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The Economics of Endangered Species Poaching

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The Economics of Endangered Species Poaching

1 Introduction

The poaching of endangered species is a global problem. In Africa elephants are poached for their ivory and rhinoceroses are poached to produce medicinal products from their horns (Fischer 2004). In North America grizzly bears are poached because their body parts are valuable, particularly gall bladders (Unknown 2004). In southwestern British Columbia there have been increasing occurrences of bald eagle poaching for the value of their feathers, but one poacher was only fined $1450 (Keating 2007). In a letter to the editor an outraged citizen called for greater penalties for those caught poaching as a means of deterrence (Foss 2007). This brings up an important point that has not received enough attention in the economics literature: poaching is a criminal activity and poachers make the same economic decisions as other criminals. The focus of this paper, therefore, is to examine the interaction between the economic decision making of poachers and the dynamics of endangered species.

The literature regarding endangered species poaching has evolved largely in the context of the African elephant. One of the general goals of this literature has been to understand the impacts of an international trade moratorium on the survival of an endangered species. A common method by which researchers have contributed to the understanding of this subject is to examine the static impact on quantity poached that results from a policy change. For example, Fischer (2004) and Bergstrom (1990) develop static models to analyze policy changes. While such analyses provide valuable insights, a more complete approach would be to assess how policy changes would effect the population dynamics of the species. Under certain circumstances, policies will have ambiguous effects on the quantity of the resource that is poached, but this does not necessarily imply that the impact on the species population will also be ambiguous. It may still be possible to determine how the potential steady states of the species population will change.

Two notable examples of work that examines changes in both the amount of poaching that occurs and the steady state resource population are Bulte and Damania (2001) and Kremer and Morcom (2000). Bulte and Damania examine the role of captive breeding in endangered species conservation in the context of imperfect competition. Kremer and Morcom investigate the possible impacts of storage on endangered species equilibria. Both studies use dynamic frameworks and provide results regarding steady state populations to give a complete account of the impact of policy on the vitality of the endangered species.

There has been considerable controversy over the ban on international trade in ivory. Thornton et al. (2000) report that the one-off sales of ivory in Zimbabwe, Botswana and Namibia in 1997 led to an upsurge in poaching. Bulte, van Kooten and Damania (2007) find that on a broad scale there have not been lasting increases in elephant mortality caused by the one-off sale, except perhaps in some specific remote regions. Similarly, Milliken et al. (2004) conclude that one-off sales of ivory do not create onerous market signals. Fully legalizing trade is arguably a much different subject than one-off sales. In an unrestricted market there would be much less control and accountability in terms of where products originate. Heltberg (2001) finds that the impacts of imposing a trade ban, as opposed full legal trade, are ambiguous, but concludes that an international ban on ivory trade is likely to reduce poaching if it facilitates the interception of smugglers. Bulte and van Kooten (1999) find that the elephant stocks in Namibia will be higher under a trade ban regime than without one. Basic economic theory supports legal trade: if confiscated ivory is not sold in the market, the price received by poachers will consequently rise and give a greater incentive to poach (Bergstrom 1990). Fischer (2004) points out that, if legal sales of ivory effect poaching, there must be a link from illegally harvested ivory to legally harvested ivory through a mechanism like laundering. The role of banning international trade may be to make it more costly for poachers to get their product to the market as laundering is no longer an option. In this context, allowing one-off sales may let poachers into the market through corruption, similar to the findings of Smith et al. (2003).

The effect of increasing anti-poaching enforcement has been the subject of some debate. Fischer (2004) finds that, when there is a single market in which endangered species are sold, greater enforcement unambiguously reduces poaching if confiscated resources are sold in the market. If confiscated resources are not sold in the market, increased enforcement has ambiguous effects on poaching that depend on the elasticity of demand. Fischer also finds that when separate markets for legal and illegal harvests exist, the effect of increasing enforcement is ambiguous even if confiscated resources are sold. What is neglected in these studies is how increasing anti-poaching enforcement will impact the population of the endangered species.

Most researchers model poaching as a competitive industry by imposing the condition that price equals marginal cost. Empirical evidence to support or dispute this assumption is essentially non-existent. Bulte and Damania (2001) argue that this assumption is overly simplistic and show that assuming imperfect competition has a bearing on results. Another approach to modeling poaching behavior that has received only limited attention is one in which poachers are modeled as criminals (Messer 2000). A benchmark model of criminal activity is that of Becker (1968) and Ehrlich (1973), in which agents can divide their working time between legal and criminal activities. Positive theory regarding the role of law enforcement and the differing effects of positive and negative incentives emerge from an analysis using this framework.

A key component of crime models is the separation of the various costs faced by criminals. Opportunity costs associated with foregone legitimate employment, the costs of sanctions imposed against criminals in the case of apprehension, and the likelihood of apprehension itself are all treated separately. In the context of poaching, a model that separates various costs would provide a richer framework for analyzing the efficacy of trade bans, increased enforcement and changes in sanctions, such as shoot on sight policies. In a model of perfect competition, in which costs are not differentiated, detailed analysis of policy alternatives is not as easily accomplished. Some past models of poaching have provided some cost differentiation, such as Bulte and van Kooten (1999) who use a per unit cost as well as an expected apprehension cost, but do not explicitly model poaching as a criminal activity.

A dynamic model of endangered species poaching is developed in this paper. Poachers are modeled as criminals who make optimizing decisions between legitimate employment and poaching. The optimal decision of poachers in the model is governed by the various distinct costs and market incentives that they face. The market for endangered species products is modeled as a general demand curve and a supply curve that depends on the poacher's decision. Equilibrium in the model requires that poachers make optimal choices and that the market for products from endangered species clears. The feedback between these two elements plays a considerable role in analysis of policy alternatives.

