Betting on Extinction: Endangered Species and Speculation

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ABSTRACT. *For a number of animal species, speculators are betting on future price increases by holding large stockpiles of commodities from the animal. We develop a model to explain this behavior. We derive conditions where it can be optimal for a speculator to induce poachers to harvest so rapidly as to make extinction of the species inevitable. Results from a simulation based on the black rhino indicate that ''betting on extinction'' may be profitable for reasonable parameter values. We also find that extinction is favored by low discount rates or high growth rates.* (Q22)

I. INTRODUCTION AND MOTIVATION

An increasing number of wildlife species are endangered because of over-harvesting, habitat destruction, pollution, or a combination of these factors. Because environmental or demographic stochasticity could drive small populations to extinction, ecologists have introduced the minimum viable population (MVP) concept to indicate safety margins for maintaining ''acceptable'' extinction probabilities for a certain time horizon. MVP estimates are misleading, as they fail to incorporate rational responses by economic agents to increasing scarcity. Certain agents may have an incentive to drive species to oblivion, and ''bet on extinction.''

''Betting on extinction'' may be defined as the behavior of a private party holding a private store of a renewable resource in the hope that the combination of ill-defined (or ill-enforced) property rights and high prices will lead to a depletion of *in situ* stocks in the near future. With natural stocks depleted, the investor would then enjoy considerable market power, allowing him to obtain supra-normal profits. For example, *The Economist* (2002, 85) describes a shark-fin trader who ''is so convinced that stocks are collapsing that a few years ago he cornered the market in Norwegian shark fins and stockpiled the result in Japan. He still seems confident that his stockpile will make him a fortune.''

But holding a private stockpile of a valuable species is only the first step. Under certain conditions, it can be rational for a speculator to *actively contribute* to the depletion of the natural stock, speeding up or even triggering the extinction process. This may be achieved, for example, by subsidizing poachers harvesting from the wild, by providing poachers with improved technology, or by blocking conservation efforts. For example, Meecham (1997, 134) writes that ''[m]assive stockpiles of rhino horn have been discovered, along with anecdotal reports from poachers claiming to have been instructed to kill rhinos in the wild whether they have usable horns or not. If the animal becomes extinct, . . . those stockpiles become infinitely valuable.'' Similarly, Kremer and Morcom (2000, 231) cite anecdotal evidence that suggests large-scale killing of wild rhinos (even dehorned ones) increases the value of *ex situ* stocks.[1]

Our goal in this paper is to develop a model that explains these anecdotal observations. We set up and solve a stylized stor-

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[1] Bulte, Horan, and Shogren (2003) suggest an alternative motive for speculators to promote extinction, namely that extinction will trigger the lifting of CITES trade bans.

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age model in Section 2, and apply it to the case of rhino poaching and horn storage in Section 3. Our model is built upon a set of simplifying assumptions to represent the polar-opposite case of the well-known, and equally stylized, model by Kremer and Morcom (2000). Some of our main results run counter to those of Kremer and Morcom, highlighting the importance of considering the (institutional) context before implementing any of the conflicting policy recommendations. Reality is likely somewhere in between our model and Kremer and Morcom's, and may be studied with a much more complex hybrid model. While the discussion and model are cast in terms of competing supplies from private stockpiles and from poachers harvesting endangered species under open access conditions, it is clear that key insights also apply to other settings.[2] The key element is that output from private and common stocks are substitutes on markets where demand curves are downward sloping.

II. A SIMPLE MODEL

Our model includes two types of economic agents. One agent, whom we refer to as the speculator, has a pre-existing stockpile of the resource. All other agents are poachers. Poachers myopically harvest the resource under open access conditions, so that instantaneous profits are always competed away. The distinction between our model and the traditional open-access model is that the speculator can offer a per-unit bribe to poachers so as to induce them to harvest more rapidly. The motivation for offering such subsidies is the possibility that they will lead to sufficiently rapid harvesting as to doom the resource to extinction.

