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How many to dehorn? A model for decision-making by rhino managers

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Abstract

A stochastic dynamic programming model is presented for decision-making by the manager of a small rhino reserve facing a poaching threat, with the objective of maximizing the rhino population size in the long term. The manager decides annually what proportion of the budget to spend on dehorning as opposed to law enforcement. Poacher incentives depend on revenues from illegal horn sales, which are related to the manager's decisions through the mean horn size of the rhino population (affected by spending on dehorning). Poacher incentives also depend on hunting costs, which are related to the manager's decisions through the risk of capture and punishment (affected by spending on law enforcement). The results suggest that, at realistic parameter values, the optimal strategy is to dehorn as many rhinos as possible annually except at very low rhino population sizes, budgets or mean horn sizes. The simple strategy of dehorning annually regardless of population size or mean horn size gives very similar results to the optimal strategy. Other potential strategies (such as dehorning only half the rhinos each year) performed badly. Selling horns and reinvesting the proceeds in rhino conservation did not provide enough revenue to significantly increase rhino population sizes.

INTRODUCTION

Black rhinos (*Diceros bicornis*) have suffered severe population declines in recent years, due to demand for their horns, principally for Far Eastern medicines (Leader-Williams, 1992; Martin & Vigne, 1997). The majority of the healthy rhino populations that remain in Africa are found in protected areas or on private land, and are subject to intensive, and expensive, protection (Cumming, du Toit & Stuart, 1990). Usually wildlife managers can only attempt to increase poacher costs through law enforcement, but rhino managers also have the option of decreasing poacher revenues by dehorning. There has been much debate about the merits of dehorning as a conservation strategy, linked to the wider issue of whether international trade bans are useful conservation tools (Milner-Gulland, Beddington & Leader-Williams, 1992; t'Sas-Rolfes, Bate & Morris, 1994; Lindeque & Erb, 1995; Berger & Cunningham, 1996).

Little research has been done on clarifying the objectives of conservation management, or quantifying the decision-making process for managers of an endangered species (but see Possingham, 1996). The theory of decision-making by commercial managers, particularly fisheries managers, is more developed (Hilborn & Walters, 1992), and most of the decision-making tools are directly transferable to conservation. Similarly, Sutinen & Anderson (1985) and Mazany, Charles & Cross (1989) have modelled the economics of imperfect law enforcement in fisheries, but there have been few studies on the economics of law enforcement when conserving hunted endangered species (Milner-Gulland & Leader-Williams, 1992; Jachmann & Billiouw, 1997).

In this paper, a model is developed for the decision-making process of a rhino manager faced with a poaching threat. The manager's optimal strategy when law enforcement and dehorning are both considered as options is compared to the results when only law enforcement is used. It has been suggested that the horns removed during dehorning could be sold and the proceeds reinvested in rhino management. The model is therefore also used to explore the manager's optimal strategy, and its success in conserving rhinos, when horns can be legally sold.

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METHODS

A decision-making framework

The framework for modelling decision-making requires various components:

- A set X of outcomes from the decisions, x_i.
- A set Y of the decision-maker's states, y_i.
- A set D of decisions, d_i.
- A set Ω of states of nature, ω_i.
- A set P of the probabilities of the states of nature occurring, p_i, where $p_i \geq 0$, $\sum p_i = 1$.

The outcome of a decision is a function (f) of the decision-maker's state, which decision is made, and the state of nature: $x = f(y,d,\omega)$. For example, a farmer's decision about which crop to plant (d_i) might depend on his or her current wealth (y_i) and the likelihood of a drought occuring (ω_i). The outcome of this decision (x_i) would be the yield obtained at the end of the year. The decision-maker's objective is assumed to be to maximize his or her utility, $u(x)$, which is a function of the outcome of the decision (for example the probability of being able to feed the family from the yield obtained that year).

The objectives of a resource manager, max $u(x)$, are often couched in monetary terms, for example maximizing long-term profits. However, it is not necessary to model decision-making in monetary terms, and managers of endangered species are more likely to be concerned with maintaining their populations at a healthy level. Thus, it is assumed here that the objective of the rhino manager is to maximize the rhino population size over the long term. Given that population growth is density dependent, this equates to keeping the population as close as possible to carrying capacity. So in this model, x is assumed to be the expected rhino population size next year.

The number of state variables, y_i, that can be included in a model is constrained by computational practicalities. In this model, three state variables are used: the rhino population size in the current year, N_t, the mean horn size in the rhino population, B_t, and the budget available to the manager, F_t. The manager's decision, d_t, is assumed to involve choosing the proportion of the budget to be spent on two activities each year: dehorning rhinos and other law enforcement activities (such as anti-poaching patrols or informant networks). The manager's decision determines the number of rhinos that are poached in a given year, and so affects the rhino population size the next year, because the poacher's decision-making is influenced by the revenues to be made (dependent on the mean horn size) and the costs incurred (dependent on law enforcement).

The majority of rhinos live in very small populations; in 1992, it was estimated that there were only five populations containing more than 100 black rhinos, and seven containing more than 100 white rhinos, *Ceratotherium simum* (Brooks, 1993). Rhinos are increasingly being confined to small areas with low carrying capacities. At these small population sizes, stochasticity in birth and death rates can play a major role in the fate of a population (Soulé, 1987). Thus the state of nature, ω_i, is modelled using stochastic birth and death rates, and p_i is the probability of a rhino population of a given size reaching a different size next year because of stochastic births and deaths.

The stochastic dynamic programming model

The modelling tool used here is stochastic dynamic programming (SDP). SDP is a tool for finding a resource user's optimal strategy in a stochastic environment, when the state of the system is an important determinant of the optimal decision. It has been most widely used in behavioural ecology (Houston & McNamara, 1988; Mangel & Clark, 1988). Some use of SDP has been made in fisheries science (Walters, 1978; Clark, 1990) and in pest control (Jaquette, 1970; Shoemaker, 1982). The technique has also been applied to terrestrial wildlife management (Reed, 1974; Anderson, 1975; Milner-Gulland, 1997) and conservation decision-making (Possingham, 1996).

SDP is a discrete-time optimization method, in which the model works backwards from an end-point. A final value is assigned to each possible state of the system at the end time T. The value of each decision at time T–1 can then be calculated for each state of the system, because for a given state, each decision will lead to a particular outcome in the final period with a known probability. The optimal decision in period T–1 for a particular state of the system is the decision that maximizes the expected value. The optimal decision is taken, and the model moves to time T–2 and repeats the calculation. After a number of years, the optimal strategy is no longer dependent on how long there is to go until T. The long-term optimal strategy has been found, which maximizes the expected value of the system for an indefinite period of time. This is the strategy that is relevant to resource managers who are interested in the long-term survival of the resource.