Policy analyses using the model developed here lead to not only static results regarding the amount of poaching that takes place, but also dynamic results regarding the potential steady-state equilibria of the endangered species itself. Policy alternatives analyzed include enforcement measures, criminal sanctions and international trade moratoriums. Static results are, for the most part, consistent with previous literature. The dynamic results regarding endangered species population dynamics provide significant insights into policy alternatives. These dynamic results are potentially very important as they indicate that trade moratoriums, increased anti-poaching enforcement and increased poaching penalties can all save a species that would otherwise become extinct.

The remainder of this paper proceeds as follows. Section two introduces the model of endangered species poaching, section three analyzes endangered species policy alternatives and section four discusses and concludes.

2 A Model of Endangered Species Poaching

2.1 Poaching Behavior

Poaching behavior follows closely the crime model of Erlich (1973) and Becker (1968). Poaching agents are assumed to be risk neutral and have utility that is an increasing function of income, such that $u'(Y) > 0$ and $u''(Y) = 0$. The assumption of risk neutrality is required to make the model tractable and intuitive. Individuals are usually assumed to be risk averse, however, by the very nature of their choices, poachers are likely to be more risk inclined than the average person. This implies that risk neutral may not be unrealistic.

There are two states of the world in this model: state A in which the poacher is caught occurs with probability π, and state B in which the poacher is not caught occurs with probability $1 - \pi$. The agent then has an expected utility function given by,

$$EU(Y_A, Y_B) = \pi u(Y_A) + (1 - \pi)u(Y_B).$$

Agents have an initial wealth y_0 and can spend their time in either legitimate employment or poaching. The fraction of time spent poaching is given by τ, with $1 - \tau$ the time spent in legal employment. The fraction of a person's time spent poaching, τ, can be interpreted as the effort spent on illegal harvesting.

Let x be the proportion of the species population carrying capacity that is alive.[1] This implies that at any given time x will between zero and one. The poaching production function is then $h(\tau, x)$, which is assumed to be strictly monotonically increasing (SMI) and strictly concave in both arguments. Poachers sell what they produce at a price p (unless it is confiscated) and earn a wage w for time spent in legitimate employment. These agents are assumed to be price takers in both markets so that time spent poaching does not effect the wage rate and vice versa. This implicitly assumes that poachers cannot make strategic decisions to alter the market prices of endangered species products.

If state A occurs agents' production of the poached good is confiscated and they pay a sanction $\delta(h(\tau, x))$. It is assumed that sanctions are linear and increasing in the amount poached, which implies that $\delta'(h) > 0$ and $\delta''(h) = 0$. The agents' net incomes in the two states are:

$$\begin{aligned} Y_A &= y_0 + w(1-\tau) - \delta(h(\tau, x)) \\ Y_B &= y_0 + w(1-\tau) + ph(\tau, x). \end{aligned}$$

In a strict sense, poachers maximize the present discounted value of future utility, $\int_0^\infty EUe^{-rt}dt$; however, since they have no property rights over the resource they are poaching, they do not take into account its dynamics. The poacher's problem simplifies to a static expected utility maximization problem. Assuming an interior solution, the first order condition can be expressed as:

$$h_\tau \left[(1-\pi)p - \pi\delta'(h)\right] = w. \tag{1}$$

Equation (1) simply states that the expected marginal benefit of time spent poaching equals the marginal opportunity cost. Implicitly defined by equation (1) is the solution to the poacher's problem, $\tau^*(x, p, \pi, \delta', w)$. The poacher's optimal choice is not explicitly a function of time, as no account is taken of the resource dynamics. It is a static optimal that will vary over time only as a consequence of fluctuations in the exogenous variables.

A condition describing whether or not poaching will occur in terms of the price of the poached resource can be derived from the first order condition:

$$[w/(h_\tau(1-\pi))] + [\pi\delta'/(1-\pi)] \begin{cases} = p \quad if \quad \tau > 0 \\ > p \quad if \quad \tau = 0 \end{cases} \tag{2}$$

In the remainder of this paper the LHS of (2) will be defined as $z(\tau^*, x)$ such that if poaching occurs $p = z(\tau^*, x)$. This condition will be used in §2.3 to examine the implications of a reservation price on the demand for endangered species products.

2.2 Endangered Species Dynamics

The dynamics of the endangered species are governed by the differential equation:

$$\dot{x} = g(x) - h(\tau^*, x), \tag{3}$$

where $g(x)$, the species' growth, is assumed to be dispensational with minimum viable population level m such that $g(x) < 0$ if $x < m$.[2] For any $x > m$ the sign of $\dot{x}$ will depend on the relative magnitudes of $g(x)$ and $h(\tau^*, x)$. If $g(x) > h(\tau^*, x)$ then $\dot{x} > 0$, and the opposite if $g(x) < h(\tau^*, x)$. Examples of the appropriate phase diagrams are found in figure 1 (as explained below).

2.3 Supply, Demand and the Market for Endangered Species Products

Demand for the endangered species product is given by a continuous function $D(p)$, where $D'(p) < 0$, with the market clearing when supply equals demand. The supply of the endangered species product is some fraction of the total illegal harvest. The fraction of the poached product that is supplied to the market depends upon the proportion of the poached resources that are confiscated through anti-poaching enforcement, and the proportion of those confiscations that are legally sold. It is assumed that the expected poacher apprehension rate π is realized, so π is also the fraction of the poached harvest that is confiscated. The proportion of resources confiscated from poachers that is not sold in the market is given by $\phi \in [0, 1]$. The supply of endangered species products is given by $(1 - \phi\pi)h(\tau^*, x)$, such that if $\phi = 1$ none of the confiscated resources reach the market and if $\phi = 0$ all do. The market clearing condition is then,

$$D(p) = (1 - \phi\pi)h(\tau^*, x). \tag{4}$$

Assume that there is some finite reservation price $p = p_R$ such that $D(p \geq p_R) = 0$. This is the price at which endangered species products are expensive enough that consumers are just indifferent between purchasing them and not purchasing them. The existence of p_R is an assumption that is critical to the analysis because it is required to define an important point on the function $h(\tau^*, x)$.

