 4 are for a single (aggregate) landowner with $Z_i(x) = Z(x)$. If instead we were to consider N landowners with $Z_i(x) = Z(x)/N$, then condition (15) could be written as $r = g_x + \Psi/N$, where $\Psi = (-c_x - Z_x)/\lambda_i$, and λ_i is the same $\forall i$. Given that $\Psi < 0$ in a nuisance equilibrium and also that $g_{xx} < 0$, we expect that, for a given r, each steady state value of x is increased as N is increased (this is confirmed numerically for several values of N). The reason for this result is that landowners do not consider the damages to neighbors and therefore do not deplete the stock enough. This problem is compounded as N is increased. Note that it is not necessary to specify the number of landowners and hunters to determine the commodity open access equilibria.