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Open access harvesting of wildlife: the poaching pit and conservation of endangered species

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Abstract

We extend the traditional G–S model of open access by defining a non-concave harvesting function. We demonstrate the possible existence of multiple equilibria and perverse comparative statics and show that small changes in the underlying economic parameters may trigger large jumps in species' abundance. Finally, we briefly discuss implications for management.

Keywords: Poachers; Non-concavity; Holling type III predation; Property rights; Jumps; Hysteresis; Black rhino

1. Introduction

Property rights, or rather their absence, have played an important role in the literature on natural resource economics. Originating with ground-breaking work by Gordon (1954), economists have analysed exploitation of resources when property rights are absent, unclear or ill-enforced. For obvious reasons, marine resources attracted a lot of attention in early periods. In the late 1970s, the UN announced that countries could declare sovereign rights within 200 mile zones, anticipating the 1982 Law of the Sea Convention. These exclusive fishing zones captured most economically viable fisheries, hence the issue of open access appears less pressing today than, say, 30 years ago. However, the economics of 'open access' or 'poaching' is still at the core of the research field. The reason is simply that while de jure open access is rare nowadays, many renewable resources are de facto still exploited under conditions resembling open access. This obviously applies to many fisheries world-wide but also to the management of wildlife and the conservation of endangered species, especially in developing countries.

Economists have predominantly applied one particular model to analyse steady states and dynamics of open access resources (Wilen, 1976). A simple system of two differential or difference equations, dubbed the Gordon–Schaefer (G–S) model, has proven to be sufficiently general to permit study of the exploitation of such diverse species as lobsters (Bell, 1972), herring (Björndal and Conrad, 1987), whales (Amundsen et al., 1995) and elephants (Bulte and van Kooten, 1999b). It is an open question, however, whether the G–S model is applied because of its analytical tractability, or because it provides an appropriate description of reality. In this paper we demonstrate that relaxing some of the (implicit and) restrictive assumptions underlying the traditional G–S model has dramatic effects.

The main objective of this paper is to explore the consequences of assuming a more realistic specification for open access harvesting. Specifically, we consider a convex–concave production 'harvest'

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function, argue why such a specification is plausible and draw parallels with ecological models of predation. While retaining the conventional assumption of entry and exit of firms in the extractive industry proportional to profit (see Berck and Perloff, 1984 for a model of open access with rational expectations), we demonstrate that the resulting dynamics are more complex than predicted by the G–S model. Also, the traditional result of a unique and stable steady state to describe open access outcomes in the long run may be false. Rather, multiple equilibria may exist and 'jumping' from one steady state to another may be triggered by small changes in economic parameters. We present anecdotal evidence on species abundance supporting this result, and discuss some implications for management.

2. Traditional analysis of poaching and open access

Following Ciriacy-Wantrup and Bishop (1975), economists usually distinguish between common property and open access resources. Common property refers to the case where a well-defined group of resource owners is able to exclude entry by others. Such a group may or may not be able to regulate exploitation efficiently (Baland and Platteau, 1996). Open access, on the other hand, is about the case where property rights do not exist (the high seas), or are too expensive to enforce. If the government or a group of private resource owner(s) cannot control access by third party 'poachers', the situation may thus be characterised as open access. In what follows the terms 'poaching' and 'open access' are used interchangeably. Assume a single population of a single species, whose growth is described by the following quadratic (or logistic) function:

$$G(x) = \gamma x(k - x), \tag{1}$$

where x measures abundance of the stock, γ is the (scaled) intrinsic growth rate of the population and k the population's carrying capacity. The population is subject to open access exploitation, and harvesting (h) is modelled by the well-known Schaefer production function:

$$h = qEx, \tag{2}$$

where q is a species-dependent catchability coefficient measuring how easy it is to catch the species in question and E the aggregate harvesting effort (Schaefer, 1957). The equation of motion of the population is therefore

$$\frac{\mathrm{d}x}{\mathrm{d}t} = G(x) - h = [\gamma(k - x) - qE]x. \tag{3}$$

To solve for the resource stock and effort level, differential equation (3) is supplemented with an equation that describes poachers' behaviour. It is usually assumed that entry will occur as long as individual poachers will find it profitable to do so (accounting for the full opportunity cost of their time) and that exit will occur when poachers are earning a loss. Profits are typically defined as follows:

$$\pi = ph - cE = E[pqx - c], \tag{4}$$

where p is the price per harvested unit that the poacher receives and c measures the full cost per unit of effort. Eq. (4) is readily extended to include (expected) fines when poachers face a certain probability of being caught and sentenced (Millner-Gulland and Leader-Williams, 1992a,b). Assuming that adjustment is not instantaneous, the development of effort over time is given by

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \phi\pi = \phi E[pqx - c], \tag{5}$$

where ϕ is an adjustment coefficient.