Equation (2) gave a condition for the price of the endangered species product when poaching occurs, which could be be expressed as $p = z(\tau^*, x)$. The existence of p_R implies that, *ceteris paribus*, there is some reservation endangered species population x_R at which $p_R = z(\tau^*, x_R)$. This reservation population is the one at which the species is scarce enough that the price at which poachers are just willing to supply endangered species products is equal to the price at which consumers are just indifferent between purchasing and not purchasing the products. It is at x_R that $h(\tau^*, x) = 0$ as is illustrated in figure 1.

Assuming that the marginal product of poaching time is zero if the endangered species is extinct ($h_\tau(\tau, 0) = 0$), from equation (2.b), $\lim_{x \to 0} z(\tau^*, x) = \infty$. In order that p_R be finite, as it is assumed to be, it must be the case that $x_R > 0$. This means, very sensibly, that in order for the price of the endangered species product to be high enough to induce poaching, and low enough to induce consumption, there must be a positive resource population.

2.4 Steady-State Equilibria

A steady-state solution is characterized by $\dot{x} = 0$, which implies $g(x) = h(\tau^*, x)$. The market clearing condition $D(p) = (1 - \phi\pi)h(\tau^*, x)$ must also hold. There are many possible scenarios regarding the relative shapes of $h(\tau^*, x)$ and $g(x)$, leading to many possible steady state equilibria. For the current purposes is will suffice to examine two sets of scenarios: $x_R \geq m$ and $x_R < m$. The usefulness of the distinction between these scenarios is that the species can only be made extinct by poaching if $x_R < m$.

Figure 1 illustrates in phase diagrams an example of each of these scenarios. In the first panel of figure 1 the only steady state equilibira if poaching occurs is at $x = x^*$.[3] This would be a desirable outcome as the species is in a stable positive steady state. In the second panel the species is endangered as the only steady-state equilibrium is $x = 0$.[4] In this case, poaching will push the resource to extinction.

A species that is on an extinction path is one whose dynamics will push the species to $x = 0$. If the species population is initially at some x_0 greater than the minimum viable population, the species can only become extinct if poaching pushes the population below the m. For this to occur the amount of the species poached will have to exceed natural reproduction for all population levels from some $x < m$ up to $x = x_0$. If natural reproduction is greater than or equal to poaching for any species population in that range then there will be a steady state at a population greater than m that prevents extinction. This is why extinction can only occur if $x_R < m$. Intuitively, if the minimum resource population required to sustain poaching is greater than the minimum viable population, then poaching will never push the species population below the point at which it cannot recover.

3 Analysis of Policy Alternatives

3.1 Sanctions

Recall that the sanctions paid by poachers, if caught, are linear in the amount that they poach. An increase in the penalties levied against poachers is equivalent to increasing the slope of the sanction schedule, $\delta'(h)$. In this section the effect of changing the slope of the sanction schedule is explored in some detail, as is the efficacy of shoot on sight policies, which are modeled as $\delta'(h)$ approaching infinity.

Figure 2 plots poaching time against the slope of the sanction schedule, and the price of endangered species products against supply and demand. An increase in sanctions from δ'_0 to δ'_1 initially causes movement along the τ_0 curve. Optimal poaching time falls from its initial level of τ_0^*. This decrease in poaching time feeds into the market for the endangered species product through an upward shift of the supply curve from $S_0(p)$ to $S_1(p)$. There is a price increase associated with this supply shift, which feeds back to the poacher's decision. The poaching time curve shifts up from τ_0, resulting in an increase in optimal poaching time. These feedbacks continue until an equilibrium is reached. This graphical analysis does not adequately show that the new equilibrium τ_1^* will be less than τ_0^*, although that result emerges analytically. The results that price increases and quantity sold in the market decreases also emerge.

3.1.1 Static Analysis

A more rigorous treatment of the above intuition involves the development of a system of equations from the model components built in section two of this paper. Specifically, an expression for $\partial\tau/\partial\delta'$ is derived by implicitly differentiating the poacher's first order condition (equation (1)). A second expression, for $\partial p/\partial\delta'$, is derived by implicitly differentiating the market clearing condition (equation (4)). The two expressions form a system of two equations and two unknowns as follows:

$$\begin{aligned}
\partial\tau/\partial\delta' &= [\pi h_\tau - (1-\pi)h_\tau(\partial p/\partial\delta')]/[h_{\tau\tau}((1-\pi)p - \pi\delta')] \\
\partial p/\partial\delta' &= -[(1-\phi\pi)h_\tau(\partial\tau/\partial\delta')]/[(1-\phi\pi)h_\tau\tau_p - D'(p)].
\end{aligned}$$

Each of the above equations has two components: a direct component and a feedback component. In the numerator of the top expression, the first term represents direct effects on τ from the increase in sanctions, and the second term represents indirect feedback effects. In relation to figure 2, the direct effects can be thought of as the movement along the τ_0 curve, and the feedback effects can be thought of as the curve shifting up from τ_0 to τ_1.

By solving the above system of two equations and two unknowns, the changes in poaching time and price can be found:

$$\partial\tau/\partial\delta' = [\pi h_\tau((1-\phi\pi)h_\tau\tau_p - D'(p))]/ \\ [h_{\tau\tau}((1-\phi\pi)\tau_p - (D'(p)/h_\tau))w - (1-\pi)(1-\phi\pi)h_\tau^2] < 0 \quad (5)$$

$$\partial p/\partial\delta' = [-\pi(1-\phi\pi)h_\tau^2]/ \\ [h_{\tau\tau}((1-\phi\pi)\tau_p - (D'(p)/h_\tau))w - (1-\pi)(1-\phi\pi)h_\tau^2] > 0. \quad (6)$$

Equations (5) and (6) reveal that in equilibrium poaching time will fall and the price will rise if there is an increase in the slope of the sanction schedule. This implies that the direct impact on the poacher's optimal choice from an increase in δ' outweighs the indirect effect from the price increase and poaching time is reduced.

