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*A MARKET SOLUTION FOR PRESERVING BIODIVERSITY: THE BLACK RHINO**

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I. Introduction

Economic principles guiding human behavior have a minimalist role in the framing of the Endangered Species Act (ESA) in the United States (Brown & Shogren, 1998). Its principles and procedures make sense only if the individuals adversely affected by the ESA simply acquiesce, making no effort to avoid the cost of compliance. Illustratively, if my land has habitat characteristics for a species about to be listed, regardless of the cost imposed on me by the listing, I will not remove the specific flora in order to preserve the value of my land which will be lost when the species is listed. Such an assumption is empirically false and the species are the worse for it (Brown and Shogren, 1998; Mann and Plummer, 1995).

The formal procedures taken to manage the black rhinoceros exhibits the same shortcoming. The consequence for the black rhino of disregarding economic incentives guiding human behavior has been profound as we portray below. We show how fairly simple economic reasoning can be exploited to restore the black rhino population from its current endangered status. We hope this dramatic example of mismanagement and our antidote will lead to the inclusion of more economic reasoning in setting policies for managing endangered species in the future.

Recent years have witnessed a growing public antipathy toward trade in parts of popular animals, particularly megafauna such as the elephant and rhinoceros. Conservation groups such as World Wildlife Fund (WWF) and the International Union for the Conservation of Nature were instrumental in instituting a ban on trade in rhino horn since 1977 and a ban on ivory since 1989. The animals and products are listed in Appendix I of CITES.

It may come as a surprise to economists to learn that the ban on ivory trade has been more successful than we might have expected. The reasons for success seem to be threefold. First, much of the demand for ivory was to produce tourist type trinkets, for which there are many substitutes.

Second, a continuous flow of gruesome pictures of hacked off heads of dead elephants poached only for their ivory, grieving family members of the dead standing with heads bowed, and the bonfire of ivory in Nairobi Park seems to have informed and shocked many, if not most people to change their tastes. Third, WWF launched a successful research project to find a substitute material in color, texture and feel, for ivory piano keys.

In contrast, the ban on rhino horn trade has been disastrous for the African black rhino (Diceros bicornis). The population has fallen continuously and precipitously from around 65,000 to about 2,600 in two decades. See Table 1. Poaching rhinos has provided a ready substitute for formerly legal trade with the result that black rhinos are locally extinct over substantial areas in Africa. The reason for the ban's apparent success for ivory and failure for rhino horn is surprisingly simple. African rhino horn has no close substitutes. A very large fraction of the sales are used by millions in China and Korea as a traditional medicine, primarily to treat persistent fever.[1] Much horn has also been used for dagger handles in Yemen, which for cultural reasons seems to have few substitutes either. Demand is inelastic and real prices have risen by a factor of six or more since the

[1] Traditional Korean medicine has 16 rhino horn prescriptions, in Taiwan there are at least 15 different horn medicines [Milliken et al., 1993].

This can be accomplished without injury to the animal. Without their horns, there is little reason for poachers to kill rhinos. Fortunately, or unfortunately depending on how one views the problem, rhino horns grow back. Milner-Gulland et al. (1992) first studied the problem, and the idea of using dehorning to deter poaching goes back at least to 1980.[4,5] The results of Milner-Gulland et al. (1992) suggest that since rhino horn is so valuable (at current world prices), poachers would poach rhinos more frequently than resource managers would wish to dehorn them, leading to the probable failure of dehorning as an anti-poaching technique. Of course, it is recognized that even if dehorning wouldn't deter poaching, allowing the legal sale of dehorned rhino horn could still raise considerable funds for rhino protection.

An important feature in the debates about the profitability and efficacy of dehorning rhinos has been a failure to distinguish between the aggregate or macro

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[4] See Milliken et al. (1993) for a discussion and history of the concept. Under the assumption of no poaching risk, Loon and Polakow (1997) assess the profitability of dehorning. Rachlow and Berger (1997) consider horn re-growth in white rhinos, and comment on dehorning intervals from the perspective of profit maximization and as a poaching deterrent.

[5] Naturally, calls for dehorning wild rhinos raises questions about dehorning's impact on rhinos. This has led to a raging debate over the biological implications of dehorning, if any, on rhinos and whether dehorning would actually deter poachers. See Berger et al. (1993); Berger et al. (1994); Loutit and Montgomery (1994); Macilwain (1994); Berger and Cunningham, (1994a,b,c).

impacts of dehorning many rhinos, causing prices to fall and the impacts of dehorning a small population of rhino which would not cause price to fall. The literature, written mostly by non-economists, often has agents like poachers who face local prices acting as if they were the direct suppliers in wholesale markets. To get the story right, there must be both local and world markets, properly connected. Market structure cannot be assumed but must be consistent with observed facts.