The system of differential equations (3) and (5) is the famous G–S model, and may be used to analyse the open access steady state and approach dynamics of effort and the resource stock. Due to free entry, profits will dissipate in the long run. Setting the right-hand side (RHS) of (5) equal to zero yields an expression for the equilibrium resource stock:

$$x = \frac{c}{pq}. \tag{6}$$

Next, upon setting the RHS of (3) equal to zero, we find an expression for equilibrium harvest effort:

$$E = \left(\frac{\gamma}{q}\right)(k - x). \tag{7}$$

Drawing the $\mathrm{d}x/\mathrm{d}t = 0$ and $\mathrm{d}E/\mathrm{d}t = 0$ isoclines in a phase plane in E–x space illustrates that a unique and stable steady state may exist (e.g., Conrad, 1995). Assuming that an interior solution exists, it is described by $x^* = c/pq$ and $E^* = (\gamma/q)[k - (c/pq)]$. Consistent with intuition, the resource stock is declining in the price of the resource and its catchability coefficient and increasing in the cost per unit of effort.

Depending on initial values, the resource-effort system approaches the equilibrium either monotonously or as a counter-clockwise spiral (i.e., the equilibrium is a stable focus). Using a system of differential equations, open access extinction is prevented because the harvest cost per unit of output will approach infinity as the stock gets depleted. Open access extinction may occur, however, when there exists a delay in the response of entry and exit to profit levels.

While elegant and of great pedagogical value, the fundamentals of the G–S model have been debated and falsified in both the ecological and economic literature (see below). Nevertheless, the G–S model is still used extensively to model open access and poaching. Indeed, it would be no exaggeration to claim that this simple specification dominates the current literature on resource management with imperfect property rights. This is exemplified by the fact that the basic model has recently been applied to study resource exploitation in relation to such diverse issues as trade (Brander and Taylor, 1997a,b), management and regulation (Homans and Wilen, 1997), metapopulations (Sanchirico and Wilen, 1999), and ecological interactions between mangrove forests and fisheries (Barbier and Strand, 1998). It is no surprise, therefore, that Brown (2000) concludes the following about the Schaefer production function:

> "this production function ... is remarkable for the rare times it has been modified in the literature to satisfy economists' concern for diminishing returns in the factors of production. The form of Eq. (2) has attractive pedagogic features and is kept for that reason."

3. Open access as Holling type III predation

Consider a species that is subject to poaching or open access exploitation. To motivate the need for an extension of the G–S model as presented in the previous section, we mention a number of considerations that may characterise actual exploitation but are disregarded by the G–S model:

- Marginal harvest costs increase in harvesting levels, for example because potential members of poaching expeditions have to be 'teased out' of increasingly profitable occupations (such that the opportunity cost of labour increases when aggregate harvesting goes up).
- The harvested species is subject to downward sloping demand, thus yielding lower prices as supply expands (even though prices for individual agents are likely exogenous).
- There are diminishing returns to the wildlife stock as an input because of gear saturation.
- The species is not spread evenly over the terrain but tends to cluster in small migrating groups (or is spatially heterogeneous).
- The species is but one out of a number of species that poachers could choose to pursue and turn their special attention to, depending on the relative profitability of harvesting, but 'incidental' killing (i.e., as a bonus) at low prey densities may occur.

These considerations can be incorporated in an extended version of the G–S model. Endogenous prices and increasing marginal costs are readily captured by defining functions $p(h)$ and $c(E)$ with $p' < 0$ and $c' > 0$, $c'' > 0$—as opposed to constant p and c. The potential issue of gear saturation may be tackled by defining a more general production function than the one presented in (2). To capture the complexities posed by the remaining two assumptions, however, we need to define a production function that is (much) more complex than the Schaefer specification. Indeed, for spatially heterogeneous populations Clark (1990, p. 225) demonstrates that "*there will be no general direct relationship between aggregated effort, stock abundance and catch*".[1] Therefore, we will choose a different route in what follows.