In this model, for each value of the state variables N_t, B_t, F_t, the manager first decides what proportion of the budget will be spent on dehorning. The integer number of individuals that can be dehorned using this amount of money is calculated, and the remainder of the money is allocated to law enforcement. Dehorning takes place, and the new mean horn size of the population is calculated. Next, poaching takes place, with the number killed by poachers depending on the mean horn size, the population size and the amount of money spent on law enforcement. Finally births and natural mortality occur, and the expected population size next year is calculated. The optimal decision is chosen, which is the proportion of the budget spent on dehorning that maximizes the benefit to the manager (eqn (1)). This procedure is repeated for all combinations of initial population size, intial mean horn size and budget, and for enough years from the end-point for the optimal decision to be independent of time (about 50 years).

$$V_t[N_t, B_t, F_t] = \max_{d_t} E_\omega[V_{t+1}(N_{t+1}, B_{t+1}, F_{t+1})] \qquad (1)$$

where V_t = value of the decision at time t; N_t = population size at time t; B_t = mean horn size at time t; F_t = budget at time t; d_t = proportion of the budget spent on dehorning at time t; and E_ω = expectation of V_{t+1} over the probability distribution of population size.

The SDP model can also be run forwards, generating a probability distribution of rhino population sizes for a given decision-making strategy. This allows the relative effectiveness of the optimal strategy to be compared to that of other, suboptimal, strategies. Rules of thumb can be developed, that capture the essence of the optimal strategy, but are simple and practical to apply.

Specifying the model

Horn growth rates, both from birth and after dehorning, vary with the age and sex of the rhino (Rachlow & Berger, 1997). However, in this model, it is only possible to consider the mean horn size for the population as a whole. Rachlow & Berger (1997) found that although the rate of regrowth depended on the age and sex of the rhino, it did not change significantly with time since dehorning. Thus the mean horn size of the population is assumed to increase linearly after dehorning until it reaches a maximum. This assumption is consistent with data on the time taken for horns to regrow (Milner-Gulland, Beddington *et al*., 1992) and prevents errors caused by using more complicated non-linear assumptions about individual horn growth at the population level. The effect of this assumption on the costs of dehorning or poaching is negligible if neither managers nor poachers select in advance which rhino to target. The mean horn size after dehorning, B_1, is calculated as:

$$B_1 = p_d B_d + (1 - p_d)[\min(B_t + g, B_{\max})], \qquad (2)$$

where B_t = mean horn size at time t; p_d = proportion of the population dehorned; B_d = amount of horn left after dehorning; g = amount of horn growth each year; $B_{\max}$ = mean horn size in an undehorned population. Because poachers are assumed to kill rhinos non-selectively, $B_{t+1} = B_1$.

The cost of dehorning, C_d, is assumed to be:

$$C_d = N_d \times \frac{C_m \times N_{\max}}{N_t}, \qquad (3)$$

where N_d = number dehorned; C_m = cost of dehorning a single rhino when the population is at $N_{\max}$; $N_{\max}$ = maximum number of rhinos in the area. This model assumes that dehorning costs increase as density decreases, because the less dense the population is the more time is needed to find each animal. It also assumes that the manager decides on the total number to be dehorned at the beginning of the exercise, rather than deciding whether to continue after each rhino is dehorned, and that search costs depend on rhino density at the beginning of the dehorning exercise. This is a reasonable assumption if the dehorning operation is well planned in advance, as has been the case in previous dehorning operations. I assume no rhino mortality as a result of dehorning, because recent dehorning exercises have led to virtually no casualties (Milner-Gulland, Leader-Williams & Beddington, 1993).

Currently, rhino horn cannot be sold legally on international markets. However, it has been suggested that it may be feasible to sell it legally in future, in order to fund rhino conservation. This would follow the precedent set at the 1997 CITES Conference of the Parties, at which it was agreed to allow countries to sell their ivory stockpiles (in strictly controlled circumstances) in order to fund elephant conservation. In order to model this possibility, the budget for law enforcement is updated after dehorning, to become:

$$F_1 = F_t - C_d + P_m[p_d N_t (B_t - B_d)] \qquad (4)$$

where F_1 = budget for law enforcement after dehorning has taken place; P_m = price per kilogram paid for legally-sold horn. Note that in order to keep the model tractable, there is no carry-over of revenues from the sale of horn into future years; the baseline budget remains the same, and all revenues from horn sales must be used in the current year (ie. $F_{t+1} = F_t$). If there is no sale, $P_m = 0$, and the budget for law enforcement is simply $F_1 = F_t - C_d$.

The effect of dehorning is to reduce the expected amount of horn that a poacher obtains from killing a rhino, thus reducing the poacher's revenues. Law enforcement is assumed to increase the costs of poaching. The poachers' incentives are modelled as:

$$\Pi_t = HP_p B_1 - \sum_{h=0}^{h=H} \left[\frac{N_{\max}\left(C_p + LF_1\right)}{N_t - h} \right] = 0, \qquad (5)$$

where Π_t = total profits to poachers in year t; H = total number of rhinos killed by poachers in year t; P_p = price per kilogram of horn for the poacher; C_p = cost of killing a single rhino when the population is at $N_{\max}$; L = proportion of the manager's budget, F_1, that is transferred to poachers as a cost. The model is solved by iterating over the number killed so far, h, until the total number killed by poachers that year, H, is such that total poacher profits, Π_t, are zero. Poaching is assumed to be open access, rather than monopolistic. In open access hunting, the equilibrium hunting rate gives zero profits (Clark, 1990). It is also assumed that poachers weigh up the profitability of continuing to hunt after each kill, rather than deciding how many to kill at the beginning.

Rhino population dynamics are modelled using the simple model:

$$N_{t+1} = N_1\left(S_a + \phi_t S_j\right), \qquad (6)$$

where N_1 = population size after poaching has taken place ($N_1 = N_t - H$); ϕ_t = annual birth rate as a proportion of the total population size; S_a = survivorship of rhinos >1 year old; S_j = survivorship of rhinos in their first year. It is impractical to model rhino population dynamics using an age- and sex-structured model because of the computational limitations of SDP. Using a lumped population model may underestimate the effects of hunting at very high hunting mortalities, when the mean age of the population may be low enough to affect female fecundity because few sexually mature females remain in the population (Milner-Gulland, 1991).