We build a rigorously justified economic model of the world market for rhino horn that acknowledges the inelastic demand function for horn, recommends free trade and supplies the market with horn at a price below the opportunity cost of the poachers. Our economic model consists of all the important actors, poachers, African range states, consumers, speculators, and the relevant data that each considers. This model allows us to see the macro impacts of a policy of allowing free trade in rhino horn that is supported by a dehorning effort that is large enough to support world demand at a price low enough to deter poaching.[6] To preview our results, we show that such a policy is in fact very likely to work. Before turning to the model, a few more details are necessary.

Substantial stocks of rhino horn are held by the African range states. Other inventories, relevant for the empirical analysis, are held by speculators located in Asian countries. Speculative stocks are held with the expectation that rhino horn is a non-renewable resource because the population either will continue to decline or horn flows

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[6] See C. Fernandez and T. Swanson for a model with some of these features ["The Role of a Controlled Rhino Horn Trade as a Means to Control Illegal Trade," mimeo, University of Cambridge, November 1994].

from existing stocks will be inadequate to meet demand at current prices. In either case the return on speculative holdings is earned through the expected price rise. If these expectations are not fulfilled, holding speculative inventories at current levels cannot be a good investment. Suppose the African range states can credibly commit to a policy of drawing down their inventories and further augment the flow of horn by dehorning operations. Insofar as these policies have been imperfectly forecasted, the time path of horn prices expected by the speculators is wrong. Price will not rise as fast as they anticipated. Therefore profit oriented speculators will have to adjust to the changed expectations by bringing some of their inventories on the market.

Nor surprisingly, we will show that horn price drops when the African range states behave strategically, and then rises at the rate of interest. The price for the inventory flows is the same for all parties and for this reason we treat the inventories from the range states and Asia as one. For present purposes, we assume that the African states act as *if* they purchased the inventories of the speculators. We could also have assumed that the speculators purchase the inventories of the range states. The policy consequences would be qualitatively the same in either case.

In recent years, managers of rhino populations have cropped their horns to dissuade poachers. Rhino horn cropped systematically adds to the annual supply. Finally, there is a substantial white rhino population whose horn is a perfect substitute for black rhino horn, and it turns out that white rhinos are a far more economical supply of African rhino horn. White rhinos can be dehorned alone, or in combination with black rhinos to keep the market price of horn at a strategically low level.

II. Model

Readers preferring to read an explicit model should turn to appendix 1.

Let us start with inventories, inventories are drawn down by sales and augmented by horn from dead or cropped rhinos. We imagine the African states can act in unity, not in competition. Most of the rhinos are in South Africa, Namibia and Zimbabwe and the inventories currently are held mostly by South Africa and a smaller share is owned by Zimbabwe.

The horn cropping feature is simplified in this analysis. One might treat horn cropping as a maximization problem in which the solution closely resembles the Faustmann approach to determine the optimal time to harvest trees because horn re-grow [Milner-Gulland, et al., 1992]. However, this is not the correct approach in this model because under legal trade with cropping, rhinos are not scarce. In reality, the optimal quantity supplied can be met by minimizing the cost of harvest, achieved by letting the horn grow to its approximate maximum size in about six years. As it turns out, the estimated horn growth function is such that the practical results are insensitive to a reasonable range of dehorning times.

Rhino population dynamics is governed by a logistic growth function [Milner-Gulland and Leader-Williams, 1992] whereby "population grows very rapidly when the population is small, and then the rate tapers off as the population increases". Losses occur as a result of natural mortality and poacher kill. African states and poacher kill both supply the market.

In this model, poachers take on the role of agents and the African authority is the principal. Poachers are assumed to maximize profit in each period by selling their horn.

The poacher is assumed to maximize revenue net of cost taking sales by the African States as known and given. The standard rule follows: poach until marginal revenue = marginal cost. Obviously, if marginal cost is greater than the poacher's marginal revenue because the African states have supplied enough to drive price sufficiently down, then the poachers will be out of the picture.

African States

It is assumed that the African states want to maximize revenues from cropping rhino horn, less cropping costs and the cost of collecting horn from dead rhinos. This specification has the advantage of simplicity without doing much injustice to reality. It is doubtful that the African states possess very strong altruistic attitudes towards the consumers' surplus of foreigners. However, if the African states maximize profit, less horn would be sold which slows the drawdown of horn inventories. That is good. Such a goal will imply higher prices charged and that could be bad for conservation if the higher prices attract poachers into the market. We can offset this outcome by introducing a willingness to pay more to have more rhinos preserved, reflecting the preferences of the rest of the world. Having done this, we have to crop horn strategically to keep horn yield so low that poachers will not have an incentive to enter. The rest of the world, will then have to pay the African countries to keep prices low. Let us see whether the results of the simple objective function are agreeable before pressing for a revision to incorporate world preservation values into it.