Rather than specifying a spatial relation between (multiple) prey density, harvest effort and output, we define a reduced-form poaching function. Due to downward sloping demand, diminishing returns and/or increasing marginal costs, poaching will eventually level off when prey densities (and output) increase. A realistic production function will thus be

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[1] We will present some empirical results in Section 4 for the case of black rhino conservation in Africa. Brown and Layton (2001, p. 38) mention that black "*rhinos actually and potentially are spatially distributed*".

concave when the variable input x (wildlife abundance) takes high values. What will the production function look like when this input is only available in small quantities (i.e., when wildlife stocks are depleted)? Since poaching is in some senses akin to predation, we turn to ecologic theory on predation to shed light on this issue. One particularly interesting feature of some predation models is prey switching. Writing about birds feeding on budworms, e.g., Ludwig et al. (1978, p. 317) argue that

> "birds have a variety of alternative foods, and when one of them is scarce, that particular prey item is encountered only incidentally. As the prey item becomes more common, however, the birds begin to associate reward with that prey and they begin to search selectively for it."

Hence, predators have the option to switch between alternative prey species, so that predation rates may increase for a range of prey densities. For some density levels, there is an upward sweep in the functional response curve because an increase in prey density elicits an increased amount of hunting after this particular species. Similar considerations may apply to poachers in a multi-species setting. Different species likely have different feeding and migration habits and may require somewhat different hunting techniques for maximal profitability. In heterogeneous habitat, relative levels of abundance for different species will also be different, suggesting that poachers will choose a particular species as their predominant target, perhaps treating others as mere bonuses. Hence, while harvesting blue whales may be considered a bonus in periods when this species is rare, hunters may turn their attention to these species and consider them their main target species if stocks become more abundant.[2]

The combination of an upward sweeping functional response due to prey switching at low prey densities and the gradual levelling off due to saturation at high prey densities causes a sigmoid functional response curve. In ecologic theory, a function that specifies such a functional response is called a Holling type III predation function (Holling, 1959).[3] In Appendix A, we demonstrate how a simple Holling type III poaching model may be derived from micro-foundations. However, since there are many alternative ways to derive a convex–concave production function (think of including congestion externalities, endogenous prices or avoidable fixed costs), we wish to emphasise the generality of the results by developing a more general reduced-form relation between off-take h and abundance x. Such a function may be defined as follows:

$$h(x) = \beta \frac{x^2}{\alpha^2 + x^2}. \tag{8}$$

This specification is not really in the spirit of the G–S model because of the absence of effort, but it provides the convex–concave features discussed above and is consistent with, e.g., Ludwig, Jones and Holling's specification of birds feeding on budworms. The parameters α and β have a special meaning. The parameter α measures the level of prey abundance at which saturation begins to take place. The parameter β is the maximum level of off-take per period or the saturation level of harvesting. These parameters are not without economic meaning but it takes a structural model to shed more light on this issue. Here we can simply acknowledge that α and β are determined by the benefits and costs of hunting the species in question and really are implicit functions of price and marginal harvest cost (including considerations related to expected fines, elasticity of demand, attitude towards risk, gear saturation, etc.).

Assuming logistic growth, the equation of motion for the hunted species is simply

$$\dot{x} = \gamma x(k - x) - \beta \frac{x^2}{\alpha^2 + x^2}. \tag{9}$$

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[2] Clark (1990, p. 313) develops a simple open access model with both fin and blue whales, concluding that incidental killings of the rare species enhances the risk of extinction if the abundant species is able to support the fishery. For models of harvesting in the context of ecologically interacting species, possibly resulting in discontinuous shifts in abundance, see, e.g. Murphy (1967) and Johnston and Sutinen (1996).

[3] The standard Schaefer production function $h = qEx$ is consistent with the so-called Holling type I functional response: *for a given level of effort* (say, one predator or one poaching gang on a 1 week hunting trip) there is a proportional linear relation between prey density and predation (or poaching) rate. The Holling type I response, however, is not at all common in ecological systems (Begon et al., 1996). Much more common is the Holling type II functional response, consistent with economists' understanding of well-behaved concave production functions (where prey density represents the variable input).

