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A model of incentives for the illegal exploitation of black rhinos and elephants: poaching pays in Luangwa Valley, Zambia

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Summary

1. The decline of Africa's rhinos and elephants over the past decade has alarmed conservationists, yet little is known about the interaction between law enforcement and the economic incentives for illegal exploitation. This study models the relationships between financial gains, detection and penalties for poaching rhinos and elephants in Luangwa Valley, Zambia during 1979–85.

2. We explore how sentencing strategies affect the decisions of poachers in relation to changes in detection rate, penalty and economic variables. We show that a penalty which varies with the output of a poacher is, in theory, a more effective tool against poaching than a fixed penalty. However, the probability of capture is a highly significant factor in the poacher's decision to hunt.

3. The incentives to poach are modelled for an open access situation, the industry structure for a local poacher, and for a monopolist who employs organized gangs. Organized and local gangs have very different reactions to law enforcement. Local poachers will respond to local investment schemes, but the deterrence of organized gangs can only be achieved with improved law enforcement operations.

Key-words: elephant, rhino, poaching, law enforcement, Zambia.

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Introduction

The rapid decline of elephant (*Loxodonta africana* Blumenbach) and black rhino (*Diceros bicornis* L.) populations in most countries in Africa over the last few years has led to attempts to control or ban the international trade in ivory and rhino horn (Martin 1983; Martin 1986; ITRG 1989). Evaluation of the success of the recent (1989) ban on sales of ivory is awaited with interest, but the high demand for rhino horn seems so far to have confounded efforts to halt the trade via a longer-standing (1977) trade ban (Western 1989). Given that current policies focus on banning trade, there is increasing recognition of the importance of investing adequately in Protected Areas (PAs) in order to control supply of ivory and rhino horn and to prevent the decline of both species (Leader-Williams & Albon 1988; Parker & Graham 1989). A crucial issue that needs to be addressed, so far not studied, is how law enforcement relates to a poacher's incentives to hunt, and thus how best to invest the limited funds available to developing countries to deter illegal exploitation of their wildlife resources.

Lessons learned from studies on other illegal activities, such as theft and burglary in the USA, can provide useful insights into the regulation of trophy hunting. These studies suggest that prevention of crime should occur if there is: (i) an increase in the perceived probability or severity of punishment; (ii) a decrease in profit from the crime; or (iii) an increase in the opportunity cost of the crime through improved wages elsewhere (Cook 1977). The third factor obviously depends on an improvement in the national economic climate, and the second on international trophy prices and exchange rates. The second factor also depends on harvesting costs, which are affected by law enforcement, as is the first factor. The probability of being caught and convicted (strictly two separate factors, but usually combined) is a strong deterrent to crime. Opinion is divided as to whether the severity of a sentence has a deterrent effect at all, but studies do agree that the penalty rate is less of a deterrent than detection rate (Ehrlich 1973; Avio & Clark 1978). This suggests that it is a better strategy to concentrate on detection than on penalties.

Very few studies of law enforcement in relation to illegal exploitation of wildlife resources have been carried out (e.g. Bell & McShane-Caluzi 1986). Only one study in Africa documents both sightings and capture of poachers and the sentences subsequently passed on gang members, and this covers the Luangwa Valley in Zambia over the period 1979–85 (Leader-Williams, Albon & Berry 1990). That analysis concentrated on whether Zambia upheld its own wildlife laws in the sentences delivered to offenders and on the manpower levels necessary to deter illegal exploitation. In this study, we examine the incentives for illegal exploitation by developing a model for the optimization of a poacher's harvest under imperfect law enforcement, which is used to explore the effects of different sentencing strategies.

Materials and methods

STUDY AREA

A description of the study area may be found in Leader-Williams *et al.* (1990). The Luangwa Valley contains a complex of four national parks (NPs) and seven game management areas (GMAs) as well as villages and agricultural land, and so is an excellent example of an area of high human and wildlife interaction (Abel & Blaikie 1986). The area has long been subject to traditional hunting (Marks 1976), but the distinction between traditional and illegal hunting became blurred for local people when PAs were first established and game laws passed. From the perspective of wildlife managers, however, a serious increase in illegal rhino and elephant hunting was evident during the late 1970s and 1980s. Thus, as the area has been well studied by biologists and anthropologists the Luangwa Valley is ideal for a case study of the law-enforcement/poaching interaction.

DATA

Law enforcement has several components: the probability of detection, of capture once detected, and the probability and severity of sentencing once captured. The poacher's incentives will not necessarily change in the same way for each component, and the costs of increasing enforcement will also vary between components. External economic factors, such as the economic health of the country, and the value of trophies and returns to the hunter and his accomplices, must also be taken into account if effective protection of wildlife resources is to occur. The data on law enforcement comprise records of anti-poaching units (APUs) and of sentences handed out by the courts (Leader-Williams *et al.* 1990), and provide most of the data needed in the models. Additional data are derived from a small sample of confessions made by apprehended poachers to heads of APUs and from intelligence information collected during raids on poachers' villages, and from other published sources. Some parameters notably the probability of detection, had to be estimated very approximately. All parameters are estimated as if for 1985, and Annexes 1–4 give the detail of their calculation.

Sentencing strategies in Luangwa Valley changed during the 1980s. Fewer prison sentences were delivered for non-elephant and rhino offences, while more were delivered for elephant and rhino offences (Leader-Williams *et al.* 1990). The penalty level for elephant and rhino offences, including both fines and prison sentences, did not vary significantly with the number of trophies found with the gang, nor with the year, although there is large variation between sentences, due no doubt to the idiosyncracies of particular magistrates in individual cases. Fines were often given with a prison sentence in default in case the fine was not paid.