A more complete statement of the objective function is to maximize the present value of net willingness-to-pay, using some discount rate.

A Solution

Using standard intertemporal maximization procedures, we obtain two solutions. Case 1, which conservationists hope is empirically true, refers to the solution when inventories and cropping yields are high enough and rhinos grow fast enough so that there is never any poaching, $s_t = 0$. We show in the empirical section that this is true and limit our analysis to Case 1. Case 2 occurs when the supply of horn is inadequate to supply the market at prices low enough to keep poachers out for some periods.

There are two important management regimes for the rhino; the transition period when inventories are being drawn; and the steady state when the flow of rhino horn on the market, obtained from removing horn from rhinos dying naturally and cropped horn, is constant. A discussion of the steady state is a natural starting point.

Steady State

Rhinos start out at the initial low level, B_0, and grow to their steady state level $B^*_{\hat{T}} = \overline{B}$, the carrying capacity, after $\hat{T}$ amounts of time have passed.[7] $\hat{T}$ is routinely solved from the maximization procedure. Remember poaching kill equals zero in case 1. Formally solving the model guides the steady state price which is less than the threshold entry price of poachers, the condition for being in case 1.

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The steady economic state occurs when the flow of horn from natural mortality and from cropping, if necessary, reach a price just below the entry price of the poachers. The steady biological state occurs later, in general. Of course, in the steady state, inventories are a fiction because harvest equals sales. The maximization procedure also confirms standard reasoning that horn will be sold at a price which reflects the marginal cost of cropping horn or collecting it from dead rhinos when these activities occur. Since inventories represent an investment from an economic perspective, the only reason to make such an investment is that the price of sales from inventory must rise at the rate of interest. If this were not true, then the representative investor should divest some inventory and invest the proceeds where they will earn the market rate of interest. We label the annual value of a kg of horn in inventory λ_t and in this model it is the same as the price of horn on the market. Once inventories are exhausted, dehorning is used to supply the market. It is a routine calculation to determine the fraction of rhinos annually dehorned.

III. Data

Much of the data needed to parameterize our model is not available in a form suitable for statistical analysis. This is not due to a lack of interest, as considerable effort has been made by rhino experts to describe all of the facets of the poaching crisis that has decimated rhino populations around the world. It is instead attributable to the fact that the trade in rhino horn has long been illegal, meaning that data has to be covertly acquired. When this is accomplished, the data are typically "best estimates" made by knowledgeable people as opposed to actual records that would support econometric estimation. Before the advent of the trade ban, there were some official records, but these have substantial gaps in coverage, and of course with customs data there has always been strong incentives to under-report sales so as to avoid duties. This does not mean that we can not build a model that represents what is known about the illicit trade in rhino horn. Quite a lot is known about rhino horn trade, but this knowledge is just more qualitative than economists would typically like. Next we describe how we generate parameters for our model. Importantly, despite the fact that there are uncertainties associated with parameter assumptions, the qualitative results of the model are robust.

Population parameters—The intrinsic rate of growth *(r)* for rhinos is estimated to be 0.16.[8] The value of the coefficient which creates asymmetry in the growth function $\alpha = 7$, is estimated by Milner-Gulland and Leader-Williams (1992) drawing on analysis by Fowler (1984). By 1992, the black rhino population had fallen to 3,000 [Leader-Williams, 1992]. A more recent estimate is 2,600 which we adopt.[9]

Estimating the carrying capacity of the rhino population is a place where care and judgment is essential. Carrying capacity is the equivalent of a fixed factor that causes decreasing returns in a production function. In the biological production function for rhinos, the fixed factor is the land which is the source of the food supply. Rhinos actually and potentially are spatially distributed. The population dynamics in one area is

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[8] Milner-Gulland and Leader-Williams (1992), drawing on data in Hall-Martin (1986) and Hitchins and Anderson (1983).

[9] From the International Rhino Foundation, Internet address www.rhinos-irf.org, citing IUCN/SSC African & Asian Rhino Specialist Groups and T.J. Foose, 1998.

independent of the population dynamics in another area. The empirical analysis requires a choice of the number of areas and the size for each one. One provisional solution is the following. From Leader-Williams' (1985) estimate of rhino density at carrying capacity in the Luangwa Valley, Zambia and data on elephant densities and population in that region [Milner-Gulland and Nigel Leader-Williams, 1992, Annex 4], the rhinos at carrying capacity are estimated at 6,700. It is assumed that the goal is to restore black rhinos to a population of 67,000 which approximates the estimated population of 65,000 25 years ago [Berger and Cunningham, 1994c]. Thus we assume that rhinos will be restored in ten separate areas. Increasing the number of areas, shortens the time until the goal is reached. Decreasing the density lengthens the time the goal is reached. Suitable habitat to achieve this goal does not appear to be a binding constraint. Poaching, not habitat removal, is the source of the decline in black rhino population.