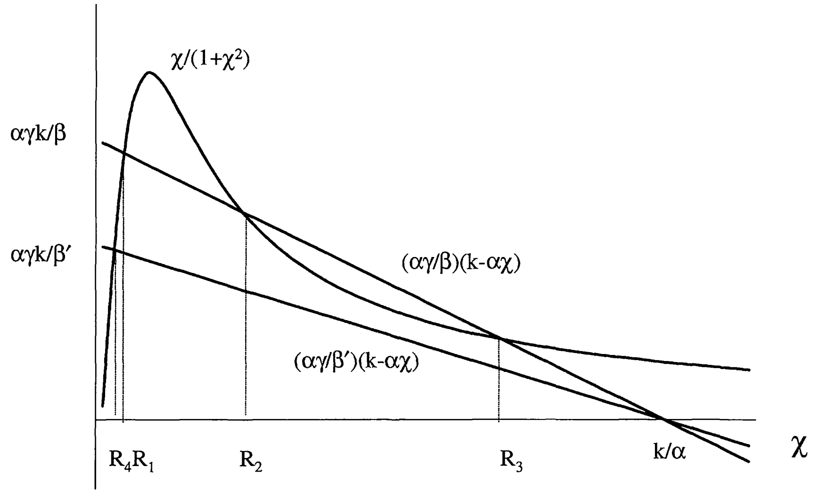

Fig. 1. Growth and harvesting with a type III poaching response.

In what follows, we will consider the steady states of this equation in more detail. For this purpose, set

$$\gamma(k-x)-\beta\frac{x}{\alpha^2+x^2}=0. \tag{10}$$

Following Ludwig, Jones and Holling, we scale wildlife abundance by defining $\chi = x/\alpha$ and multiply by α/β, yielding

$$\frac{\alpha\gamma}{\beta}(k-\alpha\chi)-\frac{\chi}{1+\chi^2}=0. \tag{11}$$

We graphically solve the cubic relation (11) by plotting the left and right terms separately in Fig. 1.

Consider the benchmark scenario where there are three possible equilibria, or levels of abundance where poaching just equals growth: R_1, R_2 and R_3. While R_1 and R_3 are stable equilibria, this is not true for R_2. If due to some shock the system is temporarily removed from this steady state, the population will either grow to R_3 or decline until R_1. Our first result is, therefore that depending on the starting values of the parameters and the initial level of species abundance (i.e., past exploitation intensity), different steady states may materialise rather than a unique stable equilibrium as predicted by the G–S model.

The comparative statics of this model are readily analysed by shifting the relevant curves. First, consider the effect of increasing the parameter β (e.g. because the price of output has gone up or because poaching costs have gone down). Increasing β implies that $(\alpha\gamma/\beta)(k-\alpha\chi)$ rotates counter-clockwise. If the initial stock of the species under consideration is R_1 or R_3, the steady state stock declines, which is consistent with intuition.

Second, the comparative statics of the unstable equilibrium R_2 are perverse: rising prices and falling costs have the result of contributing to thicker stocks as β is increased marginally. This does not mean that rising prices (or falling costs) discourage poaching at the unstable equilibrium. It still holds that aggregate exploitation at the new steady state is greater than before. This is not inconsistent if we realise that: (1) the unstable steady state R_2 is located at $x < 0.5k$ (i.e., on the upward sloping part of the growth function $G(x)$) and (2) that the poaching function h is less steep than the growth function $G(x)$. Shifting the poaching function up then increases both stock size and growth (and exploitation, in the steady state).

Finally, the effect of increasing the parameter α is ambiguous as the linear curve shifts outward but rotates inwards.[4]

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[4] In a similar fashion, we can consider the effect of changing the 'ecological parameters'. If extra (secure) habitat becomes available (i.e. k takes on a higher value), the stable equilibria will support thicker stocks as both intercepts ($\alpha\gamma k/\beta$ and k/α in Fig. 1) shift out. Again, the comparative statics of the unstable equilibrium are perverse: extra habitat leads to fewer animals. Finally, for some species it may be possible to manipulate the in situ growth rate

An important further result of the extended model, and one that we will discuss in further detail below, is that changes in ecological or economic parameters may trigger 'jumps' in species' abundance. For example, assuming a price increase such that the economic parameter increases from β to β', it is clear that a discontinuity occurs if the initial population was at a 'high steady state' (R_3). As the parameter β continues to increase, the steady states R_2 and R_3 converge and eventually coincide. A marginal further increase in β implies that the high equilibrium is lost such that only one (low) equilibrium exists. For example, from Fig. 1 it is readily verified that for the value β' there exists only one steady state, R_4, suggesting a dramatic change in population size. A reverse jump may also occur. Starting from a low steady state (say, R_1), if we decrease the value of β the steady states R_1 and R_2 will approach each other, then coincide and eventually disappear. The system will jump to a high steady state. Such a jump or discontinuity in dynamic systems is usually referred to as a 'catastrophe'. Catastrophe theory was developed by Thom (1975) and discussed in the context of economic systems by, e.g., Rosser (1999). Jumps in abundance are quite different from the gradual changes predicted by the G–S model, but not at all at odds with actual experiences in conservation biology (see Farrow, 1995 for a discussion of the plight of the passenger pigeon and buffalo).