For simplicity, we assume the speculator does not pay poachers to harvest the wildlife for him, so he cannot convert the public stock into a private one. One explanation for this behavior could be that the speculator fears his entire stockpile would be confiscated if he were caught making purchases. Alternatively, our assumption may be consistent with the hotly debated anti-poaching policy of "dehorning" wild rhinos (e.g., Berger et al. 1993; Berger and Cunningham 1994). If a fraction of the wild stock is unexpectedly dehorned, killing living rhinos does not yield a marketable asset to be transferred from the poacher to the speculator.[3] Similarly, there is evidence that the Hudson Bay Company paid fur trappers to decimate the beaver population in Canada during the nineteenth century without acquiring the fur pelts from the harvested animals (Mason and Polasky 1994, 2002). By assuming no private stock accumulation, we effectively bias our results away from profitable betting on extinction by assuming (unexpected) dehorning of the complete wild stock.

For analytical convenience, we assume poachers behave myopically. It is conceivable that a cohort of forward-looking poachers might wish to store some of their harvest, in an attempt to capitalize on future extinction (Gaudet, Moreaux, and Salant 2002). We assume the speculator is insulated from such future competition by sufficient barriers to entry into speculative markets. Such barriers might be formed by set-up costs or asymmetric information, entry deterrence by the incumbent (Mason and Polasky 1994), or by moral or ethical considerations. In this regard, we offer a discussion of the polar extreme case from Kremer and Morcom (2000), who assume instantaneous entry and exit in response to profit differentials, and model all agents as atomistic. It is important to realize that the key element driving our result is not the literal monopoly assumption, but the much less restrictive assumption of market power. For example, the speculator would face a downward-sloping demand curve in a model where a collection of atomistic stockpiling firms created a competitive fringe.

Following extinction, the speculator acts as a monopolist, extracting from his stockpile

[2] A particularly notorious example along these lines might be trade in illegal drugs.

[3] Note that the dehorning exercise should be unexpected. If poachers know in advance that a certain fraction of the wild stock does not carry a marketable product, they will adjust their effort instantaneously so as to preserve zero profits.

in a fashion analogous to an exhaustible resource monopolist. Denoting the speculator's stock at time t as R_t and the rate of sales from that stockpile as y_t, his stockpile evolves according to:

$$\dot{R}_t = -y_t. \qquad [1]$$

An individual poacher's total harvest costs, $c(x, S)$, are declining in the *in situ* resource stock, S, and increasing in the harvest level, x. The marginal cost of harvest is positive and non-decreasing. Poachers' revenues may come from two sources: market-based revenues and speculator subsidies. Inverse demand for the commodity is denoted $p(Q)$, where Q is aggregate supply. Harvested and stockpiled commodities are perfect substitutes so that aggregate supply is the sum of aggregate poacher harvests, X, and any sales from the speculator's stockpile ($Q = X + y$). The per-unit bribe paid at time t is b_t.

Individual poacher's harvests are profit maximizing, so that marginal cost is equated to average revenue (the sum of price and the per-unit bribe):

$$p(Q_t) + b_t = \partial c(x_t, S_t)/\partial x_t. \qquad [2]$$

If costs are linear in harvest, so that marginal cost is constant, then the individual poacher's optimal harvest is not determined (though aggregate harvest would be). If marginal costs are increasing, then the individual poacher's optimal action is well-defined for any combination of price and stock. In turn, this relation induces a supply curve for poachers, which determines aggregate harvest. Because of the open-access condition, aggregate harvests adjust at each instant so as to make the typical poacher's costs equal to its revenues:

$$[p(Q_t) + b_t]x_t = c(x_t, S_t). \qquad [3]$$

Equations [2] and [3] imply that each poacher operates where marginal cost equals average cost (i.e., minimum efficient scale). Whether marginal costs are constant or increasing in harvest, equating average and marginal costs ensures that a poacher's optimal harvest level is uniquely determined by stock size, that is, $x_t(S_t)$ solves $c(x_t, S_t)/x_t = \partial c(x_t, S_t)/\partial x_t$. This common level of marginal and average cost, $c(x_t(S_t), S_t)/x_t(S_t)$, is thus determined by stock; we write it as $c_a(S)$.

In either case, the equilibrium conditions for poachers determine equilibrium instantaneous aggregate harvest as a function of natural stock, speculator sales and any bribe the speculator offers, which we write as $X^*(S, y, b)$. For any combination of subsidy and speculator sales, there is a non-negative minimum economically viable population, $\hat{S}$. Based on the discussion above, we note that

$$p(X^* + y) = c_a(S) - b, \qquad [4]$$

for $S \geq \hat{S}$. For stocks below, $\hat{S}$, $X^*(S, y, b) = 0$.