Inventories—Estimated stockpiles of horn held by the producing nations were about 3,600 kg based on data collected between 1980-1990 [Leader-Williams, 1992]. An updated estimate, considering additions to inventories by the Natal Parks Board, puts the current level at 5,200 kg.[10]

Stocks of rhino horn held by the consuming countries are less easy to document. Inventories held in Taiwan are estimated to be about 10,000 kg [Nowell et al., 1992]. State medical corporations and manufacturers in China had an estimated 8,500 kg in 1992 and the private sector in China was believed to hold 4,883 kg [Milliken et al. 1993]. If accurate, total world inventories of rhino horn exceeded 25,000 kg in the early 1990's.

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[10] Personal communication with Nigel Leader-Williams 3/31/97.

Over the remainder of the decade, stocks have been drawn down through consumption, but additions have no doubt been made through poaching. Further stocks are probably scattered throughout Yemen, Korea, and the rest of Asia. With this in mind, we use 20,000 kg as a rough estimate for world inventories. The qualitative nature of the results do not hinge on this assumption. If stocks are smaller, then dehorning simply begins earlier, and if stocks are larger, then dehorning can be delayed.

Poacher's reservation price—A potential poacher seeks another income earning activity if the opportunity cost of poaching exceeds the expected benefits from poaching. If a policy lowers the returns from poaching such that the returns are lower than the expected costs, then poaching will cease. So the reservation price (or wage) for poaching rhinos is crucial to our analysis. Unfortunately, it is essentially impossible to come by. Instead, we use simple economic reasoning to suggest a reasonable number for the reservation price for poaching.

There should be relatively free entry into the market for poachers, and therefore poachers will be paid their opportunity costs. These costs will depend upon three main factors: prevailing wages, anti-poaching enforcement, and poaching productivity. Ascertaining prevailing wages in alternative employment seems straightforward enough, at least conceptually. Enforcement consists of two main components that are both hard to estimate: the probability of being caught and the severity of punishment. Punishment can range from fines, to jail time, to death, and the associated opportunity cost depends critically on the value of a poacher's life and risk preferences, neither of which is known. Finally, poaching productivity depends upon the population levels of rhinos, but also may depend upon the population levels of other relevant species such as elephants, and could be affected directly by enforcement as well.

Given the considerations above, we think it unlikely that the poacher's reservation wage can be built up from data on each of the above factors, and instead use estimates of what poachers actually receive when they sell rhino horns to middlemen. This is not without its own difficulties as some poachers are essentially paid wages with a bonus for delivering horn, while others self-organize and are only paid when they sell their horn. It is this latter group that will best shed light on the poachers' reservation wage. There are a number of estimates for the amount poachers receive for delivery of a rhino horn. Using figures from Milliken et al. (1993) we take the 1998 reservation price for rhino poaching to be $140 per kg. [11] Finally, one needs to relate this figure to the Asian wholesale prices upon which our demand curve is based (discussed below). The available evidence

[11] All monetary amounts are in 1998 US dollars. This is the high end of the estimates listed on page 59 of Milliken et al. (1993), which we take to be most likely for a self-organized poaching gang. The low number would not appear to even cover the basic costs of a poaching trip as described for instance by Milner-Gulland and Leader-Williams (1992). Milner-Gulland and Leader-Williams (1992) do parameterize models based on data collected in the Luangwa Valley, Zambia in 1985. Given that we desire numbers that are applicable across a variety of locales, and under different enforcement regimes than were in place in the Luangwa Valley in the early 1980's, we think it more prudent to use informed estimates of the prices that poachers receive for horn, and then consider the sensitivity of our results.

summarized in Milliken et al. (1993) (Table 11, page 60), leads to the conclusion that poachers are probably not receiving more than 40% of the wholesale price. So in terms of wholesale prices, the reservation price is taken to be approximately $350 per kg. in 1998 dollars.