The equation for the birth rate (following Lankester & Beddington, 1986) is:

$$\phi_t = \phi_{\min} + (\phi_{\max} - \phi_{\min}) \times \left[1 - \left(\frac{N_j}{K}\right)^{\beta}\right], \quad (7)$$

so that ϕ_t takes the value $\phi_{\max}$ at very low population sizes, and $\phi_{\min}$ at carrying capacity, K. β is a measure of the non-linearity of the density-dependence. $\beta = 1$ would give standard logistic population growth, with maximum recruitment at $N = 0.5K$, $\beta > 1$ gives maximum recruitment nearer to K.

Stochasticity is included in the birth rate and both survivorship rates. The number of births or deaths at a given population size is assumed to follow a binomial distribution (Brown & Rothery, 1993):

$$P(R = r) = {}^{n}C_r\, p^r (1-p)^{(n-r)} \quad \text{for} \quad r = 1, 2, \ldots, n. \quad (8)$$

The values of r, R, n and p depend on which of the rates is being calculated. If adult survivorship was being calculated, eqn (8) would be interpreted as: the probability of the number of adults surviving, R, being a particular number, r, is a function of the mean adult survivorship, p, when the maximum number that could survive is the current population size, n. The model does not include any genetic stochasticity, nor does it consider the effects of stochastic variation in sex ratio at very small population sizes. Genetic isolation is already being addressed for many rhino populations through translocation exercises (eg. Hall-Martin & Penzhorn, 1977), and skewed sex ratios are not likely to be exacerbated by poaching because the two sexes are very similar in appearance. This simple model is justified because the issue being explored here is short-term population decline due to

Table 1. Parameter values used in the model

Parameter	Symbol	Value	Comments
Carrying capacity	K	50	Typical; Cumming *et al*. (1990)
Largest population size	$N_{\max}$	55	Allowing for variability around K
Maximum law enforcement budget (1991 US$)	$F_{\max}$	100 000	
Mean horn size in an undehorned population (kg)	$B_{\max}$	3	Value for black rhinos; N. Leader-Williams, pers. comm.
Mean horn size left after dehorning (kg)	B_d	0.5	J. Rachlow, pers. comm.
Horn growth per year (kg)	g	1	Rachlow & Berger (1997)
Cost to manager of dehorning one rhino at $N_{\max}$ (1991 US$)	C_m	1000	Various authors; see Milner-Gulland, Leader-Williams *et al*. (1993)
Price of dehorned rhino horn (1991 US$/kg)	P_m	0 or 2000	US$2000; R. Martin, pers. comm.
Cost to poacher of killing one rhino at $N_{\max}$, excluding law enforcement cost (1991 US$)	C_p	159	Luangwa Valley 1980s; Milner-Gulland & Leader-Williams (1992)
Price poacher receives from selling horn (1991 US$/kg)	P_p	2000	Luangwa Valley 1980s; Milner-Gulland & Leader-Williams (1992)
Proportion of law enforcement budget entering poachers' decision-making as a cost	L	0.00005 0.005	Luangwa Valley, 1980s or 1990s (crude estimate); see Appendix 1.
Fecundity at K (births as a proportion of population size)	$\phi_{\min}$	0.0675	see Table 2
Fecundity at low population size (births as a proportion of population size)	$\phi_{\max}$	0.12	see Table 2
Annual survivorship of rhinos >1 year old	S_a	0.95	Calculated from ϕ; Milner-Gulland (1991)
Annual survivorship of rhinos ≤ 1 year old	S_j	0.81	Calculated from ϕ; Milner-Gulland (1991)
Non-linearity in density dependence	β	3.4	Maximum recruitment occurs at 0.6K; Fowler (1981)

All economic data in the model have been standardized to 1991 US$, to provide comparability between data sets from different countries and years.

Table 2. Data on fecundity rates for black rhino populations

Area and date	Calves/female/year	Calves/population/year	Comment	Reference
Ngorongoro, 1967	0.25	0.068	Stable?	Goddard (1967)
Ngorongoro, 1981	0.24	0.107		Kiwia (1989)
Olduvai, 1967	0.26	0.068	Stable?	Goddard (1967)
Tsavo, 1970	0.30	–		Goddard (1970)
Amboseli, 1972	0.25	0.068	Stable/poached	Western & Sindiyo (1972)
Addo, 1977	0.46	–	Increasing	Hall-Martin & Penzhorn (1977)
Hluhluwe, 1983	0.19	0.074	Recovering	Hitchens & Anderson (1983)
Corridor, 1983	0.28	0.098	Increasing	Hitchens & Anderson (1983)
Umfolozi, 1983	0.33	0.099	Increasing	Hitchens & Anderson (1983)
Luangwa, 1985	0.17	0.046	Poached	N. Leader-Williams, pers. comm.

Calves/population/year is the parameter value required for the model, but can only be calculated when the proportion of adult females in the population is given. Whether the population is stable, increasing and/or poached gives an idea of how close to carrying capacity it is likely to have been.

poaching, rather than the long-term viability of small populations (Caughley, 1994).

Parameterizing the model

The parameter values used in the model are given in Table 1. Density dependence is assumed to affect the birth rate rather than mortality rates, and to be non-linear (eqn (7)). There is evidence for density dependence being manifested at high population densities in the form of delayed sexual maturity and long interbirth intervals (Hitchens & Anderson, 1983). β is chosen to give maximum recruitment at $N = 0.6K$. In large mammals density dependence tends to occur at population sizes above $0.5K$ (Fowler, 1981, 1984); this is also suggested by Hitchens & Anderson's (1983) observations. The values chosen for $\phi_{\max}$ and $\phi_{\min}$ are derived from the literature for black rhinos (Table 2). The value for K is chosen to represent an average-sized managed rhino population, but one that is large enough to persist in the medium term with the stochastic dynamics specified in eqn (8). At a carrying capacity of 0.4 individuals/km^2 (Leader-Williams, 1985), this represents an area of about 125 km^2. An isolated population with a K value much less than 50 would not be viable in the medium term irrespective of the manager's decisions (Fig. 1). The survivorships used in eqn (6) are concordant with the literature, but because survivorships must take values that make the population stabilize at K in the absence of human-induced mortality, they are derived from the birth rates (for which more reliable data exist).