We assumed above that an increase in the *in situ* stock leads to lower costs for a given level of harvest. It seems natural to regard an increase in natural stock as akin to an increase in productive capital within the neoclassical framework. Under this interpretation, an increase in the *in situ* stock shifts the individual poacher's marginal cost and average cost curves down, thereby lowering unit cost at minimum efficient scale. Accordingly, $c'_a(S) < 0$. It follows from equation (4) that $\partial X^*/\partial S > 0$ for values of S such that $X^* > 0$.

The *in situ* resource stock adjusts over time in the usual fashion, with the rate of change equal to recruitment less total harvest, where recruitment is given by $g(S)$:

$$\dot{S} = g(S) - X. \qquad [5]$$

There is a critical mass or MVP, $\underline{S} > 0$, such that $g(\underline{S}) = 0$ and $g'(\underline{S}) > 0$. There is also a larger value of stock, $\bar{S}$, referred to as the carrying capacity of the resource, with $g(\bar{S}) = 0$ and $g'(\bar{S}) < 0$. For levels of the resource between the MVP and the carrying capacity, recruitment is a positive, strictly concave function of stock. One of the main points we will develop is that the speculator may prefer a time-path of subsidies that forces the natural stock below $\underline{S}$, even though stock would not fall so low in the absence of any subsidies.

The speculator chooses subsidy and extraction rates to maximize the present value of net benefits over time:

$$\underset{y,b}{\text{Max}}\ PVNB = \int_0^\infty [p(X + y)y - bX]e^{-rt}dt$$
$$s.t.\ \dot{S} = g(S) - X;$$
$$\dot{R} = -y;$$
$$p + b - c_a(S) \leq 0;\ X \geq 0;$$
$$[p + b - c_a(S)]X = 0$$

The current value Hamiltonian for the speculator's problem is:

$$H = p(X + y)y - bX + \gamma[g(S) - X] - \mu y + \lambda[p + b - c_a(S)], \quad [6]$$

where γ and μ are the co-state variables on the *in situ* stock and private stockpiles, respectively, and λ is the Lagrangean multiplier on the poacher participation condition.

To describe the solution to the speculator's problem we first identify the marginal impact of a change in the two control variables upon the present value Hamiltonian:

$$\partial H/\partial y = p - \mu + (y + \lambda)p' + (\partial X/\partial y)[(y + \lambda)p' - b - \gamma]; \quad [7]$$

$$\partial H/\partial b = \lambda - X + [(y + \lambda)p' - b - \gamma](\partial X/\partial b). \quad [8]$$

In addition to these effects, we note that the speculator's choices may be constrained by the aggregate behavior of poachers, as described by equations [9] and [10]:

$$\lambda \geq 0;\ [p + b - c_a(S)] \leq 0;\ \lambda[p + b - c_a(S)] = 0;\ \text{and} \quad [9]$$

$$[p(X + y) + b - c_a(S)]X = 0. \quad [10]$$

We start by considering equation [7], the implications of which depend on whether or not the zero profit condition is binding. Since a state variable is fixed at any instant, $c_a(S)$ is also fixed. At any instant where the zero-profit condition binds, $p + b = c_a(S)$; accordingly, any changes in y and X must exactly offset: $\partial X/\partial y = -1$. It follows that equation [7] reduces to

$$\partial H/\partial y = p + b - \mu + \gamma, \quad [7']$$

in this case. Observe that the right-hand side of equation [7′] is invariant with respect to y. If this expression is negative, the speculator chooses the smallest possible value of y, namely $y = 0$. If this expression is positive, the speculator chooses the largest possible value of y. As the context of this particular thought experiment is the range where $p + b$ is fixed, the largest possible value of y would be the value that forces poachers to stop harvesting. That is, when $\partial H/\partial y > 0$ the optimal value of y is the level of y where $p(y) + b = c_a(S)$ (whence $X = 0$). Thus, either poachers or the speculator are inactive when the zero profit condition binds: $y = 0$ or $X = 0$.[4]

If $p + b < c_a(S)$, then it follows that $X = \partial X/\partial y = 0 = \lambda$. Equation [7] then reduces to:

$$\partial H/\partial y = p(y) + p'(y)y - \mu. \quad [7'']$$

The speculator's optimal harvest would then set the right-hand side of equation [7″] equal to zero, which yields the traditional Hotelling (1931) result: the speculator extracts from his stores such that marginal revenue is set equal to the shadow price of remaining reserves.