Although in-default sentences show the magistrates' perception of the conversion rate between prison and fines, rather than the prisoner's, these were used to convert prison sentences to fines so as to allow all penalties to be expressed in monetary terms (Fig. 1). This method of conversion is quite different to the standard method, which is based on loss of earnings when in prison (Becker 1968; Sesnowitz 1972). However, using loss of earnings fails to take major components of the penalty of being in prison into account, such as the difficulty of getting a job with a criminal record, the loss of freedom, the inability to support the family and so on. It also implies that prison is a less severe punishment for the poor than for the rich, who lose more earnings. Although there is no satisfactory

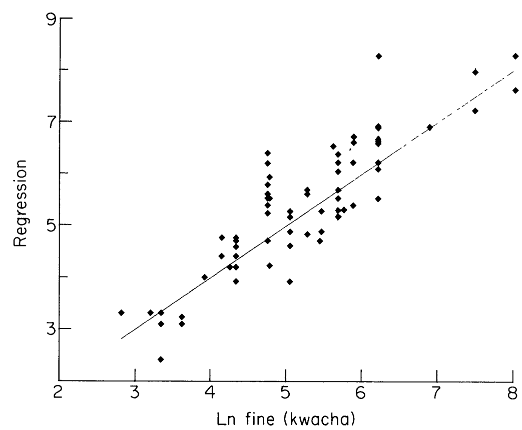

Fig. 1. The regression of log fines given by magistrates to poachers against the prison sentences given in case of default. There is a good log-linear relationship between the length of the sentence and the size of the fine ($r^2 = 0{\cdot}72$). This relationship was used to convert all prison sentences into monetary terms. Fines are expressed as real values at 1985 prices.

way to express these penalties in monetary terms, a person's perception of the penalty must be better than a wage-based conversion, even if that person is the judge. Certainly the prison sentence will not be less severe than the fine, or there would be many defaulters, with the consequent expense to the state of imprisonment.

The elephant population of Luangwa Valley was estimated to number 25 323 in 1985 (Kaweche & Lewis in Douglas-Hamilton 1987). Total rhino numbers have not been assessed since 1979, when an aerial survey suggested an approximate total of 2500–3500 rhinos (Douglas-Hamilton *et al.* 1979). Due to the difficulties involved in counting rhinos from the air (Goddard 1967a), changes in abundance of rhinos were estimated from sightings by foot patrols during 1979–85. A total for rhinos was approximated by extrapolating from the ratio between sightings of elephants and the total populations of elephants to rhino sightings (Annex 1).

Incentives to poach under open access

Mazany, Charles & Cross (1989) have extended a model by Sutinen & Andersen (1985) to explore the effects of various penalties on the incentives to fish above a legal limit, when enforcement is imperfect. This model can easily be adapted to any situation in which hunting involves some risk of penalty, and we have adapted it to the poaching of wildlife.

Two functions for poacher output are used: (i) a simple linear relationship between input and output, and (ii) a non-linear function developed for red deer hunting (Beddington 1973). The latter function was empirically determined, and makes production proportional to the square root of the area searched. This is equivalent to making production proportional to the radius of a circular area, implying that instead of sweeping it, hunters take paths inwards from the perimeter. The use of two functions allows us to see how sensitive the model is to each production assumption, and which results hold for both.

THE MODEL

Hunters aiming to maximize short-term profits will face the classic optimization problem:

$$\max_x \{pq - wx\},$$

where p is the price per unit output, q is the quantity of output, x is the quantity of input, and w the price per unit input. This optimization results in the condition that profit is maximized when marginal revenue equals marginal cost:

$$pq_x = w.$$

To include a risk associated with the harvest due to law enforcement, Mazany *et al.* (1989) looked at a situation involving several input bundles, a threshold below which fishing is legal and regulation occurring either on input or on output. The situation for an elephant and rhino poacher is more clearcut, and we therefore assume the following: (i) all hunting of rhinos and elephants is illegal; (ii) there is only one input bundle; and (iii) regulation is in terms of output. These assumptions will be discussed in more detail for the specific case of the Luangwa Valley.

In the above scenario, the poacher's short-term profit maximization problem becomes:

$$\max_x \{pq - wx - \Theta F\},$$

where Θ is the probability of detection, and F is the level of the fine, so that the expected value of the fine is ΘF. The output q is assumed to be a function of the level of input, and of the biomass available for exploitation, Θ is a function of enforcement and the output of the poaching gang, and F is also a function of the output of the gang. The condition for profit maximization becomes:

$$pq_x = w + q_x\,[\Theta_q F + F_q \Theta],$$

the marginal revenue equals the input cost per unit plus the marginal change in the expected fine with a change in output. The optimum output can then be calculated as:

$$q^* = q(x^*, B),$$

where B is the biomass of the hunted population.

PRODUCTION FUNCTION

The linear production function used is:

$$q = axB,$$

where a is the 'catchability coefficient' of fishery management models. The probability of being caught is proportional to input:

$\Theta = bx$, where $0 < b < 1$.

The fine, which also includes the confiscation of one trophy, is proportional to output:

$$F = rq + p.$$

This function can be put into the maximization equation:

$$\max_x [p(axB) - wx - bx(raxB + p)]$$

giving the condition:

$$paB - w - 2braxB - bp = 0$$

which rearranges to:

$$x^* = \frac{paB - w - bp}{2braB}$$

Since $q^* = ax^*B$, then the optimum output will be:

$$q^* = \frac{paB - w - bp}{2br}$$

The non-linear function is:

$$q = aBx^{\frac{1}{2}}$$

where a is a constant based on the area hunted. This gives the optimum output at:

$$q^* = \frac{(w + bp) \pm \sqrt{(w + bp)^2 + 3brpa^2b^2}}{3br}$$

A CONSTANT FINE LEVEL

Examination of the conviction records of poachers in the Luangwa Valley during 1979–85 suggests that the penalty imposed does not depend on the number of trophies, so long as at least one trophy is captured ($\chi^2 = 2{\cdot}46$, df $= 3$, $p > 0{\cdot}05$). There is still a penalty if there are no trophies, but it is smaller ($\chi^2 = 11{\cdot}74$, df $= 2$, $P < 0{\cdot}01$). Therefore, a flat-rate fine for any poacher who is caught, regardless of output, provides the more appropriate model. The equation to be optimized, using a linear production function, then becomes:

$$\max_x \, [p(axB) - wx - bx(r + p)]$$

To maximize, set:

$$f_x = paB - w - b(r + p) = 0$$

Thus, the optimal hunting mortality can only be determined implicitly by varying the population size until the left-hand side of the expression reaches zero.