Demand—Wholesale quantities purchased and prices paid by importing countries are available for four principal countries (Japan, Korea, Taiwan and Yemen) for selected years during the 1951-1986 period [Leader-Williams, 1992]. These data include significant gaps, and do not cover the entire world market. Using these data would result in a very significant under-estimate of world demand. The best qualitative estimates are that 8,000 kg. of rhino horn were exported annually from Africa during the 1970's and that this number fell to around 3,000 kg. annually during the early 1980's [Leader-Williams (1992), citing work by Martin]. These numbers are based on biologist's estimates of the number of rhinos poached during the period. To form a crude demand curve, we match these quantity estimates to average wholesale price during the period. Our underlying model is that at any point in time, all quantities traded should be traded at roughly the same price. Assuming that the price of recorded trades were honestly reported, then we can use these prices as an estimate of average prices during the period. Using the weighted average of prices from 1969-71 for Taiwan and Japan, and prices in Yemen from 1980-84 from Leader-Williams (1992), we estimate that 8,000 kg.'s were traded at about $168, and 3,000 kg.'s were traded at a price of $1351 (1998 dollars). Using this information, a simple iso-elastic wholesale demand curve is parameterized as:

$Q = 89160*P^{-.47}$

Cropping—Horn growth is believed [Milner-Gulland, et al., 1992] to follow a von Bertalanffy growth curve used commonly in fisheries literature

$$v(\tau) = \hat{v}\left(1 - \alpha_1 e^{-\alpha_2 T}\right)^{\alpha_3}$$

$\hat{v}$ = 3 kg.

α_1 = 0.8

α_2 = 0.87

α_3 = 3,

where $v(\tau)$ is the horn mass in t years and $\hat{v}$ is the maximum horn mass. The von Bertalanffy growth function captures rapid, smooth growth at first and then the growth tapers off, which the following helpful calculations indicate.

	$v(\tau)$	$v(\tau)/\tau$
τ = 1	.88	.88
τ = 2	1.91	.96
τ = 4	2.78	.70
τ = 6	2.96	.49

The model to be empiricized requires that a choice be made about the fraction of the rhino population to crop annually. Recall that dehorning is a good idea if the price of horn exceeds the cost per kg of dehorning. The estimated cost falls with the number of rhinos dehorned at one time, rhino density, and the experience of the crew [Milliken et al., 1993]. We use the lower estimates in Milliken et al. (1993) as dehorning costs have fallen since the first largely experimental dehorning efforts. This results in a figure of $395 per rhino (1998 dollars). To translate to a per kilo number, we need to know the rotation length. It will turn out that we can use a maximal rotation of 6 years, which for black rhinos yields 2.2 kg. (2.96 kg. times .75 as one can not take the whole horn).[12] For white rhinos, we assume the same basic growth pattern, but they yield more horn at any point in time. Milliken et al. (1993) (page 50) cite work in which 59 white rhinos yielded 240 kg. of horn, or approximately 4 kg. per animal.[13] So at maximum rotation length, the marginal cost of dehorning in per kilo terms is $180 for black rhinos, and $99 for white rhinos (1998 dollars). Therefore, economic considerations dictate that white rhinos should be dehorned before black rhinos. For use in the analysis section, we note that there are currently more than 8,400 African white rhinos (in addition to the 2,600 black rhinos).[14]

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[12] 70%-80% of the actual horn can be taken when dehorning without hurting the animal, as discussed in "Dehorning" by Dr. Mark Atkinson, from the International Rhino Foundation, Internet address www.rhinos-irf.org.

[13] These estimates are sufficient for our purposes. Should the need for a much more detailed analysis arise, Rachlow and Berger (1997) provide von Bertalanffy growth curves for white rhinos for horn size and basal circumference as a function of age for anterior and posterior horns for both sexes.

[14] From the International Rhino Foundation, Internet address www.rhinos-irf.org, citing IUCN/SSC African & Asian Rhino Specialist Groups and T.J. Foose, 1998.

IV. Analysis

Instead of a fully faithful empirical analogue to the formal model in the appendix, in this section we demonstrate that existing rhino populations and horn inventories are adequate to solve steady state demand. We next check the solution for sensitivity to parameter uncertainty and then discuss the results. Our strategy is to find a "steady state" solution, albeit at existing population levels. As stocks build up, horn available from natural mortality will become available and diminish the need for dehorning.

The derivation of the results can be described in the following manner. We first use the demand curve to find the quantity of horn that the world market demands at the poacher's reservation price (or just under the poacher's reservation price). This is the quantity that the African range state cartel must be able to supply in perpetuity in order to deter poaching. The next step is to determine if there are sufficient rhinos to supply the necessary quantity. As rhino populations will grow if poaching ceases, a sufficient condition is that the *current* rhino population is large enough. If it isn't, then one could do the much more complex calculation to check if the population will grow enough by the time the current inventory of horn is exhausted to supply the market with sufficient horn to maintain a price below the poacher's reservation price. Next we check to see if at the poacher's reservation price, there are sufficient rhinos to use the maximum rotation length. If this is the case, then this yields a fixed marginal cost of dehorning. Finally, if the marginal cost of dehorning is less than the poacher's reservation price, then the policy is profitable for the African range state cartel.