Next, we turn to a discussion of the optimal subsidy. Again we consider the two cases: $X = 0$ and $p + b < c_a(S)$, or $X \geq 0$ and $p + b = c_a(S)$. In the first case, all the terms in equation [8] fall out, so that the

[4] It is possible that the shadow prices and cost function are such that $c_a(S) - \mu + \gamma = 0$. In this case, the optimal value of y is not defined, so we cannot rule out the potential for both speculator and poachers to operate at that point in time. If such a combination were to obtain for only a moment, nothing of importance is lost by ignoring this possibility. If such a combination were to obtain for a period of time we would have $c_a'\dot{S} - \dot{\mu} - \dot{\gamma} = 0$, which along with the necessary conditions for the co-state variables that we describe below, indirectly determines the optimal y at each moment along this part of the solution path. But the resulting condition is not a function of R, and so either the singular solution does not exist or it is not uniquely determined. We therefore ignore this possibility in what follows.

speculator is indifferent between all levels of b. Accordingly, it is (weakly) optimal to pay no subsidy, and so we will assume $b^* = 0$ in such instances. Next suppose that $X = 0$ and $p = c_a(S)$. Offering a bribe would induce entry so that $X > 0$, in which case $y = 0$ is optimal. Accordingly, the speculator strictly prefers $b = 0$ over all other subsidies; $b > 0$ would not yield an equilibrium outcome. It follows that $b^* = 0$ whenever $y > 0$.

Now consider the case where $X > 0$, so that $y = 0$ and $p + b = c_a(S)$. Total differentiation of equation [4] then yields $X/b = -1/p'$. Inserting into equation [8] and collecting terms, we then have:

$$\partial H/\partial b = -X + (b + \gamma)/p' = 0. \qquad [8']$$

The co-state variable γ reflects the speculator's value of a marginal increase in S. Because such an increase in S lowers c_a it must negatively impact the speculator. Thus, γ must be non-positive, and can be interpreted as a nuisance value. Either the speculator must wait longer for the *in situ* stock to be eliminated or else he must extract faster (so as to use up his reserves before poachers start to produce). The latter case results in a smaller stream of prices and hence a smaller discounted value.

For any positive value of X, it is possible that γ is smaller than (i.e., more negative than) X'_p. If so, the optimal subsidy is positive:

$$b^* = X'_p - \gamma. \qquad [11]$$

Otherwise, the optimal subsidy is nil. A positive subsidy will only be offered when the existence of the wild stock and associated poaching activities sufficiently reduces the speculator's discounted profits. In this case, the speculator will forgo current sales (i.e., $y = 0$) and will instead subsidize poachers. He does so either to drive the wild stock below $\hat{S}$ but above $\underline{S}$, so as to obtain a temporary monopoly, or to drive the wild stock below $\underline{S}$ (whence extinction becomes inevitable), so as to obtain a permanent monopoly. Subsidizing the harvest of the species to extinction is profitable if the nuisance value of the wild stock $|\gamma|$ is sufficiently high.

At the other extreme, if the potential competition by poachers does *not* create sufficient losses for the speculator to warrant offering a subsidy, the speculator may temporarily force poachers out of the market by driving price down. Along such an optimal path, the speculator times his sales so that $p + b < c_a(S)$ and $y(t)$ is governed by [7″].[5]

In addition to the conditions for optimal y and b, and the conditions characterizing poacher behavior, the solution is governed by equations [1] and [5], and the equations of motion for the co-state variables

$$\dot{\mu} = r\mu; \qquad [12]$$

$$\dot{\gamma} = [r - g'(S)]\gamma + (\partial X/\partial S)[(b + \gamma) - (y + \lambda)p'] + \lambda c'_a(S). \qquad [13]$$

Equation [12] is the usual rule indicating that the shadow price of a non-renewable resource must appreciate at the rate of interest. When $y > 0$ and the zero profit condition does not bind, then equations [12] and [7″] indicate that the speculator's marginal revenue should rise at the rate of interest. When the zero profit condition does bind, neither the speculator's marginal revenue nor prices are required to rise at the rate of interest.