The data on the cost of dehorning are derived from previous dehorning operations (Milner-Gulland, Leader-Williams & Beddington, 1993). The effect of assuming that costs increase as the reciprocal of population density is that costs increase slowly at first as density decreases, then increase dramatically at very low densities. This is the standard assumption made concerning the effect of increased search time on harvest costs. The price of legally sold horn is difficult to estimate, because the international rhino horn trade has been illegal under CITES since 1975. However, the illegal price of rhino horn and the poacher's costs of hunting were estimated for the Luangwa Valley, Zambia in the early 1980s (Milner-Gulland & Leader-Williams, 1992); no other comparable study estimates poacher costs and prices, so these data are used to parameterize the model.

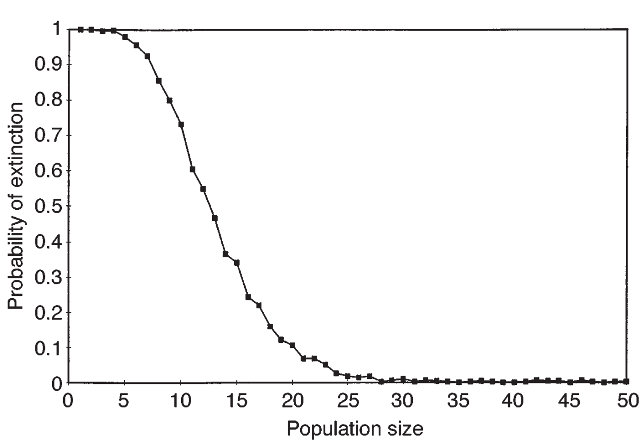

Fig. 1. The probability of a rhino population, with the dynamics specified in eqns (6)–(8) and biological parameter values specified in Table 1, reaching extinction within 50 years, starting from carrying capacity (K) at the population size specified on the x-axis. A total of 200 simulations were run for each population size.

A major assumption is that it is meaningful to model law enforcement as transferring a proportion of a manager's budget to poacher costs (eqn (5)). The cost that a manager can impose on a poacher has two components: the probability of being caught, and the punishment inflicted once caught. Evidence from empirical studies of burglary in the USA suggests that the major deterrent to law-breaking is the perceived probability of being caught, not the punishment inflicted (Ehrlich, 1973; Avio & Clark, 1978). Similar results have been found for natural resource users (Sutinen & Gauvin, 1989; Clayton & Milner-Gulland, in press), which is convenient because a manager is better positioned to influence the perceived probability of capture than the penalty imposed. The penalty imposed is generally the responsibility of another authority, and can vary greatly irrespective of the legislated penalty (Leader-Williams & Milner-Gulland, 1993).

Two recent studies on elephant and rhino management suggest that the probability of capture is a function of the manager's law enforcement budget. In the data presented by Jachmann & Billiouw (1997), there is a significant relationship between poacher activity (proxied by the number of elephants found killed) and the number of bonuses paid to law enforcement officials, as well as between the budget in the previous year and the number of bonuses paid in the current year. Because bonuses are paid on the arrest of a poacher, this suggests a relationship between law enforcement effectiveness and funding. In the data presented by Martin (1996), the total law enforcement budget does not show a significant relationship with poaching rates, but the total budget for intelligence gathering does.

Thus it seems plausible to assume some relationship between the poaching rate and the size of a manager's budget. If arrested poachers are fined then the relationship is clearly expressible monetarily, but even prison sentences can be expressed in monetary form (Milner-Gulland & Leader-Williams, 1992). Note that the aim of the model is to examine the effects of the law enforcement budget on poacher incentives, on the assumption that the budget is optimally allocated. If a redistribution of the budget, for example towards intelligence-gathering, would have a significant effect on poacher incentives, this cannot be captured in the model. The relationship between the law enforcement budget and poacher costs is assumed to be linear (eqn (5)). Given the paucity of the data, this seems the simplest assumption to make. The degree of cost transfer from the law enforcement budget to the poacher (L) can be crudely estimated for the Luangwa Valley, Zambia (see Appendix).

RESULTS

The modelled rhino population can sustain a poaching rate of up to 2% of the population a year (<1 rhino killed each year) without serious decline, but reaches dangerously low levels at higher poaching rates (Fig. 2(a)). The effect of the degree of cost transfer from the law enforcement budget to the poacher was explored, assuming that the rhino population was hunted by poachers with the same costs (C_p) and prices (P_p) as those for the poachers operating in the Luangwa Valley in the 1980s (Fig. 2(b)). The very low rates of cost transfer that prevailed then (see the Appendix) led to very low law enforcement costs to poachers, and so the rhino population was extirpated in the late 1980s. For the model rhino population to remain stable, the poacher's law enforcement cost (LF_1 in eqn (5)) would need to be around US$5000. The poacher costs and prices estimated from the Luangwa Valley data are so favourable to poachers that even if all the rhinos in the model population were dehorned, it would still be worthwhile for poachers to kill virtually all of them for the small amount of horn that remains after dehorning. Only if poacher costs increased and prices decreased to around $P_p = C_p = 500$ would it not be worthwhile to kill dehorned rhinos (Fig. 2(c)).

The results of the SDP model are presented in Fig. 3 for four population states; a high or low budget and a large or small mean horn size. Figure 3(a) shows the situation for the parameter values of the Luangwa Valley in the 1980s. With a low budget, it is optimal to dehorn about half the rhinos irrespective of mean horn size; it would be financially impossible to dehorn more. At a high budget, it is possible (and optimal) to dehorn all the rhinos, so long as the population is large enough for it to be worth poaching (≥3 rhinos). The larger the mean horn size, the more attractive the population is to poachers, so the optimal number dehorned reaches 100% at a lower population size. With a higher cost transfer rate, the results are similar, but because law enforcement is more effective, the population size at which dehorning starts is six if the mean horn size is large, 12 if it is small (Fig. 3(b)). If it were possible to sell the horn and reinvest in law enforcement, there is very little difference in the strategy, except that if population size, mean horn size and budget are all high, the minimum proportion that needs to be dehorned is lower, because a lower dehorning proportion generates enough money to fund law enforcement (Fig. 3(c)). Finally, if poacher profits were low, dehorning would only be necessary at high population sizes, when poaching is worthwhile. The smaller the mean horn size, the higher the population size at which dehorning becomes necessary (Fig. 3(d)).