It is possible to derive multiple equilibria models with the possibility of 'catastrophic' jumps, akin to the one above, without abandoning the G–S framework.[5] Copes (1970) was the first to demonstrate that the equilibrium supply curve in the G–S model is backward bending, possibly giving rise to catastrophic results. Intuitively, supply first increases when the price of the resource commodity goes up, but after the stock has been depleted to the maximum sustained yield level (or $x = k/2$ for a logistic growth function), further price increases (triggering more entry by poachers) will result in a reduction in wildlife stocks and, hence, equilibrium supply. When demand for the resource commodity has a finite demand elasticity (the inverse demand curve is downward sloping), it is possible that demand and supply are equated at multiple levels of wildlife abundance, giving rise to similar results as discussed above.[6] Note that a downward sloping demand curve is necessary to obtain multiple equilibria and 'jumps' in the G–S setting, while the current analysis also allows for such results when resource prices are constant.

4. An example: the case of black rhino conservation

Black rhinos provide a famous example of the potential dramatic effects of poaching on species viability. The population of this animal was decimated from about 100,000 in 1960 to about 2500 in the mid-1990s, representing a 95% reduction in abundance in 40 years (Dublin and Wilson, 1998). Moehlman et al. (1996) discuss some of the genetic and demographic threats to fragmented and disjunct remnants of a once thriving population. While habitat conversion has played a role in the rhino's demise, the insatiable demand for rhino horn is the foremost cause of its decline. Rhino horn is an ingredient in traditional remedies to reduce fever but is also seen as status symbol when used as a handle for curved daggers. (Black) rhinos were listed as an Appendix A species in 1977 by the newly ratified CITES convention, thus effectively banning *legal* trade in rhino horn. This ban, however, had little demonstrable effect on the decline in rhino numbers, with some analysts arguing that the ban has contributed to the species' fall in abundance (e.g., Brown and Layton, 2001). It is a fact that illegal killing was vigorous in the 1970 and 1980s.

Many people are concerned that without further actions the black rhino (and some of its relatives) will become extinct in the foreseeable future. However, carefully observing recent trends in rhino numbers suggests that the species is not on a toboggan ride towards absolute zero. Rather, the population appears to be approaching a new, but low steady state. Indeed, Dublin and Wilson (1998) argue that there may be grounds for 'cautious optimism' in the 1990s. The

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(Grafton and Silva-Echenique, 1997). From (11), it is obvious that the comparative statics with respect to γ are the same as for k. If extra (secure) habitat becomes available (i.e., k takes on a higher value), the stable equilibria will support thicker stocks as both intercepts ($\alpha\gamma k/\beta$ and k/α in Fig. 1) shift out.

[5] I would like to thank an anonymous referee for bringing this to my attention.

[6] For additional insights and analyses, refer to Jones and Walters (1976) and Rosser (2001).

population of black rhinos appears to be stabilising and is even slowly increasing in some places. The reasons for this stabilisation are as yet ill-understood. Some interpret it as proof that the trade ban is finally bearing fruit, whereas others argue that it is "*the result of new approaches to rhino conservation, improved intelligence and the consolidation of the majority of Africa's rhinos within sanctuaries, conservancies and other intensively protected areas*" (Dublin and Wilson, 1998).