3.1.2 Dynamic Analysis

Consider a scenario in which a species is on an extinction path, but can still be saved. Recall from section 2.4 that, to be on an extinction path, it must be that $x_R < m$, and that, *ceteris paribus*, the species will enter a steady state at $x = 0$. An example of such a scenario is illustrated in the second panel of figure 1. If it is still possible for the species to be saved then it must be that the population is still at least as big as the minimum viable population ($x \geq m$).

From the static analysis, poaching time decreases as a result of an increase in sanctions. This decrease is independent of the species population, i.e. $\partial\tau/\partial\delta' < 0 \; \forall x$. Since the poacher's harvest function $h(\tau, x)$ is increasing in τ, the harvest function will shift down from its initial level to some $h(\tau, x)'$. When the harvest function shifts downward, the point at which it intersects the x axis will shift to the right. This implies that the reservation species population increases from x_R to a new point x'_R. The species will be saved if the increase in the reservation species population is large enough that $x'_R \geq m$.

Figure 3 provides a phase diagram to illustrate this scenario. Initially the model is as illustrated in panel two of figure 1, with a species population $x_0 > m$. The species is on an extinction path, but can still be saved since the population is greater than the minimum viable population. The slope of the sanction schedule is increased, causing the harvest function to shift down to $h(\tau, x)'$, and the reservation species population to increase to x'_R. The bottom panel of figure three shows that the movements in the top panel cause the $\dot{x}$ function to rotate up. Since it is assumed that $x'_R > m$, the $\dot{x}$ function rises enough to become positive over over a range of x values. Included in that range is x_0, thus the change in species population reverses and x begins to grow. The species ultimately arrives in a steady state at x^*.

3.1.3 Shoot to Kill Policies

If only the welfare of the individual poacher is considered, the death penalty for poaching can be represented by $\delta' = \infty$. If the welfare of an entire family is considered, the death of one member may not be an infinite penalty, so this may not be the best way to model shoot on sight policies. It could be the case that poachers consider the expected utility of their family in their decisions to poach. In that case the utility loss due to death would only be the foregone earnings of the poacher, and not the extreme loss one would associate with their own death.

If $\delta'(h) = \infty$, then according to equation (2) the market price of the endangered species product would also have to be ∞ for poaching to occur. Since the reservation price of consumers is assumed to be finite, this will not occur and poaching will be eradicated. If a shoot on sight policy is not equivalent to $\delta' = \infty$, due to family or community considerations, then it is not entirely clear what the outcome of a shoot on sight policy would be. The outcome might be a strong steepening of the sanction schedule with results as given above. An important note in this context is that if policy makers wish to pursue sanctions as a means of saving an endangered species, they will need to ensure that the shift of the harvest function is big enough so that $x'_R \geq m$. One can conjecture that the implementation of a shoot on sight policy would create the largest possible shift in the harvest function and associated increase in the reservation species population.

3.2 Anti-Poaching Enforcement

Analysis of an increase in enforcement proceeds in much the same fashion as an increase in sanctions. Similar to figure 2, poaching time can be indicated by a downward sloping function of the probability of detection (π). When there is an increase in π, there is a movement down the τ_0 curve, decreasing poaching time. This constricts supply and shifts the supply curve up, reducing the quantity sold and increasing the price. This feeds back into the poacher's optimal choice through an upward shift of the poaching time curve to τ_1. Unlike the case of sanctions in figure 2, the direction of the equilibrium change in τ^* cannot be determined as it depends on the elasticity of demand. The change in equilibrium price and quantity sold in the market increase and decrease respectively, as shown in the static analysis below. In the dynamic analysis it is shown that at the point x_R the change in τ can be determined, from which important dynamic results follow.

3.2.1 Static Analysis

The poacher's optimal choice is implicitly differentiated to yield an expression for $\partial\tau/\partial\pi$, and the market clearing condition is implicitly differentiated to give an expression for $\partial p/\partial\pi$. The optimal poaching time derivative can be separated into direct effects that push τ^* along the poaching time curve, and indirect price effects that shift the poaching time curve up. These two expressions form a system of two equations and two unknowns just as in the static analysis of sanctions. Solving the system of equations gives the following results:

$$\begin{aligned}
\partial\tau/\partial\pi &= [((1-\phi\pi)h_\tau\tau_p - D'(p))h_\tau(p+\delta') - (1-\pi)\phi h_\tau h]/ \\
&\quad [h_{\tau\tau}((1-\phi\pi)\tau_p - (D'(p)/h_\tau))w - (1-\pi)(1-\phi\pi)h_\tau^2] \gtrless 0 \qquad (7) \\
\partial p/\partial\pi &= [\phi h_{\tau\tau}hw - (1-\phi\pi)h_\tau^2(p+\delta'(h))]/ \\
&\quad [h_{\tau\tau}[(1-\phi\pi)\tau_p - (D'(p)/h_\tau)]w - (1-\pi)(1-\phi\pi)h_\tau^2] > 0 \qquad (8)
\end{aligned}$$

Equation (7) shows that the net change in poaching time is uncertain. With some re-arrangement this equation can be written in terms of the elasticity of demand, defined as $\epsilon = -D'(p)p/D(p)$. This re-arrangement is given in equation (9), which shows that, if demand is inelastic enough, poaching time will increase as a result of increased enforcement. The threshold elasticity at which the direction of change is reversed is not, however, simply unity as previous authors have found (Fischer 2004). The reason is that equation (9) reflects the complexities of the costs and benefits that poachers face:

$$\begin{aligned}
\partial\tau/\partial\pi &= [h_\tau(\epsilon(1+(\delta'/p)) + (1-\phi\pi)(h_\tau\tau_p(p+\delta'(h)) - (1-\pi)\phi))]/ \\
&\quad [D(p)^{-1}(h_{\tau\tau}((1-\phi\pi)\tau_p - (D'(p)/h_\tau))w - (1-\pi)(1-\phi\pi)h_\tau^2)] \qquad (9)
\end{aligned}$$

This indicates that there is a relationship between the elasticity of demand and the efficacy of increased enforcement.