Running the model forwards in time gives an understanding of the effects of different management strategies on the rhino population. The probability distribution of rhino population sizes under the optimal strategy is compared with that for other potential strategies, such as not dehorning, dehorning as many rhinos as possible within the budget each year, or dehorning half the rhinos

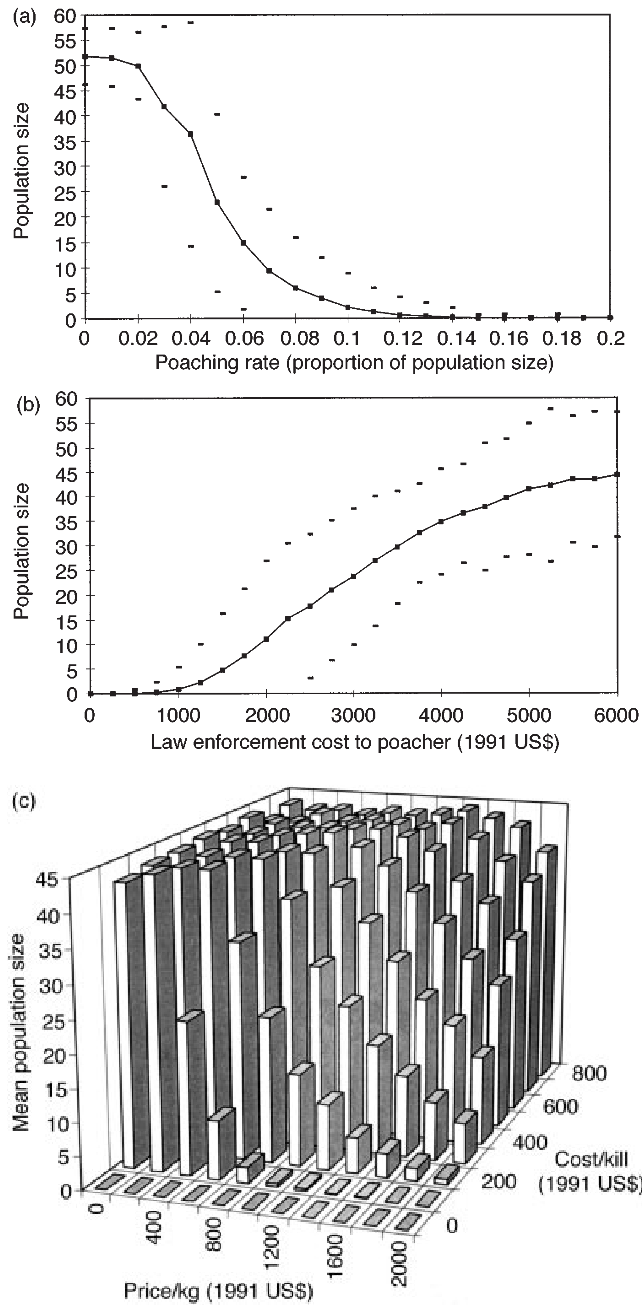

Fig. 2. Exploring the effect of changes in parameter values on rhino population sizes. Results are shown as mean population sizes after 50 years (with 95% confidence intervals in (a) and (b)), from 500 simulations for each parameter value, starting at K. (a) The effect of the proportion of the population killed by poachers each year on population size. (b) The effect of the enforcement cost imposed on poachers, calculated as $L \times F_1$, when poacher profits are high: C_p = 159, P_p = 2000. There is no dehorning. The law enforcement costs imposed on poachers in the Luangwa Valley in the 1980s were <$500. (c) The effect of the poacher's hunting cost per rhino killed, C_p, and the illegal horn price/kg, P_p, on population size, assuming that all rhinos are dehorned annually (so the mean horn weight in the population is B_d, constant at 0.5kg), and there is no law enforcement (L = 0).