The non-linear production function is more informative under the assumption of a constant fine, giving an optimum at:

$$q^* = \frac{pa^2B^2}{2[w + b(r + p)]}$$

ASSUMPTIONS MADE IN THE MODEL

Most of the explicit assumptions necessary to model illegal hunting of elephant and rhino hinge on assuming that the penalty is output-determined, while the probability of detection is input-determined. In theory, all hunting is illegal and even entering an NP without a permit risks a penalty. In practice, however, detection of poaching is likely to rise with the amount of poaching activity, and fines to rise with the number of valuable trophies, as is modelled. The model also includes the cost of confiscation of one trophy if the gang is detected. This is the average number of trophies captured from a gang, and is likely to be less than the actual number killed since members of the gang usually escape with some trophies.

The model is evaluated for two types of agent: organized and local gangs (see Leader-Williams *et al.* 1990). Confessions by poachers have revealed that the decision-maker for an organized gang is a dealer in contraband, who hires a gang for a hunting expedition and requires little capital to trade. The main expense will be guns and ammunition, which can be included in the fixed costs. Fixed costs can be spread over several operations, since the dealer tends to be involved in many illicit goods, and storage, special transport and networks for bypassing officialdom are needed for all contraband. Thus, the incentive to trade in ivory and horn can be examined in terms of marginal costs.

The hunter has rather different roles in the two scenarios. The decision-maker in the local gang scenario is the hunter himself, who uses his own labour and sells his trophies to a dealer independently. In the organized gang, the hunter is a paid employee, and the dealer is the decision-maker. Thus, although the organized gang contains both hunters and carriers, the gang is modelled as an entity since it is the dealer who decides whether to employ the whole gang. Within a gang, the carriers' incentives will be very different to the hunters', since not only are carriers unskilled and paid less, but they are more likely to be caught, and to be given harsher sentences. Hence, we shall refer to the decision-maker when discussing the optimal actions of 'the hunter', not the employee.

One problem with the analysis is that confessions suggest that the gangs are paid by output (per kilogram) rather than by day. Data on the input decisions of a poaching gang are extremely difficult to obtain, so input costs are assumed to be independent of output prices. Input costs are calculated as the opportunity cost of the wages lost while poaching because at the margin poaching must yield a competitive real wage. However, the analysis does ignore the fact that a risk premium is likely to be attached to poaching, increasing the wage necessary to attract people into poaching.

PARAMETER ESTIMATION

B and q, the biomass available and the quantity harvested, are estimated in terms of numbers of animals rather than weight of tusks or horns. Thus, there is no need to take the age and sex structure of the population into account, nor the selectivity of hunters for larger tusks, since the calculations are for a single point in time, and the population can be assumed constant. Rhinos are less subject than elephants to the problem of selectivity, as total horn weights of adult males and females are similar.

All population sizes are calculated for two areas of the Luangwa Valley, the GMA and the South Luangwa National Park (SLNP), which have very different population densities, and are mainly hunted by local and organized gangs respectively (Annex 1). The elephant population is assumed to be divided into herds of eight individuals (from data presented in Leader-Williams *et al.* 1990), but rhinos are predominately solitary except for mother–calf pairs (Goddard 1967b).

The assumptions about types of gang represent the bimodality found in gang size and composition (Leader-Williams *et al.* 1990). The organized gang generally consists of two hunters and six carriers, with an automatic rifle and another weapon. The two weapons together are assumed to be able to kill every animal in each herd encountered. The carriers are assumed able to carry the trophies from two kills each, which means that at 1985 encounter rates, they are not a limiting factor. The gang is assumed to hunt for 7 days at a time, the average expedition time for the APUs, in the SLNP. In contrast, the local gang is made up of two poachers, with one muzzle-loading gun, which has a 50% chance of killing one animal per herd encounter, and goes out for 1 day at a time in the GMA. These characteristics fit with the data from APUs and with description of the hunting habits of the Valley Bisa of the Luangwa Valley (Leader-Williams *et al.* 1990; Marks 1973).

All monetary parameters have been calculated for 1985 in Zambian Kwacha, because confessions show that poachers are paid in local currency. The costs of hunting are calculated from the opportunity costs of wages lost in other sectors. Costs are calculated per expedition since the expedition is the input unit for the decision-maker. The carriers and the local hunters are paid at the agricultural wage, and the organized hunters at the all-sectors wage, because confessions show that they are paid substantially more than carriers. The unit of output is the kill, and so the price is calculated per kill using data on price per trophy and per kilogram, and data on trophy weight from various sources (Annex 2).

The production functions used have different expressions for a, the catchability coefficient. The linear function probably characterizes the situation better than the non-linear function, becauses factors affecting catchability are taken into account explicitly. These include the number of days per expedition and area surveyed per day, herd size, effectiveness of the gun used and of encountering prey, which in turn varies with species and with gang size. All these parameters have to be estimated from patrols because there are no data on hunters' efficiency, apart from on traditional hunting by locals (Marks 1973). It seems reasonable to assume that scouts and poachers have the same ability to see wildlife (Annex 1).

The non-linear function implies that the poachers have diminishing marginal returns to the number of expeditions, and in this model the two functions intersect at 15 expeditions. This means that on the first expedition, the organized elephant poacher can take as many tusks as the gang can carry, and the number killed per expedition declines thereafter.

Enforcement is assumed to have only two components: (i) a composite measure of the probability of detection, and (ii) the penalty imposed. The composite of detection is taken as the probability of being detected, captured and incurring a penalty, since escaping carries no penalty, except that future arrests may occasionally depend on previous contacts with patrols. The actual probability of detection is the hardest parameter to measure because, by definition, it cannot be measured from patrol data, but the probability of being captured and incurring a penalty have been estimated accurately. Thus, an approximate figure of the order of 0·05 has been estimated for the composite measure of detection by two independent methods (Annex 3). This is the probability of detection per unit of input, regardless of the size of the gang. Although the probability of detection can only be estimated roughly, it is only necessary to give an order of magnitude, because the other parameters are estimated fairly accurately and sensitivity analyses show the effects of varying the value on the model results.