How successful is the G–S model in explaining the demise in rhino abundance over the past four decades? Demand for rhino horns has shifted outward since 1960, mainly reflecting rising incomes in consumer areas (oil producing Arab countries and 'Asian tiger' economies). Steadily rising demand has been well documented (e.g., Millner-Gulland, 1993), and has translated into ever higher prices for rhino horn. The G–S model predicts an inverse relation between rhino density and horn prices in the steady state (recall that $x = c/pq$ is the unique solution to the G–S model). Assuming a constant catchability coefficient and cost per unit of effort, the question boils down to whether rhino horn prices have increased enough to warrant a 95% reduction in rhino density. To explain a fall in the steady state rhino population from 100,000 to 2500 animals, prices should have increased by a factor of 40 (assuming poachers have just earned their reservation price at the beginning and end of this period, or that profits have been eroded by entry). This, however, is almost certainly an underestimation of the true required price increment. As mentioned above, conservation efforts have seriously increased as rhino populations throughout Africa were being slaughtered, effectively increasing the costs of harvesting per unit of output, c (Bulte and van Kooten, 1999a). To compensate for extra enforcement and higher costs, therefore, the price of rhino horn must have increased even further.

This 'prediction' of the G–S model is not consistent with available evidence on prices over time (which is admittedly scant, as trade has been underground since the late 1970s). Brown and Layton mention that "*real prices have risen by a factor of 6 or more since the ban was anticipated*". Additional data on rhino horn prices are consistent with this quote: prices have gone up considerably in recent decades but certainly not by a factor of 40 (e.g., Millner-Gulland, 1993).

One explanation is as follows: a type III predation response characterises poaching of black rhinos, implying that 'modest changes' in economic parameters (price increases) may result in dramatic effects on prey density. Poachers in Africa are typically not exclusively after rhinos, taking elephants as well (e.g., Millner-Gulland and Leader-Williams, 1992a,b). The possibility of switching between multiple species causes a sigmoid poaching function, such that a sixfold increase in prices may well result in a 95% collapse in abundance. This explanation is consistent with observations by Millner-Gulland and Leader-Williams for Luangwa Valley, a protected area in Zambia. While rhinos were being slaughtered on a massive scale in the 1970s by professional rhino hunters (from 4000 to 12,000 rhinos to only a few hundred animals), they noted that:

> "At the 1985 parameter values, the fate of Luangwa Valley rhinos was being determined by the incentives to hunt elephants. It was profitable to go out specifically to hunt elephants, but not rhinos. However, as with local hunters, if an organised gang happened to encounter a rhino, killing it would be very profitable .... The situation in the Luangwa Valley in 1985 was consistent with these findings: organised gangs were usually found with ivory, but occasionally with rhino horn as well. Thus the profitability of ivory actually contributed to the decline in the rhino population, despite rhinos being too scarce to be worth hunting alone" (Millner-Gulland and Leader-Williams, 1992b, p. 201).

Anecdotal evidence thus clearly suggests that the behaviour of poachers is consistent with type III predation as modelled by ecologists.[7]

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[7] There are two alternative explanations for the finding that rising prices did not keep pace with poaching effort and harvesting. First, it may be the case that poachers earned positive profits in the 1960s and/or negative profits in the 1990s. When calibrating the G–S model, analysts usually assume that free entry and exit causes instantaneous dissipation of profits. The zero profit condition is then invoked to estimate the (average) cost per unit of effort. However, adjustment may be slow in reality, depending on cultural and psychological factors. Without additional data it is not possible to confirm or refute this possible explanation, but it is clear that lack of knowledge about reservation prices is a shortcoming of most (but not all) empirical work in the tradition of Gordon and Schaefer (see also Brown and Layton, 2001). Second, it may be argued that rhino populations are not stabilising at the current low level. Instead, we may be witnessing a temporary phase in the dynamics of the G–S model, and effort and stocks are on

Assuming this explanation holds, it is interesting to ask what it takes to restore the rhino population to its initial level of abundance (see especially Brown and Layton, 2001). One of the major approaches to conservation is trying to shift demand inwards by informing consumers about the plight of the rhino and/or by searching for substitutes of rhino horn (Dublin and Wilson, 1998). If such measures reduce rhino horn prices by a factor 6, would this be consistent with population recovery to the 1960 level? We will now show that this is not true.

5. The poaching pit

If a price increase has resulted in a species collapse from R_3 to R_4, it takes more than a reversal of past price trends to establish a reverse flip from R_4 to R_3. A type III poaching function gives rise to a phenomenon that we may coin the 'poaching pit'. Once a (possibly small) change in economic parameters causes a large discontinuous decline in abundance of the prey species, *changing the parameters back to their prior values does not restore the old level of abundance*. The species is 'caught' at the low level—a phenomenon known as 'hysteresis'. To illustrate hysteresis in more detail, refer to Fig. 1 again, and assume that due to rising prices the rhino population is currently as low as R_4, while it was as high as R_3 in the 1960s. Next, suppose that, as a result of conservation programs and active enforcement, the economic 'parameter' β takes its initial value (or β as opposed to β'). While this triggers an increment in the rhino population, the stock will not grow back to the old level R_3. Rather, rhino abundance will stabilise at R_1, even though the same combination of parameters could also support a steady state with higher levels of rhino abundance.