3.2.2 Dynamic Analysis

Dynamic analysis of increased anti-poaching enforcement will not be as straightforward as in the case of sanctions because, unlike equation (5), equation (7) is ambiguous. As before, it is assumed that the species is initially on an extinction path, but that it can still be saved. The species has an initial population $x_0 > m$, but, *ceteris paribus*, will end up in a steady state equilibrium at $x = 0$ (extinction).

The key to this analysis is that the direction of the change in τ^* can be determined at the point x_R. Evaluating equation (7) at that point gives a strictly negative result. Poaching time decreases when anti-poaching enforcement increases if the species is just at the reservation population. The intuition for this result can be seen by recalling that when the species is at the reservation population, the price of endangered species products will be at the reservation demand price. At p_R, demand is perfectly elastic. Equation (9) shows that only if demand is inelastic enough will the change in poaching time be positive, but at the point p_R that is not the case:

$$\begin{aligned}\partial\tau/\partial\pi|_{x=x_R} &= [((1-\phi\pi)h_\tau\tau_p - D'(p))h_\tau(p+\delta')]/ \\ &\quad [h_{\tau\tau}((1-\phi\pi)\tau_p - (D'(p)/h_\tau))w - (1-\pi)(1-\phi\pi)h_\tau^2] < 0. \quad (10)\end{aligned}$$

Since the change in poaching time at x_R is negative, the poacher's harvest function shifts down at that point. The downward shift at x_R implies that the reservation resource population must increase to some higher level. Since the harvest function is SMI and concave in x, there must be a new point x'_R at which the harvest function intersects the x axis such that $x'_R > x_R$. Rather intuitively, if the probability that the poacher will get caught increases, the minimum species population required to induce her to poach will increase.

It is not clear what will happen to harvest for other values of x. For larger values of x, demand would become more inelastic and the poacher would supply more. In figure 4 the case where harvest would increase for larger values of x when enforcement increases is illustrated.

Figure 4 also demonstrates the potential dynamic implications of increasing anti-poaching enforcement. If the species is on an extinction path, it can still be saved if the increase in enforcement leads to a large enough increase in the reservation species population such that $x_R \geq m$. If this occurs the dynamics of the model will change to the extent that the species will evolve to a positive steady state rather than an extinction steady state. In figure 4 the increase in enforcement, and the associated increase in the reservation species population to x'_R, cause the species to evolve to a steady state at x^*. As mention above, figure 4 also illustrates the ambiguity of the change in harvest when anti-poaching enforcement increases. The result that the species will not become extinct, despite the uncertainty associated with the change in poaching, highlights the need to examine species dynamics and not just poaching quantities. The result that the endangered species can potentially be saved by an increase in anti-poaching enforcement is an important addition to the static results.

3.3 International Trade Moratorium

A critical feature of any trade moratorium will be a link to improved anti-poaching enforcement if the moratorium is successfully to reduce poaching (Heltberg 2001). The most obvious way in which a trade ban can improve enforcement is through the elimination of laundering possibilities (Fischer 2004). Without a trade ban legal sales of products may occur, often administered by government. Through corruption of government officials, or other means, poachers may be able to launder illegal products into legal markets. A trade ban may also make customs officials in receiving countries more efficient in detecting poached products, since any product they encounter will automatically be considered contraband. The impact of a trade ban on poaching and the viability of the endangered species will hinge on whether or not the moratorium improves effective anti-poaching enforcement.

The implementation of a trade ban is identical to forcing the proportion of confiscated goods sold in the market to be zero. This can be represented in the model by a shift from some $\phi < 1$ to $\phi = 1$ (recall that ϕ is the proportion of confiscations *not* sold). If the implementation of a moratorium is to impact enforcement positively, then enforcement must be an increasing function of the proportion of confiscations not sold, i.e. $\pi(\phi)$ and $\pi_\phi > 0$. Results are derived by examining the impacts of small changes in ϕ, but the implementation of a trade ban may be a large change in ϕ. The results relating to small changes in ϕ will generally not depend on the magnitude of ϕ itself, and thus be indicative of a larger change and the implementation of a trade moratorium.

Figure 5 illustrates graphically the static interactions between the poacher's decision and the market for the endangered species product. The first panel illustrates the relationship between π and ϕ, which is assumed to be positive, implying that a trade moratorium improves enforcement. The implementation of the trade ban causes a movement along $\pi(\phi)$, increasing enforcement from π_0 to π_1. This increase in enforcement causes a movement down the τ_0 curve reducing poaching time. In the goods market the supply curve shifts up because the ban reduces supply and less time is spent poaching. The price increase that results from the upward supply curve shift feeds back into the poacher's optimal choice through an upward shift in the poaching time curve to τ_1. The magnitude of the upward shift of the poaching time curve will dictate whether poaching time increases or decreases in equilibrium. This change is ambiguous, except when the species is at the reservation population (x_R).

Notice that if π has no relationship with ϕ, poaching time will unambiguously rise in equilibrium. In this scenario there would be no movement along the poaching time curve due to enforcement increases, but the supply curve would still shift upwards due to the trade ban, as all confiscated goods are removed from the market. The poaching time curve would shift up, and since π would be held constant, poaching time would increase.