The average penalty, including conversions from prison sentences (Fig. 1), given to a poacher who appears in court is K500. This penalty is used as the penalty per kill in the case where the penalty depends on the number of trophies because, although the number of trophies found with a gang is very variable, gangs are found with one trophy on average. The number of individuals caught per gang is estimated from the data to be both members of the local gang and four of the eight organized gang members, giving a penalty per gang of K1000 for local gangs and K2000 for organized gangs. Thus, the expectation of the penalty per expedition in 1985 is in the region of K50 for local gangs and K100 for organized gangs, which can effectively be added to the costs of poaching. This alone gives an idea of the relative importance of the expectation of capture, since the labour cost of poaching is estimated as K14 per expedition for locals and K500 for organized gangs. To this penalty must be added the penalty of the confiscation of trophies from one kill, which is a far larger cost than the penalty itself.

A final refinement of the model considers incentives to hunt both elephant and rhino during the same expedition, as happens in reality (Leader-Williams *et al.* 1990). In this case, the enforcement parameters are the same, as are the costs per expedition. The results are strongly influenced by the values for elephants, which are encountered and killed more frequently than rhinos.

SIMULATION RESULTS

The simulations were run for all combinations of production function, gang type and species, for two scenarios: (i) price and cost were changed as the enforcement level was held constant at the estimated 1985 level, and (ii) enforcement was changed as price and cost were held constant. The parameters were varied around 1985 values, and thus the results not only show the sensitivity of the

Table 1. Optimal hunting mortalities at 1985 parameter values. Hunting mortality is expressed as the proportion of the total population it would be optimal to kill, so that a hunting mortality of 1 means the whole population is killed, and 0 means no hunting

Production function		Linear		Non-linear	
Penalty Gang type	Species	Constant	Variable	Constant	Variable
Organized					
	Elephant	0·919	0·003	0·024	0·003
	Rhino	0	0	0·002	0·009
	Both	0·902	0·003	0	0
Local					
	Elephant	0	0	0	0
	Rhino	0	0	0	1
	Both	0	0	0·096	0·008

gangs to different parameters, but also the sensitivity of the model results to assumptions about parameter values.

The incentive to hunt at 1985 parameter values depends on the type of penalty and the production function used (Table 1). With a linear production function, it is not worthwhile for locals to hunt, because the expected revenues are less than the costs of hunting even without a penalty. It is not worthwhile for organized gangs to hunt rhinos alone, but it is worth hunting elephants. If rhinos are hunted along with elephants, the combined hunting mortality is slightly lower than for elephants alone, but it is still worth hunting both species. The type of penalty determines the hunting level: if the penalty varies with output, hunting mortality is low, but if it is constant regardless of output, hunting mortality is very high.

The non-linear production function makes it more worthwhile to hunt at low levels, when output per expedition is higher. Under this assumption, it is worthwhile for both gang types to hunt, but at low levels. The high value for locals hunting rhinos is because rhino numbers are extremely low in the GMA. Although this function is less realistic than the linear function, it shows that the results are sensitive to the function used, and that declining marginal returns to input lead to a lower optimal hunting mortality than constant marginal returns to input.

The sensitivity of hunting mortality to parameter changes in the vicinity of the 1985 values is shown for the assumptions most representative of the actual system; a linear production function with a constant fine level. Under these assumptions, it is not optimal for the local gangs to hunt elephants and rhinos. However, it is highly profitable for organized gangs to hunt, and it is only when prices are about halved and costs doubled that the hunting mortality drops significantly (Fig. 2a). Enforcement has even less effect on the hunting mortality around current levels (Fig. 2b). The results for elephants only are generally almost indistinguishable from those for hunting both species.

Thus, the 1985 parameter values are such that it is optimal for organized hunters to hunt hard in an

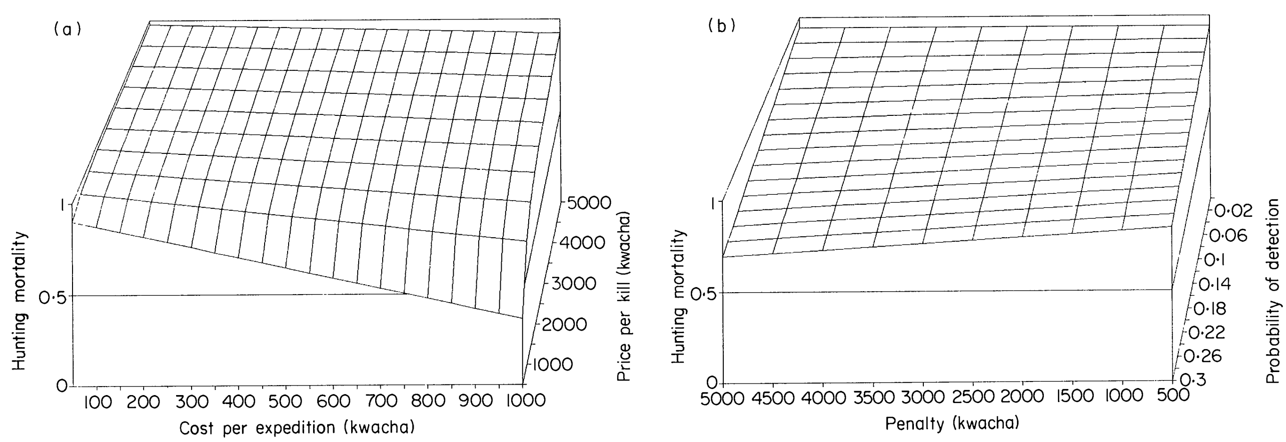

Fig. 2. Sensitivity of the optimal hunting mortality in the short run to parameter changes, when a constant penalty and the linear production function are assumed, and organized gangs are hunting elephants. Hunting mortality is shown as a proportion of the population size. The hunter's sensitivity is shown to (a) changes in the cost of an expedition and the price gained from a kill, and (b) changes in the probability of capture and penalty imposed.

open access system, and for local hunters not to hunt. The profits are such that large changes in costs and prices are needed to reduce hunting mortality. Unrealistically large increases in both the penalty imposed and the probability of detection are needed to reduce hunting mortality at the 1985 costs and prices. However, a penalty that varies with output makes a huge difference to the results, leading to much reduced hunting mortality. To achieve this, the penalty must take into account the total number of kills made by the gang and not just the trophies confiscated at the time of arrest.