First we find the quantity of rhino horn demanded at the poacher reservation price of $350 per kg. (in terms of wholesale prices). The wholesale demand curve yields 5,681 kg. per year. Next we note that if we rotate the available 8,400 white rhinos on a six year rotation, we can crop 1,400 white rhinos per year. This will yield 5,600 kg. per year, leaving just 81 kg. to be supplied by the 2600 black rhinos. Using these numbers, we need to crop an additional 37 black rhinos per year, on a six year rotation. The operation should be profitable as the marginal cost of dehorning the 1,400 white rhinos every year is $99 per kg. and the marginal cost of dehorning the 37 black rhinos is about $180 per year, as compared to a price of $350 per kg. This would yield over $350,000 per year in profits in addition to deterring poaching.[15]

In terms of sensitivity analysis, we see that we could have underestimated the marginal cost of dehorning significantly without affecting the fact that the policy should work. As long as the cost of dehorning is lower than the poacher's reservation price, then the policy is profitable for the African cartel. In terms of uncertainty over the poacher's reservation price, profitability is more sensitive than the ability of the policy to deter poaching. If we have under-estimated the poacher reservation price, then the rhinos are in even in better shape. If we have over-estimated the poacher reservation price, then we need to defend an even lower price, which means delivering even more horn every year. The worst case scenario, which can still be supported by this policy can be found as follows. Looking at the horn growth curve for black rhinos shows that a two year rotation results in maximum yields, of 1.91 kg. per rhino which after taking only 75% of the horn

[15] We do not discuss the transition to the steady state in quantitative terms during which inventories are drawn down. The transition likely is short with demand exhausting inventories in a few years.

yields 1.43 kg. per year. For white rhinos, if we assume the same pattern of growth and scale appropriately we estimate about 2.6 kg. per white rhinos.[16] At current population levels for both species, this will provide a total of 12,779 kg. per year. This would drop the world wholesale price to $62. This indicates that we could very substantially have over-estimated the poacher reservation price without endangering rhinos. Of course at this price, substantial subsidies would be needed to yield the necessary amount of horn.

In terms of demand sensitivity, we are doubtful that demand is much greater than we have used here as it is based on the best estimates of rhino poaching as opposed to incomplete trade records. In fact, we suspect that consumptive demand is much lower, because rhino poaching has been supplying both large stockpiles as well as yearly consumption, and therefore our wholesale demand curve includes both stockpiling and consumption. Milliken et al. (1993) provides estimates of the yearly quantity demanded for China, Taiwan, and South Korea. The low end of the range for these three countries yields 1,158 kilos per year, and the high ends equals 1,891 kilos per year. Adding in the 75 kilos estimated traded in recent years from Yemen [Martin et al., 1997], would yield a total world demand of less than 2,000 kg. For a sense of our conservatism, note that at the recent Yemeni wholesale price of $982 [Martin et al., 1997], our wholesale demand curve suggests that approximately 3,500 kg. would be demanded. The figure from our demand curve is 40 percent larger than sales estimated by rhino specialists. Either real demand is much lower than we are supposing or the real wholesale prices are much

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[16] We could use results from Rachlow and Berger (1997) to derive a more exact estimate.

higher than is reported, but they would have to be off by a factor of two to yield 2,000 kg a year.

It appears that if anything, demand will be lower than indicated by our demand curve. This is excellent news for the policy, and to anyone with concerns about potential biological implications of dehorning. The work of Berger and Cunnigham (1994a) suggests that one should avoid dehorning female rhinos when they are sympatric with predators. If we have over-estimated the level of demand by a fact of two, then roughly speaking, we would only have to harvest horn from half of the currently available white rhinos on a six year rotation. The other half could be left entirely alone. We very likely can avoid dehorning at least some of the white rhinos, and probably all of the black rhinos. As rhino populations grow, a smaller and smaller fraction would have to be dehorned.

So in terms of meeting market demand while deterring poaching, it is clear that we can do so. Further, we can probably achieve this while dehorning rhinos on a relatively long rotation of every six years, while still leaving a large and growing fraction of the population untouched. It also appears likely that significant sums of money could be raised to further support conservation activities.

V. Conclusion

The present policy for preserving black rhinos never has worked for reasons which follow from first principles in economics. The trade ban on rhino horn has driven up the price of horn, making poaching profitable. Moreover, the demand for rhino horn is very unresponsive to price change, because much of the horn is used in traditional medicine. People are not quickly and easily persuaded to change medicines that doctors have prescribed to them and their family for times extending beyond living memory. There is a piece of economic discipline which has explained theoretically and documented empirically the grave difficulty encountered when efforts are made to control demand by legislative fiat. It rarely has worked, and the rhino population bears the loss because of this most recent folly which replaced careful thought and fact with wish, however noble intentions may be.