3.3.1 Static Analysis

The analysis of a trade ban relies on examining small changes in ϕ and noting that they hold for all ϕ. By implicitly differentiating the poacher's first order condition and the market clearing condition, the following system is are derived:

$$\begin{aligned}\partial\tau/\partial\phi &= [h_\tau\pi_\phi(p+\delta'(h)) - h_\tau(1-\pi)(\partial p/\partial\phi)]/[h_{\tau\tau}((1-\pi)p - \pi\delta'(h))] \\ \partial p/\partial\phi &= [h(\pi+\phi\pi_\phi) - (1-\phi\pi)h_\tau(\partial\tau/\partial\phi)]/[(1-\phi\pi)h_\tau\tau_p - D'(p)]\end{aligned}$$

The different effects outlined in the graphical analysis (figure 5) can be identified in the above expressions. In the numerator of the first expression there are two terms. The first gives the changes in optimal poaching time that result from enforcement increases. These are the changes that cause movement along the poaching time curve. The second term in the first expression represents the price related upward shift in the poaching time curve due to supply reductions. The second expression gives the changes in the price level resulting from the trade moratorium. The first term represents direct supply reductions due to the removal of confiscated products from the market. The second term represents the effect of changes in the poacher's optimal choice on the price. If the poacher reduces her time allocation then the price rises further, but if she increases her time allocation due to the aforementioned price rise, the price increase is somewhat reduced. The equilibrium results are as follows:

$$\begin{aligned}\partial\tau/\partial\phi &= [((1-\phi\pi)h_\tau\tau_p - D'(p))h_\tau\pi_\phi(p+\delta') - (1-\pi)(\pi+\phi\pi_\phi)h_\tau h]/ \\ &\quad [h_{\tau\tau}((1-\phi\pi)\tau_p - (D'(p)/h_\tau))w - (1-\pi)(1-\phi\pi)h_\tau^2] \gtrless 0 \qquad (11) \\ \partial p/\partial\phi &= [h_{\tau\tau}h((1-\pi)p - \pi\delta'(h))(\pi+\phi\pi_\phi) - (1-\phi\pi)h_\tau^2\pi_\phi(p+\delta'(h))]/ \\ &\quad [h_{\tau\tau}((1-\phi\pi)\tau_p - (D'(p)/h_\tau))w - (1-\pi)(1-\phi\pi)h_\tau^2] > 0. \qquad (12)\end{aligned}$$

The net impact on τ^* from a small change in ϕ, given by equation (11), is ambiguous. The sign of (11) is not affected by ϕ itself, so the impact the imposition of a trade moratorium on poaching time is ambiguous. If the second term of equation (11) is smaller than the first, then the expression will be negative. If harvest is equal to zero, then the second term is equal to zero, and the expression is negative, but, if harvest is large the opposite may happen. Equation (12) shows that the price unambiguously rises. This is a consequence of the two sources of supply reduction explained in figure 5.

If there is no relationship between enforcement and confiscations, such that $\pi_\phi = 0$, then equation (11) is unambiguously positive. This means that, if a trade moratorium does not impact enforcement, it will increase poaching levels. This is because only changes the poacher's optimal choice would be the result of a price increase, which increases the marginal benefit of poaching time.

3.3.2 Dynamic Results

The dynamic results hinge on the assumption that $\pi_\phi > 0$. If this is true, the results are very similar to the those for an increase in enforcement. If the assumption does not hold then the dynamic result is simply an increase in the speed at which the species becomes extinct.

As with the previous dynamic policy analyses, it is assumed that the species is on an extinction path, but can still be saved. The initial state of the model is like the one depicted in the second panel of figure 1 in which poaching is going to drive the species to extinction. It is assumed, however, that the initial species population is greater than the minimum viable population ($x_0 > m$).

The result of a trade moratorium is to shift the harvest function. Equation (11) indicates that the direction of the shift is uncertain, although at the point x_R the shift will be downward (assuming $\pi_\phi > 0$). The intuition is exactly as it was in the case of an increase in enforcement. If the species population is at the reservation population, the price of endangered species products must be the reservation price. At that price, demand is perfectly elastic and the price will not rise as supply is reduced. Equation (13) gives (11) evaluated at the point $x = x_R$.

$$\begin{aligned} \partial\tau/\partial\phi|_{x=x_R} &= [((1-\phi\pi)h_\tau\tau_p - D'(p))h_\tau\pi_\phi(p+\delta')]/ \\ &\quad [h_{\tau\tau}((1-\phi\pi)\tau_p - (D'(p)/h_\tau))w - (1-\pi)(1-\phi\pi)h_\tau^2] < 0 \qquad (13) \end{aligned}$$

If it were the case that $\pi_\phi = 0$ then equation (13) would be zero, and there would be no movement in the harvest function at the point x_R.

For the case when $\pi_\phi > 0$, the properties of the harvest function and the downward shift at x_R imply that there will be a new reservation species population $x'_R > x_R$. If the increase in the reservation species population is sufficiently large that $x'_R > m$, then the species will be saved from extinction. Graphically this case is exactly as that of an increase in enforcement (see figure 4). The increase in the reservation species population causes the $\dot{x}$ function to become positive over a range of x values, causing the species to enter a stable positive steady state, rather than become extinct.

If it were the case that $\pi_\phi = 0$, then the harvest function would rotate upwards. This would cause the $\dot{x}$ function to rotate downwards, speeding up the species' path to extinction. Intuitively, in this case the trade ban would increase poaching causing the species to become extinct faster.

The dynamic impact when $\pi_\phi > 0$ provides a reasonable explanation for the dynamics of elephant populations in recent years. Prior to the introduction of the international ivory trade ban, elephant populations were dwindling and were arguably on an extinction path. As Fischer (2004) and van Kooten (2007) point out, there is some evidence that the elephant population has stabilized and begun to recover since the introduction of the trade ban. This analysis suggests that the trade ban has changed the economic conditions faced by poachers to the extent that there has been a change in the equilibrium path of elephants. The trade ban on ivory products may have improved anti-poaching enforcement in some manner and so caused the reservation elephant population to rise. It appears this increase may have been large enough to prevent elephants from going extinct.