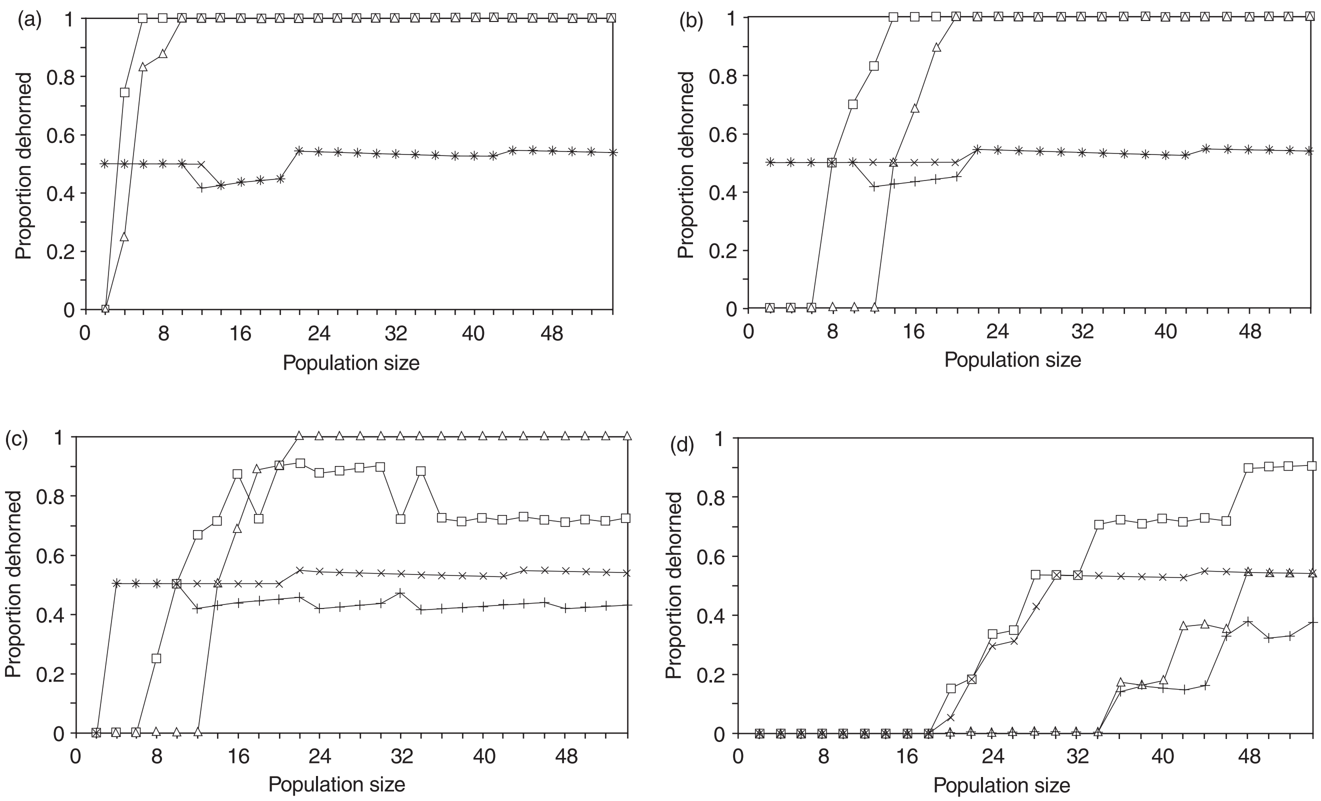

Fig. 3. The optimal dehorning strategy calculated from the stochastic dynamic programming model, shown as the minimum proportion of the population that needs to be dehorned in a year, for each population size. Four scenarios are shown: –□–, high budget and fully grown horns ($F_t = F_{max}$, $B_t = B_{max}$); –△–, high budget and recently dehorned ($F_t = F_{max}$, $B_t = 0.2B_{max}$); –×–, low budget and fully grown horns ($F_t = 0.3F_{max}$, $B_t = B_{max}$); +, low budget and recently dehorned ($F_t = 0.3F_{max}$, $B_t = 0.2B_{max}$). (a) Luangwa Valley, 1980s. $C_p = 159$; $P_p = 2000$, $L = 0.00005$. (b) Guess for Luangwa Valley, 1990s. $C_p = 159$; $P_p = 2000$; $L = 0.005$. (c) Guess for Luangwa Valley, 1990s, but the manager can sell horns. $C_p = 159$; $P_p = 2000$; $L = 0.005$; $P_m = 2000$. (d) Luangwa Valley 1980s, with low poacher profits. $C_p = 500$; $P_p = 500$, $L = 0.00005$.

each year. These strategies are not dependent on the state of the system; they are carried out each year, regardless of the population size, mean horn size in the population or budget size. The strategy of dehorning all the rhinos every few years was also explored; it produces similar qualitative results to dehorning a proportion of the rhinos each year, although it performs rather better in the model because it is more cost-effective.

At the 1980s parameter values, the population is rapidly extirpated, regardless of the size of the budget or the dehorning strategy employed, because poaching is so profitable that it brings the population to low enough levels for stochastic extinction (Fig. 1). At the estimated 1990s parameter values, the population remains extant for 50 years only at high budgets, and is only viable if either the optimal strategy is employed or all the rhinos are dehorned annually (Fig. 4(a)). At a budget of $0.75F_{max}$, the mean population size after 50 years under the optimal strategy is only four individuals. If the horns can be sold and profits reinvested in law enforcement, the results are very similar to those if the horn cannot be sold (Fig. 4(b)). This is because the revenues from selling horn are very low when the population is small and frequently dehorned. The optimal strategy leads to a spread of dehorning proportions, but with a preponderance of years when either none or all are dehorned (Fig. 4(c)).

If the poacher has low profits, then a high budget allows the manager to reduce poaching levels to near-zero either by using the optimal strategy or by dehorning as many as possible each year. Dehorning 50% of the population annually leads to a lower expected population size, and not dehorning leads to extinction being the most likely outcome (Fig. 5(a)). Even at low budgets, low poacher profits mean that the manager can reduce poaching rates substantially by dehorning as many as possible or following the optimal strategy; the results are similar to those for the high budget (Fig. 5(b)). The expected mean horn size in the population using the optimal strategy is larger at low budgets, since dehorning is too expensive for it to be possible to dehorn as many rhinos as at high budgets (Fig. 5(c)).

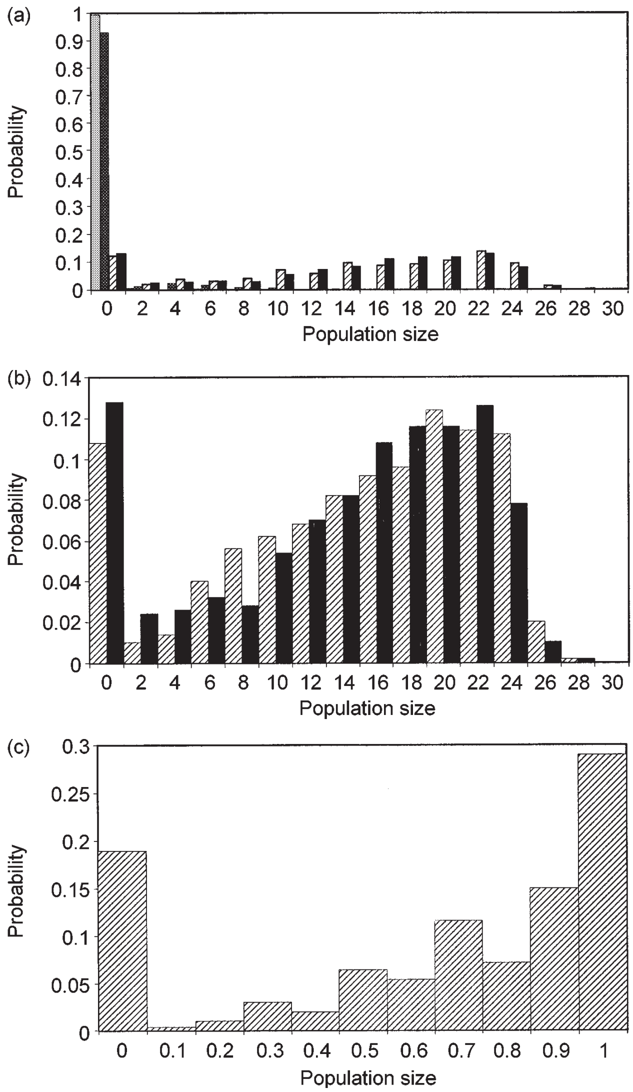

Fig. 4. (a) The probability distributions of rhino population sizes after 50 years of simulation (starting from K), using parameter values for the guess for the Luangwa Valley in the 1990s; C_p = 159; P_p = 2000; L = 0.005, $F = F_{\max}$. A total of 500 simulations was run for each of four strategies: the optimal strategy (■); spending the whole budget on dehorning (aiming at 100% dehorned each year) (▨); dehorning 50% of the rhinos each year (▩); not dehorning (spending the whole budget on law enforcement) (▒). (b) As for (a), but showing a comparision between the probability distributions under the optimal strategy when horns cannot be sold (■), and when they can be sold (▨) (P_m = US \$2000/kg). (c) The probability distribution of the proportion of the population dehorned in a year under the optimal strategy when horns can be sold (proportion dehorned at year 50 for 500 simulations).