We propose to save black rhinos by removing the ban on trade in rhino horn and to use the substantial stocks of existing horn inventories plus the cropping of rhino horn to drive down the price of horn.

Drawing on various parameter estimates in the literature, always choosing "conservative" values, we estimate that a wholesale price of $350 per kg (1998 dollars) or the equivalent of $140 per kg received by the poacher is his reservation price. Inventories can be utilized to supply the market at and below this price. Given our conservative estimates of demand and recorded estimates of cropping costs, more than one-third of a million dollars in profit can be earned by cropping under 20 percent of the white rhinos and a handful (37) of the black rhinos, assuming no yield from natural mortality. While there is an obvious biological distinction between white and black rhinos, fortunately there is not an economic distinction in as much as the horn from either species is believed to be equally effective. With insignificant poaching pressures, the black rhino population could grow to more than 11,000 in 10 years time or more than 30,000 in 20 years if there were population concentrations in 10 areas as we have assumed.

If we allow a price low enough ($62 per kg) to generate annual sales of about 13,000 kg, larger than any recorded in the literature, current rhino populations can meet the demand. The costs of cropping will not be covered by sales price so the international community will have to cover the loss in order to save the black rhino. If the contribution is not forthcoming, the policy set forth above will have delayed the extinction of the black rhino. This is better than the current failed policy.

Far more likely, the strategic use of rhino horn inventories to drive out poachers and restore the black rhino population is an extremely attractive experiment with imperceptible downside risk. Its strategic introduction cannot cause more poaching. It will earn badly needed revenues for some of the poorest countries in the world. The results of the policy can be readily monitored because the market is now legal. Illegal markets are difficult to observe accurately. Sales can be tracked and the flows of horn can be adjusted, if necessary, as the accumulating years of observations grow.

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Table 1

Decline of Black Rhino Population[a]

1960	100,000
1970	65,000
1980	14,000-15,000
1984	9,500
1985	6,000
1987	3,800
1991	3,450
1992	2,480
1994	2,162
1998	2,600

[a]Milliken et al. (1993), except for the most recent estimates. The 1994 estimate was obtained in interviews with the rhino specialist group, Mombassa, Kenya, 1994. See footnote 9 in the text for the 1998 estimate.

Appendix I

The model verbally discussed in the text is put more explicitly below.

Let us start with inventories, I, the linchpin of our model. Time subscripts are omitted unless necessary to avoid ambiguity. Inventories are drawn down by sales and augmented by horn from dead or cropped rhinos,

(A.1) $$\dot{I} = -n + (\epsilon_1 m + \gamma v)B,$$

where $\frac{dI}{dt} = \dot{I}$, I_0 known,

n = sales by African states authority,

B = black rhino population,

v = the horn per rhino (in kg) cropped,

γ = the fraction of the rhino population whose horns are harvested annually,

m = the natural mortality rate of rhinos,[17]

ϵ_1 = the horn yield per rhino at death.

Rhino population dynamics is governed by a logistic growth function [Milner-Gulland and Leader-Williams, 1992] less natural mortality *(m)* and poacher kill *(ds)*,

(A.2) $$\frac{dB}{dt} = \dot{B} = f(b) - mB - ds,$$

(A.3) $$f(B) = rB\left[1 - \left(\frac{B}{\overline{B}}\right)^{\alpha}\right], \quad r > 0,\ \alpha \geq 1,$$

r = intrinsic rate of growth,

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[17] Insofar as there is mortality due to cropping, it can be absorbed into the estimate of m.

$\bar{B}$ = carrying capacity,

α = a parameter introduced because of asymmetric growth. Maximum sustained yield does not occur at $\frac{1}{2}\bar{B}$ for black rhinos.

s = total of poacher take (kg) and sales.

d = reciprocal of horn weight per rhino poached.

From these definitions, the quantity *(q)* brought on the market by the African states and the poachers is

$$q = n + s,$$

and the inverse demand function is

(A.4) $$P = g(q).$$

In this model, poachers take on the role of agents and the African authority is the principal. Poachers are assumed to maximize profit in each period by selling their horn. Poacher total revenue is

$$sg(n,s)$$

and the total cost of harvesting s kg of horn is expressed simply as

$$C(s) = cs.$$

The poacher's maximization problem is

(A.5) $$\underset{s}{Max}\ V(s) = sg(n,s) - cs$$

which is solved from

$$\frac{\partial V}{\partial s} = \psi(n,s) - c \leq 0, s \geq 0$$

where $\psi(n,s) = g(n,s) + s\frac{\partial g(\cdot)}{\partial s}$.