4 Conclusion and Discussion

Improved anti-poaching enforcement, increased sanctions and international trade moratoriums can potentially serve to save a species that would otherwise become extinct. The results of this study have also re-iterated the finding of past authors that increased anti-poaching enforcement and trade moratoriums have ambiguous impacts on poaching. However, this study has added the important result that the survival of an endangered species may be aided by these policies despite the ambiguous static results. These results have emerged because of the structure of the model employed in analysis. By combining a basic model of criminal behavior and a standard dynamic natural resources framework, the intricacies of the relationship between poachers and endangered species emerge.

The results in this paper provide some evidence in favour of an ivory trade ban, even though it would result in exceptionally high ivory prices, which create perverse incentives for poachers. The analytical results indicate that despite large price increases, the policy still has the potential to prevent elephant extinction.

It was noted in §3.1.3 that shoot to kill policies will eliminate illegal harvesting if poacher's consider only their own utility, although poaching may not be eliminated if family or community utility is considered. In nations, such as Kenya, where shoot to kill policies have been implemented, poaching is still observed, but in lesser amounts. This suggests that poachers do consider family well-being in their decisions, and shoot to kill policies are not equivalent to $\delta' \to \infty$.

In terms of the assumptions driving the model, three warrant futher discussion: risk-neutral poachers, dispensational population growth and the existence of a reservation demand price. The assumption of risk-neutrality is necessary to make the model tractable. Poachers are likely to be less risk-averse than the average person and may even be risk takers given the nature of the activity; thus risk neutral may be a compromise assumption, but that is pure conjecture. The problem with alternative risk assumptions is that they lead to ambiguous results that depend on the relative magnitudes of the parameters. A reformulation of the model, perhaps numerically with explicit functional forms, would help sort out the alternative assumptions, but this is left for future research.

The assumption of dispensational growth departs from traditionally assumed logistic growth in that it assumes a certain minimum viable population. For most endangered species there is a strong argument for a lower bound of two on the minimum viable population, and many biologists suggest $m \approx 1000$ for mammals, making this a reasonable assumption. There is a stronger argument to be made against logistic growth as it would require that for extinction to occur, poachers be willing to spend time poaching until the species population is extinct, even if the population is very small. This would require that the price received by poachers approach infinity, which does not seem plausible. Dispensational growth allows the species to become extinct, while its value remains finite.

The ability of the price of the endangered species products to become infinite is prevented in the model by the assumption of a reservation demand price. This assumption is supported by the implausibility of the price of endangered species products approaching infinity. Even for products, such as those coming from rhinoceros horns, that are highly coveted, budget constraints limit the extent to which the price can increase. There is an upper bound to the reservation price, which then defines the reservation species population which is so vital to the analysis.

Future research into endangered species poaching needs to be able to analyze welfare effects in order to examine policy options in a more complete manner than done in this study. The contributions of this paper in terms of species dynamics are important, but they do not help to determine what the best policy alternatives are from a welfare standpoint. Models that capture the welfare of all those with interests in the endangered species (not just poachers) need to be developed in order to compare policies adequately. The present model cannot possibly compare a trade moratorium to a shoot on sight policy in terms of welfare. A model in which the costs and benefits of each can be compared is needed, although this would not be a simple exercise. A last consideration for future research is the examination of how directing revenue from the sale of confiscated goods into anti-poaching enforcement compares to the enforcement gains derived from a trade ban.

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Notes

[1]Kremer and Morcom (2000) use the same proportion structure in their analysis.

[2]This of course does not rule out logistic growth if $m = 0$.

[3]Two other steady states are $x = m$ and $x = 0$, but poaching cannot result in these equilibria.

[4]It is possible to have $x_R < m$, and $h(\tau^*, x) \not> g(x) \;\; \forall x \in (m, 1)$, in which case there would be some positive steady state, but the possibility of extinction would still exist.

FIGURE 1

Phase diagrams for $x_R > m$ and $x_R < m$.

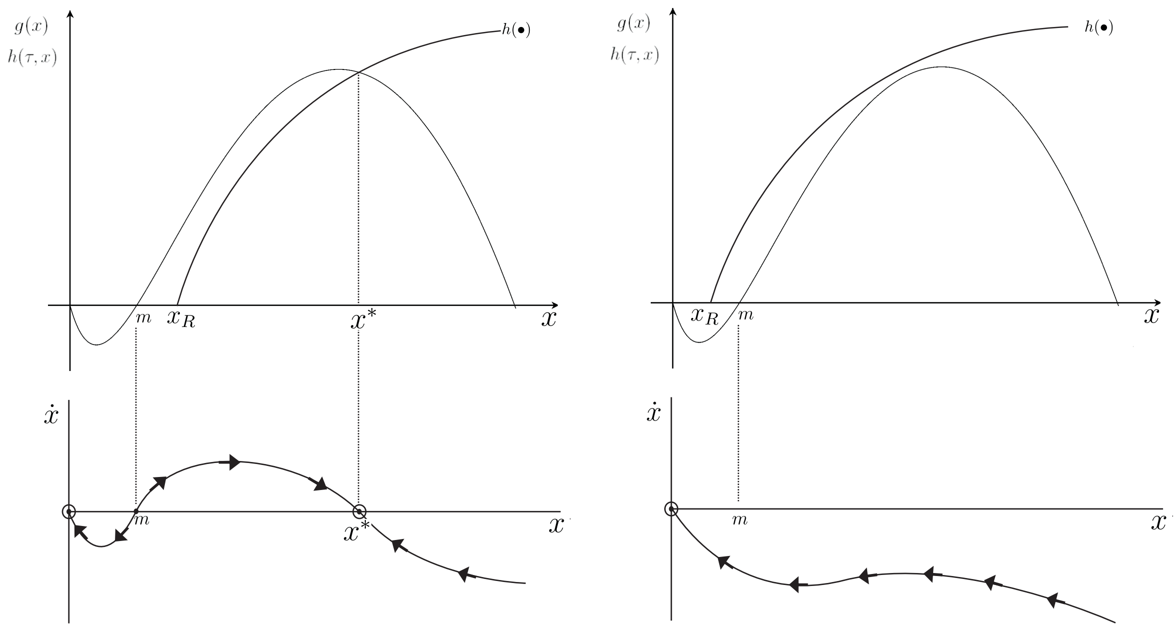

FIGURE 2

Statics of a sanctions increase.