The existence of the poaching pit is explained as follows. When rhinos are rare (at level R_4, as in Zambia in the mid-1980s), poachers will predominantly chase elephants and only shoot an occasional rhino. If the price of rhino horn decreases, poachers choose to allocate even less effort to rhino killing and the species starts to make a slow comeback. Eventually, this increment in abundance triggers a response of the poachers, who decide to change their hunting habits (see also Appendix A). Specifically, the rhino poaching rate increases (i.e., we hit the upward sloping part of the poaching function $h(x)$) because it is now worthwhile to focus on rhinos. Even though the price of rhino horn has fallen, the stock increment warrants special consideration for this target species, and will prevent the species from making a true comeback. For the rhino population to return to historic levels of abundance, the parameter β should take values (much) lower than the 1960 value. The linear curve should rotate clockwise until eventually it crosses the curve $\chi/(1+\chi^2)$ only once. Then, the species makes a fast comeback to a stable and abundant steady state.

6. Discussion: implications for management and enforcement

In this section, we will briefly sketch some of the implications of the extended model for managers of endangered species subject to poaching. Conservation funds are limited and policy makers have to decide which species are worthy of extra consideration and which are not (Mann and Plummer, 1995). Assume that enforcement has the effect of raising the cost per 'effective' unit of effort, perhaps because poachers have to take additional precautions to avoid being caught (e.g., Bulte and van Kooten, 1999a). In a G–S setting, the effect of such enforcement on steady state abundance is readily determined by taking a first derivative of the steady state stock x^* $(=c/pq)$ with respect to cost per unit of (effective) effort, c:

$$\frac{dx^*}{dc} = (pq)^{-1}. \qquad (12)$$

The 'marginal benefit' of enforcement, or the increment in steady state stock level thus is constant and determined only by the price and catchability coefficient. If it is possible to value the stock increment in monetary units, the optimal level of enforcement is found when marginal benefits are equal to marginal costs.

The marginal benefit of enforcement for the extended model is more complex, depending on a broader set of parameters. Assume that we can model

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a trajectory spiraling towards the new steady state (which could be considerably higher than the current stock). However, this is very unlikely. It would imply that current poaching is unprofitable, which is at odds with the findings by Dublin and Wilson (1998).

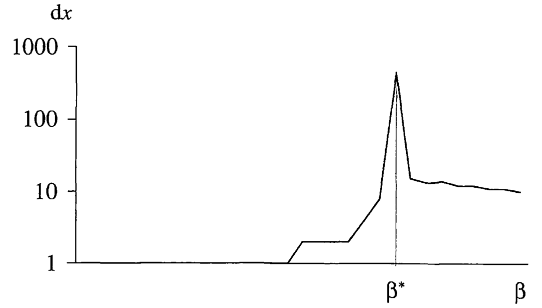

Fig. 2. Marginal benefits of conservation with type III poaching: the increment in wildlife abundance resulting from a marginal change in parameter β.

the effect of enforcement on abundance by considering changes in $dx/d\beta$. As with the G–S model, enforcement translates into higher costs, which, in turn, imply a lower value of β. In Fig. 2, we have plotted the increment in abundance (dx) resulting from decreasing the value of β (from left to right). We have numerically solved Eq. (10) for x (assuming the population is initially at a low level of abundance—such as steady state R_4 in Fig. 1), and consider the effect of changing β on wildlife abundance.[8] Enforcement consistently translates into thicker stocks, as with the G–S model, but the benefits of enforcement at the margin are far from constant (note the logarithmic scale on the vertical axis).

The change in abundance depends on the (relative) slopes of $(\alpha\gamma/\beta)(k - \alpha\chi)$ and $\chi/(1 + \chi^2)$, hence both economic and ecological parameters determine the effect of enforcement (see also van Kooten and Bulte, 2000). The sudden pike at β^* occurs when $(\alpha\gamma/\beta)(k - \alpha\chi)$ has rotated sufficiently upwards such that R_1 and R_2 coincide and are on the verge of disappearing. A marginal decrease in β causes the animal population to climb out of the poaching pit and jump to unique and high steady state.