Incentives for the resource controller

The model so far considers only strategies for short-term profit optimization by individuals with open access to the resource. This is likely to be the correct approach for local hunters, who hunt predominately for meat and make no extra investment to hunt elephants and rhinos. A dealer employing organized gangs is in a rather different position, and tends to deal in several illegal goods, so ivory and horn hauls are often discovered with other contraband. He can move in and out of a good according to the profits to be made from it. There is evidence from the Luangwa Valley that one major dealer controlled the supply of trophies from organized gangs during the early 1980s, and so had an effective monopoly control over the resource.

If a dealer is able to control the rate of hunting of elephants and rhinos in an area, he could control present use of the resource in favour of future use, instead of mining it as in the shortrun model. The dealer's incentives should thus be modelled over time, and when maximizing over time his discount rate becomes crucially important. The maximization is from the viewpoint of a single point in time, from which the optimal hunting strategy can be planned, and is taken as 1985.

The standard procedure for optimizing hunting effort over time has been discussed widely (e.g. Clarke 1990; Burghes & Graham 1986). It gives an implicit solution for optimal population size:

$$\delta = f'(B) + \frac{wf(B)}{B(pB - w)}$$

where the notation is the same as before with the addition of δ for the discount rate of the poacher, and $f(B)$ for the population growth rate. To solve the equation, the formula for the population growth rate must be specified. The optimal strategy is then either to hunt at maximum capacity or to leave the population to grow until the optimum population size is reached, when hunting is kept at $f(B^*)/B^*$, maintaining a constant population size.

The expression for present value (the objective functional) determines the simplicity of solution of the optimal control system. The only expression that lends itself readily to solution among those used in the shortrun analysis is a constant penalty level and linear production function, which is the most realistic of the scenarios anyway.

The expression for the present value of the economic rent is :

$$PV = \int_0^\infty \{e^{-\delta t}[paxB - wx - bx(r+p)]\}\delta t,$$

with the state equation:

$$\frac{dB}{dt} = f(B) - axB.$$

The Hamiltonian is:

$$H = e^{-\delta t}(paxB - wx - bx(r+p)) + \lambda(f - axB).$$

Using the standard procedure, the solution for optimal population size can be obtained:

$$\delta = f' + \frac{f[w + b(r+p)].}{B[paB - f'(w + b(r+p))]}$$

This compares directly with the solution when there is no enforcement, simply containing a more complex expression for costs.

ASSUMPTIONS AND PARAMETER VALUES

The parameters used in the shortrun model for 1985 are also used in the optimal control model (Annexes 1–3). Additional parameters to be estimated are those for the biological growth function (Annex 4). Because there are no detailed data on the population structure of elephants and rhinos, nor on the selectivity of the poachers in Luangwa Valley, we avoid using a complex model for the population growth function. Thus, the simple logistic model of population change was used, modified to take account of the non-linear response to density shown by large mammals (Fowler 1981):

$$f(B) = iB\left[1 - \left(\frac{B}{K}\right)^z\right],$$

where i is the intrinsic rate of increase of the population and z describes the shape of the density-dependent response. A value of 7 was chosen for z, for which value the maximum recruitment occurs at around 75% of carrying capacity. This is consistent with the shape of the response for many large mammals, and with the figure for elephants (Fowler 1984). The rhino has rather different biology to elephants, but calculations using Fowler's (1984) regression of i on the point of maximum response also produced a similar answer. If anything, both elephants and rhinos may respond most at population levels higher than 75% of K (Annex 4). Thus, the equation for the optimum population size becomes:

$$\delta = i\left[1 - (z+1)\left(\frac{B}{K}\right)^z\right] + \frac{i\left[1 - \left(\frac{B}{K}\right)^z\right][w + b(r+p)]}{paB - [w + b(r+p)]}$$

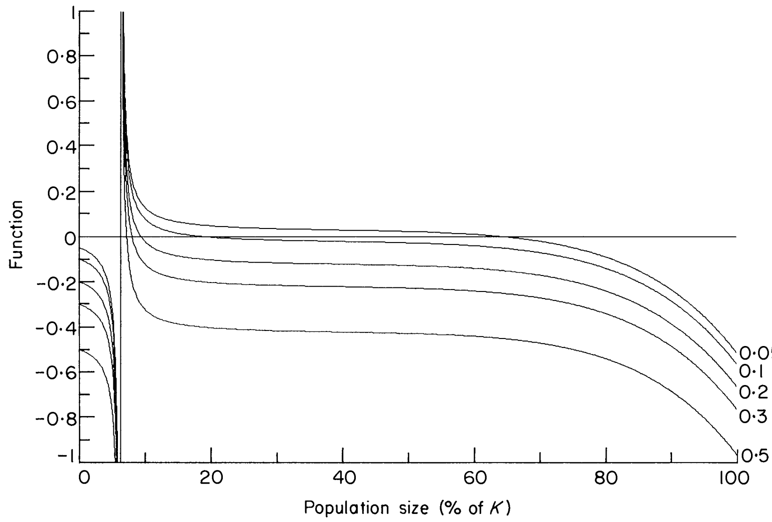

Fig. 3. Sensitivity of the optimal population size for the organized gangs to discount rate. The optimal population size occurs where the expression:

$$i\left[1-(z+1)\left(\frac{B}{K}\right)^{z}\right]+\frac{i\left[1-\left(\frac{B}{K}\right)^{z}\right][w+b(r+p)]}{paB-(w+b(r+p)]}-\delta$$

equals zero. For high discount rates, the optimal population size is near the asymptote, and not sensitive to discount rate. When the discount rate is low, the function crosses the x-axis well before the asymptote, so that the optimal population size is high and very sensitive to discount rate. The exact relationship depends on the parameter values used (the example is for organized elephant hunting).

There are two simplifying assumptions used in the model that particularly need discussion. Elephants may possibly show a negative density-dependent response at very low population sizes (Poole 1989). The effects of very low population density on rhino reproduction has not been investigated, although at fairly low population densities, the calf–adult ratio remains unchanged as populations decline (Leader-Williams 1988; Kiwia 1989). There may not be a negative effect at lower levels either, since the black rhino is a solitary species. If the model included such an effect, the very low optimal population sizes might increase slightly, due to the much lower yields at these levels.