The poacher takes n as a known and given in this maximization problem. Whenever marginal revenue, $\psi(n,s)$, is below marginal cost, poaching activity ceases.

African States:

African states maximize the total willingness-to-pay for rhino horn, less cropping costs,

$$G(n,s,B) = \int_0^{n^*} g(n,s)dn - c_1 \gamma B - c_2 Bm$$

where c_1 is the cost of cropping a rhino and c_2 is the cost of collecting horn from dead rhinos. See the text for more explanation.

More accurately, maximize the net present value of willingness-to-pay in (A.6)

(A.6) $$\int_0^{\infty} G(n,s,B)e^{-\rho t}dt,$$

where ρ is the discount rate. The problem is reduced to maximizing the current value of the Hamiltonian,

(A.7) $$\begin{aligned} H = {} & G(n,s,B) + \lambda[-n + (\epsilon_1 m + \gamma v)B] \\ & + \theta[f(B) - mB - ds] \\ & + \mu[\psi(n,s) - c], \end{aligned}$$

with variables λ, θ and μ attached to the inventory, population dynamics and poacher behavioral constraints respectively. The formulation places the African states in the position of a Stackleberg leader. In each period, the African states explicitly account for the impact of their activity on the poachers' optimal behavior.

A Solution:

Key necessary conditions for this analysis are:

(A.7.1) $$\frac{\partial H}{\partial n} = g(n,s) - \lambda + \mu(\psi_n(n,s)) = 0,$$

written as an equality because a continuous interior solution with $n > 0$ is contemplated,

(A.7.2) $$\frac{\partial H}{\partial \gamma} = -c_1 + \lambda v \geq 0, \quad \gamma \geq 0,$$

(A.7.3) $$\dot{\lambda} - \rho\lambda = -\frac{\partial H}{\partial I} = 0,$$

(A.7.4) $$\dot{\theta} - \rho\theta = -\frac{\partial H}{\partial B} = -[-c_1\gamma - c_2 m + \lambda(\gamma v + \epsilon_1 m) + \theta(f'(B) - m)].$$

Assume inventories and cropping yields are high enough and rhinos grow fast enough so that there is never any poaching, $s_t = 0$.

There are two important management regimes for the rhino; the transition period when inventories are being drawn; and the steady state when the flow of rhino horn on the market, obtained from removing horn from rhinos dying naturally and cropped horn, is constant. In the steady state, rhinos start out at the initial level, B_0, and grow to their steady state level $B_{\hat{T}}^{*} = \overline{B}$, the carrying capacity, after $\hat{T}$ amounts of time have passed.[18] $\hat{T}$ is obtained from solving (A.2). Remember poaching kill $= s = 0$.

Since Case I requires an equilibrium without poacher activity because the market price is too low, the poacher's reaction function is non-binding so

[18] Actually rhinos get very close to but do not achieve $\overline{B}$ in finite time.

$\mu = 0.$[19]

Equation (A.7.2) establishes the marginal value of horn,

(A.8) $\lambda^* = c_1 / v$,

assuming cropping in steady state equilibrium. The marginal value of horn, establishes the level of African sales (n*) from (A.7.1)

(A.9) $P^* = g(n^*, o) = \lambda^*$,

The inventory equation (A.1) establishes the fraction (A.8) of the population (B) to harvest annually since

$$n^* = (\epsilon_1 m + \gamma v)B.$$

Holders of stocks of inventory at the end of the transition period will have to receive exactly λ_T per unit otherwise arbitragers will enter to drive the value of inventories toward the market price, P^*. Necessary condition (A.7.2) is used to determine the fraction of rhinos (γ) annually dehorned.

In the steady state, in fact, at all times, the value of μ, the adjoint variable on the poacher reaction function, equals 0 under Case 1.

Having solved for the steady state, the behavior of the system during the transition is straightforward. From (A.7.3),

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[19] When $\dot{\theta} = 0$, from (A7.4) and (A7.3), $\theta = \frac{(\lambda \epsilon_1 - c_2)m + (\lambda v - c_1)\gamma}{\rho - f'(B) + m}$ if there is cropping and $\theta = \frac{(\lambda \epsilon_1 - c_2)m}{\rho - f'(B) + m}$ if there is no cropping. θ is the marginal economic value of a rhino.

$$\frac{\dot{\lambda}}{\lambda} = \rho;$$

and solving to obtain

(A.10) $\lambda_t = \lambda_0 e^{\rho t}$.

Since λ_T has been computed from (A.7.2), λ_0^* is solved from (A.10). The price of rhino horn starts out at λ_0^* and grows at the rate of interest until it hits its steady state value. Inventories are like a non-renewable resource. More sales take place in the early years compared to later, as the inventory stocks are drawn to zero. Note that cropping does not occur while the inventories are being drawn down.