To better understand equation [13], consider first the case where $X > 0$ and $y = 0$. In this case we must have $\partial X/\partial S = c'_a/p'$ (which is positive). It follows that equation (13) reduces to

$$\dot{\gamma} = \gamma[r - g'(S)] + (c'_a/p')(\gamma + b). \qquad [14]$$

If the optimal subsidy is nil, equation (14) reduces to

$$\dot{\gamma} = \gamma[r - g'(S)] + (c'_a/p')]. \qquad [14']$$

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[5] It is conceivable that the left-hand side of equation [7′] vanishes for a period of time, in which case the optimal value of $y(t)$ must be determined indirectly from equation [1]. In this scenario, the optimal program would satisfy $c_a(S) - \mu + \gamma = 0$ for a period of time, which then implies $c'_a\dot{S} - \dot{\mu} - \dot{\gamma} = 0$. But this resulting condition is not a function of R, so that one cannot determine the optimal path of y. We therefore ignore this solution in what follows.

When the optimal subsidy is positive, combining equations [11] and [14] yields

$$\dot{\gamma} = \gamma[r - g'(S)] + Xc_a'. \qquad [15]$$

We implicitly define $\tilde{S}$ by $g'(\tilde{S}) = r$. Recalling that $\gamma \leq 0$ and $c_a' < 0$, it is apparent that $\dot{\gamma} < 0$ for values of $S \geq \tilde{S}$. As stock levels shrink below $\tilde{S}$, the first term on the right-hand side of equation (15) becomes positive. Thus, at some value $\tilde{\tilde{S}} < \tilde{S}$, $\dot{\gamma} = 0$. If the *in situ* stock was to fall below $\tilde{\tilde{S}}$, $\dot{\gamma}$ would become positive, reducing the incentive for the speculator to bribe poachers. Eventually, at some positive stock S^*, the subsidy scheme will be phased out or aborted. Removing the subsidies triggers immediate exit by poachers, setting the stage for a subsequent phase where the speculator can behave as a monopolist. If the sequence of bribes has driven the *in situ* stock below MVP, the species is doomed to extinction and so the speculator will be the only supply source of supply in the future. If the in situ stock has not been driven below MVP at the moment that bribes are suspended, the speculator's monopoly phase will be temporary. The length of this monopoly interval and the maximum price the speculator can charge during this phase depend on initial stock values, price and growth parameters, and on the magnitude of the prior cull.

Consider next the case where the speculator chooses $y > 0$ and $b = 0$, whence $X = 0 = \partial X/\partial S$. If the zero profit condition is non-binding, so that $\lambda = 0$, equation [13] reduces to

$$\dot{\gamma} = [r - g'(S)]\gamma. \qquad [16]$$

This scenario would be consistent with a program where the speculator elects to exhaust his stockpile prior to the start of poacher harvest; we refer to this as the ''dumping strategy'' in the discussion below. It is also consistent with a scheme where the speculator bribes poachers to drive *in situ* stock below $\hat{S}$, so that poachers cease harvesting. In either event, if, $S < \tilde{S}$, then γ becomes less negative over time. If *in situ* stock has been reduced to a level where extinction is inevitable, that is, $S^* < \underline{S}$, it will never pay poachers to harvest. On the other hand, if parameters are such that $\underline{S} < \tilde{S}$, then for values of S^* between $\underline{S}$ *and* $\tilde{S}$ both *in situ* stock and γ will be growing. In this latter case extinction does not result, but the speculator will still enjoy a period of monopoly profits. Because *in situ* stock is growing in this scenario, at some point poaching will become economic again; at that some juncture the speculator will cede production to poachers. We refer to this scenario as the ''near-extinction'' scheme in the discussion below.

If γ does not equal zero in each period, then at some point it becomes optimal for the zero profit condition to bind; otherwise, the speculator could raise prices in previous periods and earn more revenues. If the zero profit condition becomes binding, the speculator would then choose to supply just enough to crowd out poachers (that is, where $p(y) = c_a$), and equation [13] reduces to