The other assumption made is that unit costs and prices remain constant with quantity produced, rather than following supply and demand schedules. This assumption of exogenous costs and prices is due to the scantiness and unreliability of the data on elasticities of supply and demand, particularly for rhino horn, which has been an illicit good for the last 15 years. However, there is a case for the assumption for ivory, since the Luangwa Valley was a small supplier in the world market during 1979–85 (ITRG 1989). For rhino horn, the Luangwa Valley and Selous were the two largest black rhino populations in the early 1980s. Both were depleted very quickly (Western & Vigne 1985), and so Luangwa Valley probably supplied a significant proportion of the world's horn during this period. In terms of costs, in real life, a dealer may pay his employees according to his current needs, and thus according to the quantity of trophies being supplied by the gangs. But in this model, the costs are all exogenous, being related solely to the Zambian labour market. On balance, the simplifying assumption of exogenous variables is more appropriate than a very unreliable supply and demand schedule.

SIMULATION RESULTS

Simulations were run to determine the optimum elephant or rhino population size for the organized gang, and therefore the hunting pattern to be expected at the 1985 population size. The model was run with a range of discount rates, and was largely insensitive to discount rate above a value of 0·2 (Fig. 3). Therefore in subsequent simulations, a discount rate of 0·3 was used in order to represent the discount rate of dealer working in high-risk contraband, able to switch between goods with ease. He has little incentive to husband the resource for future use, despite having sole control over it.

The optimal elephant population size at 1985 parameter values is very low (Table 2). This population size would be reached by hunting at the maximum possible rate. The simulations suggest that rhinos in SLNP are at a much lower population size than optimal, so that an organized gang would not hunt rhinos alone, although they would probably hunt them with elephants.

If the hunter wished to take the maximum sustain-

Table 2. Optimal population sizes for organized gangs as a proportion of carrying capacity, at the longrun optimum

	Population sizes	
Species	Optimal	Actual in 1985
Elephant	0·079	0·77
Rhino	0·419	0·16

able yield over time, in terms of the number of animals, the optimum hunting mortality would keep the population at the point of maximum recruitment, which is 75% of *K* due to the non-linear density-dependent response. This is the equivalent of a discount rate of zero. The elephant will provide its maximum biomass yield at a higher population size due to the exponential growth of tusks with age in males (Basson, Beddington & May 1991).

The sensitivity of these results to a range of parameters is very similar to that of the shortrun optimization. Organized elephant hunters are only sensitive to changes in price and cost below a price of around K1000 (compared to the 1985 price of K2500) but are otherwise fairly insensitive to price and cost changes (Fig. 4a). Elephant hunting is hardly affected by enforcement at all (Fig. 4b). The results for rhinos are rather different. The optimal population size is higher, and increases rapidly with increases in cost or decreases in price (Fig. 4c). Enforcement also has a fairly large effect, although the result is much more sensitive to probability of detection than penalty. This is because the penalty is much smaller than the loss incurred by the confiscation of trophies (Fig. 4d).

Discussion

The effects of imperfect enforcement of incentives for non-compliance with regulations have been analysed in recent fisheries management literature (Sutinen & Anderson 1985; Mazany *et al.* 1990). Work has concentrated on the different effects of input and output controls on fishing above a legal quota. This paper breaks new ground by applying similar techniques to a terrestrial wildlife management problem, where data collection is more difficult. On the one hand, the conditions are simpler in that all elephant and rhino exploitation is illegal, and the obvious control is on output rather than input. On the other hand, the range of possible types of penalty and the difficulty of monetary conversion between them, as well as the other influences on the penalties imposed by courts, which are separate bodies to the wildlife managers, make