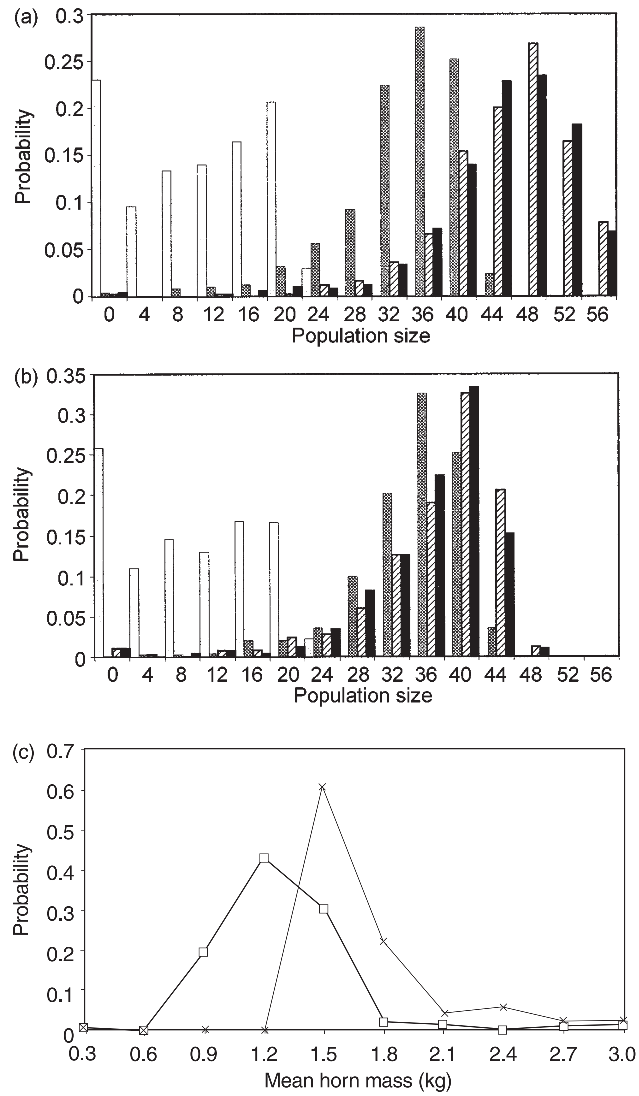

Fig. 5. The probability distributions of rhino population sizes after 50 years of simulation (starting from K), using the cost-transfer for the Luangwa Valley in the 1980s, but with low poacher profits; C_p = 500; P_p = 500; L = 0.00005. A total of 500 simulations was run for each of four strategies: the optimal strategy (■); spending the whole budget on dehorning (aiming at 100% dehorned each year) (▨); dehorning 50% of the rhinos each year (▩); not dehorning (spending the whole budget on law enforcement) (□). (a) $F = F_{\max}$. (b) $F = 0.3F_{\max}$. (c) The probability distribution of horn size in the population, under the optimal strategy, when $F = F_{\max}$ (–□–) or $F = 0.3F_{\max}$ (–×–).

DISCUSSION

The SDP model suggests that the optimal long-term strategy for the manager of a small rhino population, who is aiming to maximize the rhino population size in the face of a poaching threat, is to dehorn a large proportion of the rhinos each year, except if the population size, budget or mean horn size are very low. However, the analysis of alternative strategies shows that the subtleties of the optimal strategy are unnecessary; it is generally almost indistinguishable in its results from simply dehorning as many rhinos annually as the budget allows, regardless of the population size and mean horn size. The analysis clearly shows that dehorning only half the rhinos each year, or dehorning every other year, is not an adequate deterrent to poachers.

Under the parameter values assumed here (which are based on the available data), the strategy of not dehorning, but relying instead on law enforcement, is far inferior to dehorning. Both dehorning and law enforcement are expensive exercises that aim to reduce poacher profits, and the superiority of one over the other depends on the efficiency with which spending by managers is translated into reductions in profits for the poachers. Dehorning has the advantage over law enforcement in that its effects carry over into the next year through smaller mean horn sizes, although the effectiveness of dehorning in reducing poacher profits in a particular year depends on the horn size prior to dehorning. The cost-effectiveness of law enforcement depends on L, the cost-transfer rate of law enforcement spending to poacher costs. Data suggest that in the Luangwa Valley in the 1980s, every \$20 000 spent on the law enforcement budget caused only \$1 of costs to poachers (see Appendix); if this is typical of cost-transfer rates for spending on rhino protection, spending on dehorning will often be the more cost-effective protection measure. Figure 6 compares the pure strategies of only dehorning or spending only on law enforcement, for different costs of dehorning and cost-transfer rates of law enforcement spending, under two poaching cost and price regimes.

Being able to sell rhino horn and reinvest the proceeds in law enforcement is shown here to give a negligible improvement in the expected rhino population size. The problem is that with a small, regularly dehorned population, the amount of horn available for sale is too low for the proceeds to be more than a tiny percentage of the manager's total budget. The price of horn would have to be very much higher, or the population much larger, for this conclusion to alter. However, this analysis has not considered the effects of reinvestment of revenues from horn sales on the morale of managers, which could be a significant influence on management effectiveness.

Changing the poacher costs and prices has revealed that a major influence on the results is whether it is economically worthwhile for a poacher to kill a recently dehorned rhino for its stub. If not, then poaching can be effectively controlled by dehorning. If it is worthwhile, then at realistic cost-transfer rates and low manager budgets, a small rhino population is doomed. At high budgets, it is possible to dehorn all the animals and leave enough money for law enforcement to deter poachers.

This analysis is necessarily simplistic in several ways. A major assumption is that the horn size is treated as a population mean, rather than tracking the horn growth of individual rhinos. A more sophisticated model of individual horn growth would be more realistic, particularly if rhino age and sex were modelled, but would preclude the use of SDP to find the optimal strategy. However, as long as both poachers and managers do not select individual rhinos to target in advance, the simple model is adequate. If dehorning of the whole population was carried out periodically, rather than dehorning a proportion of the population each time, then the rhinos would have horns of much the same size, and again the model assumptions would be adequate. If dehorning led to changes in fecundity or mortality rates, a more complex specification would be needed, and dehorning would perhaps be a less attractive option (Berger & Cunningham, 1996). The parameter estimation is very crude, due to the lack of good data on poacher costs and prices (including those imposed by law enforcement). However, although the probability distribution of rhino population size is sensitive to poacher costs and prices, the near-optimal effect of a strategy of annual dehorning is robust to parameter changes.