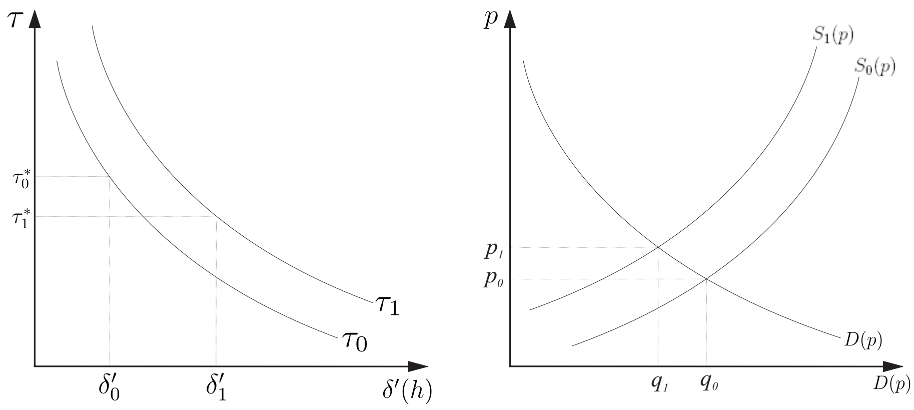

FIGURE 3

Phase diagram for a sanctions increase.

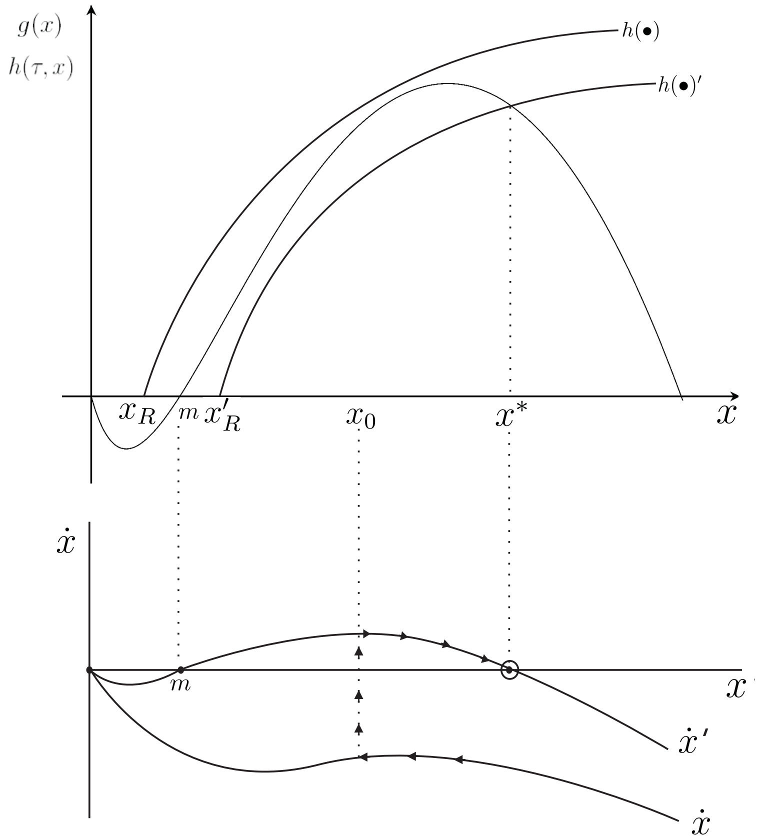

FIGURE 4

Phase diagram for an enforcement increase.

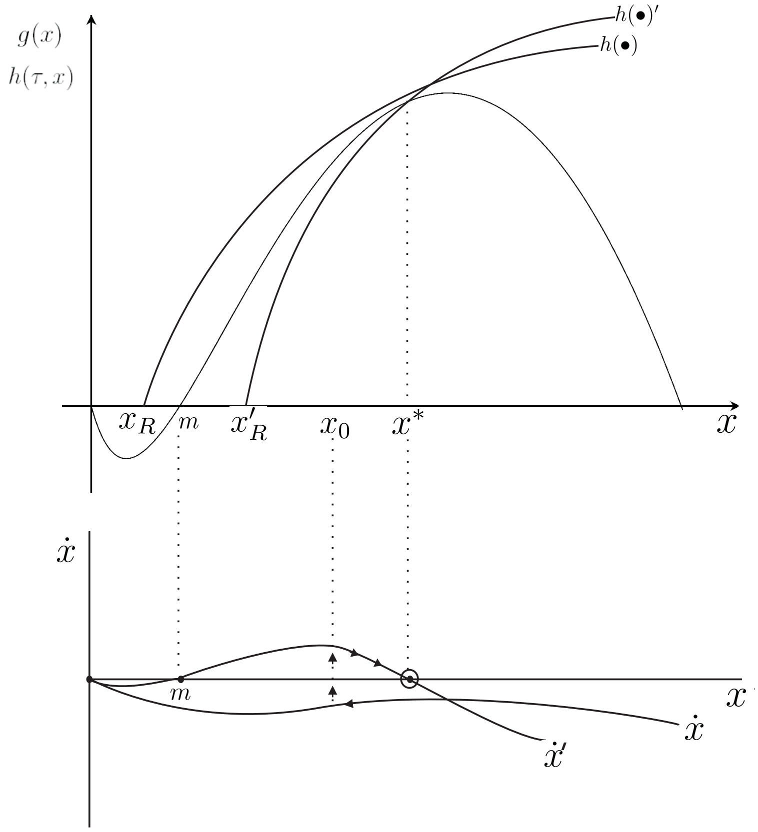

FIGURE 5

Statics of a trade moratorium.