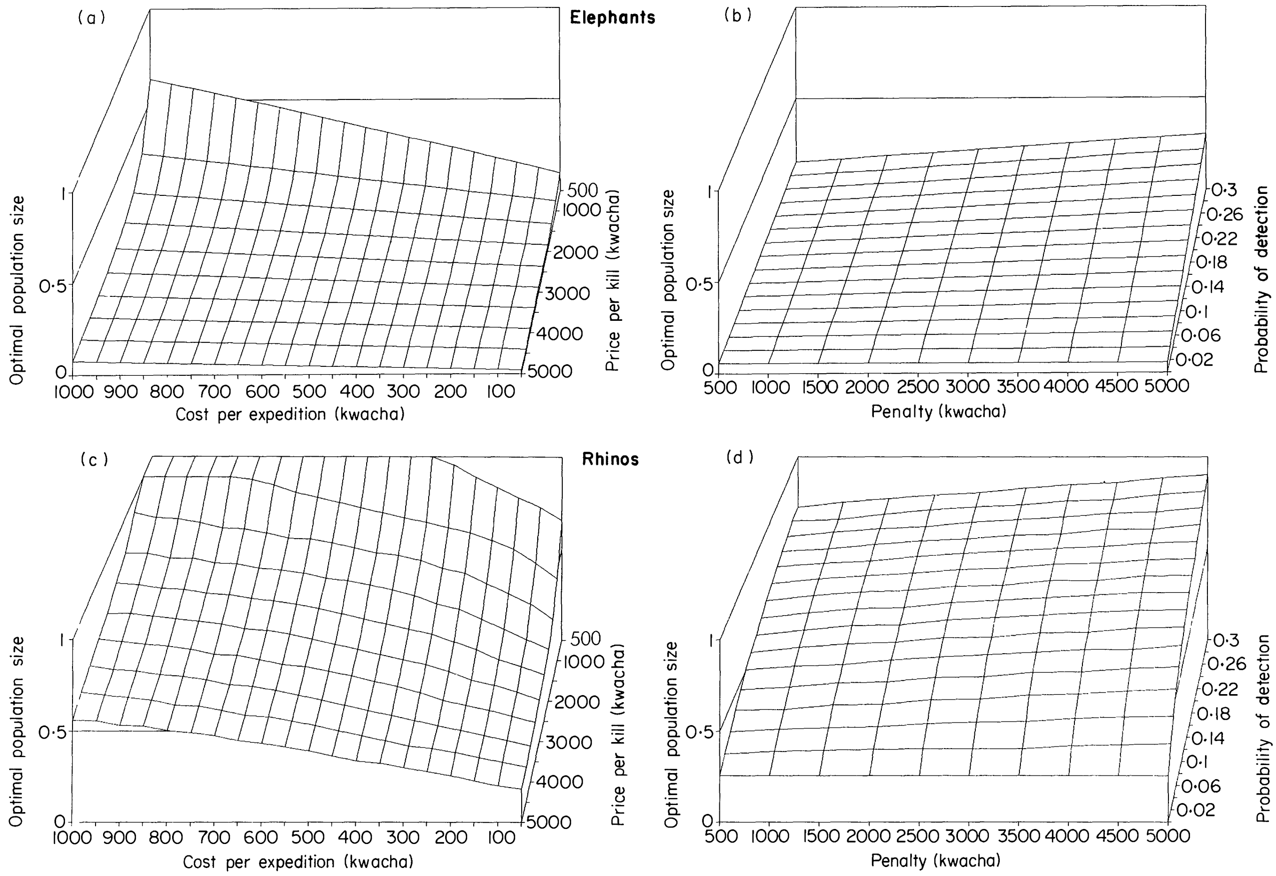

Fig. 4. Optimal prey population size for organized gangs over time as a proportion of carrying capacity showing sensitivity to changes in (a) the cost of an expedition and the price gained from a kill, and (b) the probability of capture and penalty imposed for elephant hunting; (c) and (d) show the same thing for rhinos.

the problem less straightforward. Despite these difficulties, the technique can be applied to this system, and the results are of use to wildlife managers and policy makers.

The depletion of rhinos and elephants in Luangwa Valley during 1979–85 has already been documented (Leader-Williams *et al.* 1990). The present study models the incentive structures for illegal exploitation both by local poachers and organized gangs. The open access model suggests that, although it was not profitable for either type of gang to hunt rhinos alone at 1985 parameter values, it was profitable to hunt both elephants and rhinos together. The monopolistic model shows similar results, in that it was not profitable to hunt rhinos at 1985 parameter values, but very profitable to hunt elephants.

The effects of enforcement are similar whichever industry structure is assumed. The organized hunter is only deterred at very high levels of enforcement. The open access model shows that a variable penalty with output is a much more effective deterrent to poaching than a fixed rate penalty. If a penalty is unrelated to the quantity of output of a poacher, it is a blunt tool for the enforcement of a sustainable hunting level, because it either discourages hunting or it does not. If a wildlife manager aims to reduce hunting to a sustainable level, then an output (or input)-related penalty is a much sharper instrument. It is also much more practical for the management authorities to keep hunting at a sustainable level than to attempt to stop it altogether. However, implementing a variable penalty has other political problems, such as the difficulty of effective legislation.

Changes in costs of an expedition depend under our assumptions on changes in the Zambian labour market. Changes in price paid to poachers for trophies could be influenced by changes in exchange rates. However, only large changes in these economic variables would have a strong effect on the optimal hunting mortality because it is so profitable to hunt elephants, and this has obvious policy implications for the poor countries of Africa still with large populations of elephants.

Although the paper has concentrated on the effects of regulation on incentives to hunt, regulation is expensive and there are other ways to reduce incentives. These include demand reduction in consumer countries and increasing the opportunity costs of hunting by improving wages elsewhere. The wildlife manager cannot influence demand or the economic situation in his country, but could increase the opportunity costs of hunting by some form of local investment. Projects that return some of the proceeds of safari hunting and tourism to local people and secure jobs locally have been very successful. The CAMPFIRE project in Zimbabwe is an excellent example (Martin 1986), and a similar project in the GMAs of Luangwa Valley has caused a reported drop in illegal activity, mostly because local people have been recruited to supplement law-enforcement efforts, so local poachers are no longer helped or tolerated (Lewis, Kaweche & Mwenya 1990). However, these projects do not affect the opportunity costs for the more serious problem of organized gangs, because they tend not to live locally (Leader-Williams *et al.* 1990; Tatham 1988).

The analysis has shown that levels of enforcement around the 1985 level do not discourage organized elephant hunting. It is only worthwhile to invest money in enforcement if the economic situation is such that it ensures the enforcement component of a poacher's costs outweighs product costs and prices. A wildlife manager can only encourage local investment schemes, and cannot change a country's economic situation in order to influence the activities of organized gangs. Therefore, either demand in importing countries has to be reduced, or the nature of the penalty in range states must change. In terms of regulation, the probability of detection is a more effective tool than the penalty imposed, and should be enhanced by appropriate increases in the manpower levels and efficiency of law enforcement operations (Leader-Williams & Albon 1988; Leader-Williams *et al.* 1990).

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Annex 1

POPULATION SIZES AND CATCHABILITY

For each area expected number of elephants encountered in a week is calculated as (individuals $km^{-2} \times km^2$ surveyed). The km^2 surveyed is taken as 3×7 days $= 21$, based on data from from Kasungu NP, Malawi (Bell & McShane-Caluzi 1986). From the ratio between the number seen and the number expected to be seen, an idea of elephant visibility can be obtained. This is applied to rhinos to get an approximate expression for population size, accepting the assumption that both species had similar visibilities. We also assume that data from patrols can be used for sightings by poachers. The rhino numbers are calculated as 1 in the GMA and 575 in the SLNP.

There is a similar relationship between the number of men in the patrol and the number of individuals of each species seen for both species (Leader-Williams, Albon & Berry 1990) and this can be used to alter the visibility coefficients (the proportion

Annex Table 1. 1. Data on population sizes

Area	Numbers seen* Rhinos	Elephants	Size of area (km²)†	Elephant population†
GMA	0·001	3·83	4840	2400
SLNP				13841
Nsefu	0·00	17·37	212	
South	0·13	5·99	4630	
Core	1·49	8·71	400	
North	0·32	6·69	3800	
Total			21492	25323

* From Leader-Williams, Albon & Berry (1990), standardized to 7 a-day patrol of four men in January.
† From Douglas-Hamilton (1987).

of the animals present in an area that will be seen by a group).

Annex 2

ECONOMIC PARAMETERS

Costs

Costs of expeditions do not vary with species hunted. Data on Zambian wage rates are available only up to 1980 (Zambia Central Statistical Office 1985), so it is assumed that wages kept pace with inflation to 1985 and the relationship between different sectors did not change.