$$\dot{\gamma} = [r - g'(S)]\gamma + c_a'[(\gamma/p') - y]. \qquad [17]$$

This case corresponds to a corner solution, and the derivative dX/dy is discontinuous. It does not pay the speculator to expand y such that the profit constraint is no longer binding, and accordingly we know from equation [7″] that $p + yp'$ (= MR) $\leq \mu$. On the other hand, it does not pay to reduce y, which would induce poachers to start selling, and so we know from equation [7′] that $p + \gamma \geq \mu$. Combining these remarks, we find that $\gamma \geq yp'$; moreover, equality could only occur for an instant, so that there will be a finite interval of time where $\gamma > yp'$. Therefore, γ tends to zero more slowly when the zero profit condition binds but the speculator selects its harvests so as to preempt harvesting by poachers. Since μ is increasing exponentially, eventually $p + \gamma < \mu$; at the instant where this first occurs the speculator would drop its sales to zero, and leave the market entirely to the poachers. Since the speculator's stockpile has value, the optimal path must be such that his stockpile is exhausted at the precise moment where this entry takes place.

In summary, under the speculator's optimal program, either the speculator or poachers supply the commodity to the market, but not both at the same time. The optimal path our speculator follows is quite different from the various ''non-strategic'' equilibrium conditions derived by Kremer and Morcom, where price-taking individuals can freely enter and exit the storage sector and accumulate private stocks by drawing down public ones.[6] The speculator may deter poachers' participation by depressing prices (carefully timing his sales rate) or by depressing *in situ* stocks through temporary subsidization (possibly to the point where extinction is inevitable). The speculator prefers the strategy that delivers the larger net present value; his optimal strategy depends on the initial *in situ* stock and his initial stockpile, as well as cost and demand parameters and interest rate. The speculator therefore compares two strategies. First, private stocks may be exploited without subsidizing poachers to drive the natural stock down; we refer to this as the ''dumping equilibrium'' During the dumping phase, wild stocks will gradually increase in abundance; at the moment where *in situ* stock has become large enough to make poaching economic the speculator exhausts his stockpile. Second, the speculator may subsidize poachers; there are two variants of the subsidy scheme. Wildlife stocks can be subsidized to extinction ($S^* < \underline{S}$) or near-extinction ($\underline{S} < S^*$). If wild animals are hunted to the point where extinction is inevitable, the speculator will become a monopolist immediately after he withdraws the subsidy. The near-extinction strategy is subtler. In this scenario, the speculator bribes poachers to reduce wild stocks but determines that it is optimal to terminate subsidies before extinction is assured. After the subsidy scheme is lifted, all poachers exit and the speculator enjoys a temporary monopoly. Eventually, as the wild population recovers, poachers will start harvesting again at which time the speculator leaves the market to the poachers. While the near-extinction strategy entails lower subsidy costs than the extinction strategy-fewer animals have to be killed in early periods-it poses restrictions on the timing of supply from private stocks because of the threat of future production by poachers.[7]

III. EMPIRICAL ILLUSTRATIONS: BETTING ON BLACK RHINO EXTINCTION

In this section we provide a numerical example to illustrate the potential profitability of betting on extinction. This example is loosely based on the case of the black rhino. We consider this particular case because there is evidence of speculation; in addition, there is some data with which we can calibrate the model (Millner-Gulland and Leader-Williams 1992; Brown and Layton 1998, 2001). Private parties, mainly in Asian countries, have stored large quantities of rhino horn over the past few decades. In the recent past, rhino horn prices have increased six-fold since the mid 1970s—more than enough to compensate for the lost interest. Since then, the wild population of black rhinos has collapsed from 65,000 animals to just about 2,500 rhinos at present. Although legal trade in rhino horn has been banned since 1977, a lucrative and well-established underground trade still exists and is the leading cause of the species' demise. Currently, private stockpilers hold larger quantities of black rhino horn *ex situ* than wild stocks carry *in situ*; Brown and Layton (1998, 2001) suggest these ex situ stocks are about 20,000 kilograms.

Following Brown and Layton, we define a (skewed) logistic growth function $F(S) = 0.16S[1 - (S/100{,}000)^7]$, where S is measured in number of rhinos. Next, we shift the growth function down by a constant so that it intersects the horizontal axis at 100 rhinos; Primack (1998) suggests that this is a reasonable estimate for MVP. Including an MVP of 100 in this manner implies a growth function $g(S) = F(S) - F(100) = F(S) - 16$.

[6] Kremer and Morcom also indicate competitive speculative markets can result in extinction if speculators believe that extinction will be the equilibrium outcome. We discuss this below.