The marginal benefits of enforcement are highly variable, rendering decision making more complex than before. Yet, recognising the underlying complexity of the system allows managers to make better choices. In particular, policy makers are well advised to focus their enforcement effort on the conservation of those species whose economic parameter β is close to the value β^* (unless the value of the species in question at the margin is negligible, in which case increments in abundance should not matter from an economic perspective). In general, policy makers should search for those species at the edge of the poaching pit—either on the verge of dropping down or close to jumping out—and concentrate their scarce funds to conservation of those species. This is where enforcement may be expected to yield the greatest returns.

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Appendix A. Deriving a convex–concave harvesting function

To facilitate the notation but without loss of generality, assume the following:

- There exists an arbitrarily large group of poachers, *N*, harvesting two species (in this sense the model perhaps more resembles unregulated common property than true open access as defined by Ciriacy-Wantrup and Bishop).
- Poachers allocate their time to specifically ‘target’ either species 1 or species 2. Incidental killing of the *other* species occurs proportional to the other species’ abundance.
- The abundance of species 1, x_1, is assumed fixed throughout.
- Poachers instantaneously respond to profit differentials between targeting species 1 or 2 by re-allocating their single unit of poaching effort to the species where the (expected) return is maximised.

Choosing the value of a unit of species 1 as the numeraire, the poacher’s returns to targeting species 1 are:

$$\pi_1 = q_1 x_1 + p_2 b_2 x_2, \quad \text{(A.1)}$$

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[8] Algebraically solving the cubic equation (10) for x is feasible but cumbersome. Details are available from the author upon request.

where q_1 is the catchability coefficient for species 1 when the poacher targets that species and b_2 is a bonus (incidental) catchability coefficient for the other species. In other words, when the poacher sets out to harvest species 1, he encounters some individuals of species 2, and can harvest those units too. Such units may be sold at a price p_2.

Conversely, if the poacher targets species 2, his profits are simply

$$\pi_2 = b_1 x_1 + p_2 q_2 x_2. \tag{A.2}$$

Obviously, the notion of 'targeting' a species only makes sense if $q_i > b_i$, where $i = 1, 2$. Given this simplified set-up, poachers will target species 1 or 2, depending on the (relative) abundance of species 2. They are indifferent between targeting species 1 or 2 when species 2's abundance is defined by

$$\hat{x}_2 = \frac{(q_1 - b_1)x_1}{(q_2 - b_2)p_2}. \tag{A.3}$$

This implies that aggregate harvesting of species 2 is simply described as follows: for $x_2 > \hat{x}_2$, harvesting equals Nq_2x_2, and for $x_2 < \hat{x}_2$, harvesting equals Nb_2x_2. When the population of species 2 increases from $\hat{x}_2 - \varepsilon$ to $\hat{x}_2 + \varepsilon$, aggregate harvesting suddenly increases by the quantity $Q = N\hat{x}_2(q_2 - b_2)$. Plotted in a graph, these results can be summarised as follows.

While most of the results in the paper can be produced by the simple harvest function depicted in Fig. 3, it is straightforward to add certain elements to the model that would enhance the similarity to the 'smoother' reduced-form harvest function implied by (8). For example, by introducing gear saturation (Clark, 1990, p. 222) or market saturation, the catchability may be smoothly reduced so that the harvest function gradually levels off (akin to the reduced-form harvest function (8), levelling off at β). Similarly, by introducing some heterogeneity among poachers, the knife-edge result that all poachers 'switch' from targeting one species to another at stock level $\hat{x}_2$ may be mitigated. This will result in a smoother transition between the two line segments in Fig. 3, as also implied by harvest function (8).

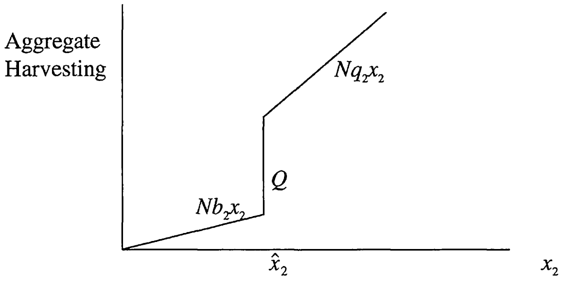

Fig. 3. A simple kinked harvesting function.

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