Wages day^{-1} = 1980 wages day^{-1} × 2·53 (inflationary index, IMF 1988):
agricultural wages day^{-1} = K6·86;
all sector wages day^{-1} = K15·36.
Local costs per expedition = K6·86 × 2 men × 1 day = K13·7.
Organized costs per expedition = (K6·86 × 6 carriers) + (K15·36 × 2 hunters) × 7 days = K503·2.

Annex Table 1. 2. Proportion of the number of individuals seen by two men that a larger group will see

Number of men	Elephant	Rhino
2	1	1
4	0·73	0·68
8	0·39	0·36

Days per expedition assumed:
local = 1 day (Marks 1973);
organized = 7 days (average for scouts).
Gun effectiveness assumed:
muzzle-loader = 0·5 deaths per herd encountered;
automatic = whole herd killed (i.e. one rhino, eight elephants).
Formula for catchability coefficient:

$$a = \frac{\text{visibility} \times \text{days/expedition} \times \text{km}^2/\text{day} \times \text{gun effect}}{\text{herd size} \times \text{area}}$$

Prices

Price of ivory. Japanese price, 1985 = \$85 kg^{-1}, converts to K485 kg^{-1} (ITRG 1989; IMF 1988).
Zairean dealers sold ivory abroad at \$60–65 kg^{-1} in 1988 (ITRG 1989), so the above seems rather high. A good assumption is \$50 kg^{-1}, which converts to K285 kg^{-1}.
K30 kg^{-1} to local hunters (from confessions).
4·8 kg × 1·88 tusks per kill (Milner-Gulland & Mace 1991).

Price of rhino horn. Wholesale price in Malaysia, Macao and Singapore 1987 = \$600–750 kg^{-1} (Martin 1989).
Assume the price to dealers in Zambia in 1985 is \$500 kg^{-1}, which converts to K2850 kg^{-1}.
K435 kg^{-1} to local hunters (confessions and Martin 1983).
1·54 kg per kill (Leader-Williams *et al.* 1990).

Annex Table 1.3. Catchability coefficients and kills per expedition for 1985

Gang type	Catchability Elephant	Catchability Rhino	Kills per expedition Elephant	Kills per expedition Rhino
Local	$1{\cdot}98e^{-5}$	$1{\cdot}67e^{-4}$	0·05	$1{\cdot}04e^{-4}$
Organized	$2{\cdot}56e^{-4}$	$2{\cdot}56e^{-4}$	3·54	0·15

Annex Table 2.1. Price and cost parameters

	Price per kill	Cost per expedition
Organized		
Elephant	2572	503
Rhino	4389	503
Local		
Elephant	271	14
Rhino	670	14

Annex Table 3.1.

Year	Kills per expedition	Expeditions	Gangs caught	Detection
1980	3·46	395	25	0·06
1981	3·31	412	22	0·05
1982	3·16	432	14	0·03
1983	3·02	453	19	0·04
Average				0·05

Annex 3

PROBABILITY OF DETECTION

This parameter was calculated as a compound measure of the probability of detection, of capture once detected, and of sentencing once captured. Accurate information was available for the last two probabilities (Leader-Williams *et al.* 1990), but the first probability had to be estimated very approximately. This was achieved by two independent methods, the first based on the decline of elephants and assumed harvest rates, and the second on the success of detecting poachers from one chief's area. The resulting compound measures of the probability of detection, capture and sentencing (hereafter 'detection') agreed closely and were of the order of 0·05.

Method 1

The elephant population of the Luangwa Valley as a whole declined from 33 510 in 1979 (Burrill & Douglas-Hamilton 1987) to 25 323 in 1985 (Douglas-Hamilton 1987). If the difference between these two figures is assumed to have been caused solely by illegal exploitation, then the number of expeditions needed to cause the decline can be estimated. We assume that the deaths were caused by organized gangs and were divided evenly between years. The number of kills per expedition was calculated from the catchability coefficient (Annex 1), and the number of expeditions needed to cause the deaths in each year was then deduced. The patrol and sentence data for 1980–83 give the total number of gangs that were caught and penalized, unlike later years when APUs 3 and 4 were working. Thus, there are four estimates for the proportion of those gangs whose members were arrested.

The trend of the number of expeditions increasing over time arises because deaths are assumed to be evenly divided between years. The trend in the number of gangs caught in the park over time is real, but may have changed when APUs 3 and 4 were formed. Since the trend in probability of detection was caused by the trend in number of expeditions, it was averaged over time.

Method 2

Data were obtained from confessions for the area of the SLNP hunted by people from Chief Mpumba's area (Leader-Williams *et al.* 1990). In 1981 the area was believed to contain 53 hunters, giving a total of 26 potential gangs with two hunters per gang. Gang members confessed they went on poaching expeditions once every 2 months, giving a total of $6 \times 26 = 152$ expeditions year^{-1}. Confessions also suggest that 2–3 gangs were hunting in the SLNP at any one time in 1980–81, so at 7 days per expedition, there will be 8–12 month^{-1}, or 96–144 gangs year^{-1}. In 1981, APUs in SLNP encountered Mpumba gangs six times, in 1981 eight times, giving detection rates varying between 6/152 and 8/96, or 0·04–0·08.

Annex 4

BIOLOGICAL PARAMETERS FOR OPTIMAL CONTROL

Elephant density at carrying capacity = 2 km^{-2} (Caughley & Goddard 1975).

Rhino density at carrying capacity = 0·4km^{-2} (Leader-Williams 1985).
Elephant intrinsic rate of population growth = 0·067 (Calef 1988).
Rhino intrinsic rate of population growth = 0·16 Hall-Martin 1986; Hitchins & Anderson 1983.

For the point of maximum rate of increase, as a proportion of K, Fowler (1984) derives the formula:

$R = 1 - 1/e - \ln(rT)/2e$

where R is the point of maximum increase, r = intrinsic rate of increase and T = generation time.

For rhino, $R = 1 - 1/e - \ln(0{\cdot}16 \times 2)/2e = 0{\cdot}80$.
The R for elephant is also estimated at around this value by Fowler (1984).
A z of 7 is used, giving $R = 0{\cdot}75$.

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