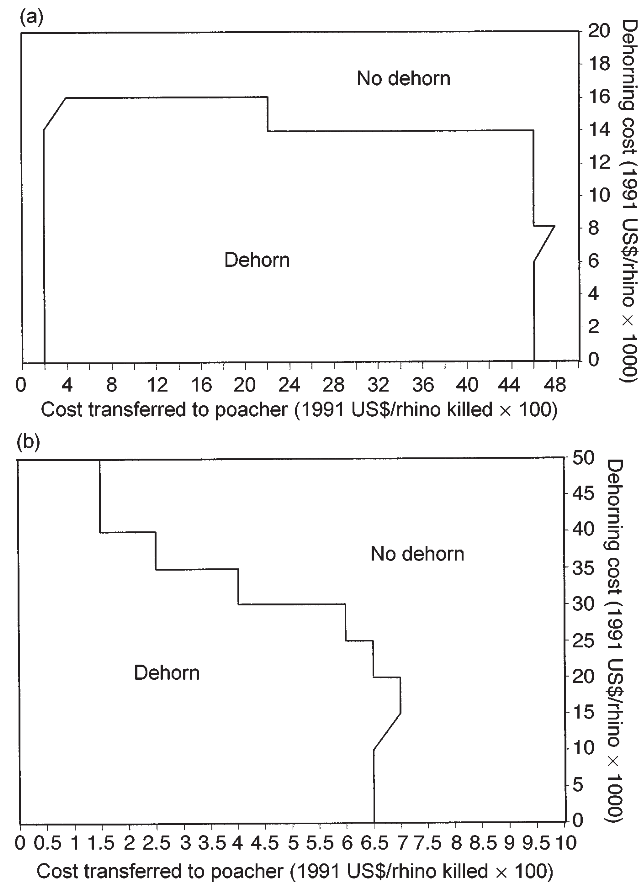

Fig. 6. Sensitivity analysis comparing the strategy of dehorning as many rhinos as possible against not dehorning any rhinos at all. A total of 500 simulations were run, and the mean population size after 50 years was calculated for each set of parameter values. The contour shows the point at which the mean population size was at least 10% higher when the rhinos were dehorned annually than when they were not dehorned (given that the mean population size was at least 1 rhino). The parameters that were varied were the cost of law enforcement to the poacher for each rhino killed (LF_1) and the cost of dehorning one rhino (C_m). The total budget available each year was F_{max}, \$100 000. Note the differences in axes between the figures. (a) Poacher costs and prices as in the Luangwa Valley in the 1980s: C_p = 159; P_p = 2000. (b) Low poacher profits: C_p = 500; P_p = 500.

Previous models of dehorning (Milner-Gulland *et al.*, 1992, 1993) calculated the optimal time between dehornings for a profit-maximizing manager, and showed that this was considerably longer than the time since dehorning at which a poacher would kill a rhino (about 2.5

years as opposed to 1 year). The model in this paper uses a different, and more realistic objective for the manager; to maximize the rhino population size in the long term. With this objective, the question is one of allocation; to what extent should money be spent on increasing poacher costs through law enforcement, compared to decreasing poacher revenues through dehorning. The poacher's costs caused by law enforcement costs are represented very simply as a proportion of the law enforcement budget; in the future, with better data, this representation of poacher incentives could be greatly improved.

This paper addresses the limited issue of the best strategy for the manager of a small rhino population, threatened by poaching, who aims to maximize the rhino population size and has a limited budget to achieve this aim. The model suggests that, under these conditions, annual dehorning of all rhinos is the best simple strategy for the manager to follow. However, this scenario is not the only one faced by rhino managers; for example, a different approach would be appropriate for a government agency that manages the country's rhino population as a meta-population, and which has more flexibility in budgetary planning. The complexities of the illegal horn trade, changing demand for rhino horn, and changing poacher perceptions of the costs and benefits of poaching are also not addressed. However, despite these limitations, a modelling exercise such as this can help to clarify the incentives faced both by managers and by poachers.

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APPENDIX

Crude calculation of the proportion of the law enforcement budget transferred to poachers as costs, L, for the Luangwa Valley, Zambia.

All data up to 1988 are from Milner-Gulland & Leader-Williams (1992), except for the total law enforcement budget, which is from Jachmann & Billiouw (1997). All data from 1988 onwards are from Jachmann & Billiouw (1997). All monetary values have been converted to 1991 US$ for the purposes of comparability.

The approximate value of L in the early 1980s can be calculated from the estimated law enforcement cost to poachers, C_L;

$$C_L \approx \frac{LKF_t}{N_t} \text{ (see eqn (5)) in the text.}$$

C_L is the average fine imposed in the Luangwa Valley courts multiplied by the probability of arrest, per animal killed, and is calculated to be 1991 US$473. K is estimated at 8597 rhinos, and N_t in 1979 is estimated at 575 rhinos. The total annual law enforcement budget at this time was 1991 US$620 474. Thus:

$$L \approx \frac{575 \times 473}{8597 \times 620474} \approx 0.00005.$$

So about US$1 in every US$20 000 spent on law enforcement was transferred to poachers as a cost during this period.

From 1988 onwards, a new law enforcement regime began, with better funding and better targetting of resources. Bonuses were paid for information and actions leading to an arrest. The relationship between the number of bonuses paid and the probability of arrest is complex, and there are no data on how the average penalty for poaching changed between the early 1980s and the early 1990s. The rhino population size was much lower in the early 1990s, because of high poaching levels in the 1980s.

There are no data available to make a good estimate of L in the early 1990s, but a crude estimate can be obtained by multiplying the value of L calculated for the 1980s by the ratio of the average number of bonuses paid in the period 1989–1995 and the number of bonuses paid in 1988, before the new regime had had a major effect. This produces a value of:

$$L \approx \frac{5808}{54} \times 0.00005 \approx 0.005.$$

As this estimate of L is so crude and unlikely to be correct, it is used as a ballpark figure for comparative purposes only, rather than as an estimate of the true value of L in the early 1990s.