[7] In terms of the theoretical model above, near-extinction can only be optimal when the *in situ* stock has been driven below $\tilde{S}$ and the optimal subsidy becomes zero at a stock level above $\underline{S}$. For the rhino case study below, it turns out that this condition holds for intermediate interest rates, so that near-extinction can be optimal.

Data on supply and rhino horn prices are difficult to obtain since the trade moved underground in the late 1970s. However, Brown and Layton suggest that 8,000 kilograms were traded at \$168/kg and 3,000 kilograms were traded at \$1,351/kg. Assuming an inverse demand curve of the form $P(Q) = be^{-aQ}$, we obtain the demand parameters $a = 0.0004$ and $b = \$4,800$ from Brown and Layton's observations.

If we interpret the recent stabilization of rhino population at 2,500 animals as a sign that the dynamic system has reached a new steady state, then replenishment of the rhino population exactly equals harvesting. It is straightforward to calculate $g(2,500) = 384$. We assume each rhino carries 3 kg of horn, so that 384 animals yield 1,152 kg of rhino horn. Using the demand specification above, we obtain $P(1,152) = \$2,950$. Brown and Layton argue that poachers receive about 37% of market price for rhino horns; accordingly, and since poachers receive zero profits, we assume unit harvesting costs are \$1,100. The initial value of the *in situ* stock is set at 7,500 kg, while the speculator's initial stock of rhino horns is 20,000 kg. Finally, we assume that harvest costs are of the form $c(x, S) = cx/S$, which can be thought of as a Schaefer-style relation.

In Table 1 we present the net present value (NPV), in millions of dollars, associated with the two potentially optimal strategies for the speculator at various interest rates. The second column shows the NPV from the subsidy scheme, in which poachers are optimally bribed. This value represents the discounted flow of monopoly profits less the discounted flow of subsidies. This subsidy cost might be considerable. At an interest rate of 8%, for example, the discounted flow of bribes associated with the optimal program (which draws the *in situ* population to just below the minimum viable population of 100) is \$2.40 million. Likewise, at an interest rate of 12%, the discounted flow of subsidies associated with the optimal program costs the speculator \$2.24 million; in this case, the *in situ* population is not drawn down below 100, so the speculator only enjoys a temporary monopoly. Despite the fact that the requisite subsidies are smaller with near-extinction, for low discount rates (below 8%), subsidizing to extinction generates profits in excess of those generated in the near-extinction variant. The reason is that the speculator wants to spread his supplies over longer periods when he applies a low discount rate, which effectively makes near-extinction unattractive because of the ultimate participation by poachers. This imminent re-entry places a restriction on the time path of prices; by subsidizing to absolute extinction, this restriction does not exist.

The third column shows the NPV from the dumping equilibrium, in which the speculator draws down his stocks prior to the start of poacher activity. In the dumping scheme, the speculator draws down his private stores, keeping price below the level that would induce poachers to become active. With this program, rhino populations recover, thereby setting the stage for poachers to start harvesting. As private stores are depleted, the *in situ* stock rises to a level where it becomes profitable for poachers to harvest wild ani-

TABLE 1
NUMERICAL ANALYSIS OF BETTING ON RHINO EXTINCTION[a]

Discount Rate (in percent)	Subsidy Scheme (NPV)	Dumping Equilibrium (NPV)	Net Gain from Subsidies
4	42.9	28.0	14.9[b]
8	32.0	24.8	7.2[b]
12	25.9	22.3	3.6[c]
24	17.1	17.1	0

[a] Net present values and net gain in millions of dollars.
[b] Extinction is optimal.
[c] Near-extinction is optimal.

mals. At the moment this occurs, the speculator completely depletes his stockpile.

The fourth column shows the net gains from the subsidy strategy, which equals the difference between the entries in the third and second columns. It is evident that bribing poachers so as to drive *in situ* stocks down is profitable for a wide range of discount rates. Offering a sufficient time path of bribes so as to obtain a permanent monopoly—betting on extinction—is profitable for a plausible, although narrower, range of discount rates (up to 9%). Again, the intuition for the key role played by the discount rate is obvious. When discount rates are high, future monopoly rents are less important relative to current subsidies, depressing the return to the ''subsidy strategy.'' In addition, at low interest rates the optimal period of time until private stocks are exhausted is considerably longer under the optimal subsidy scheme than in the dumping equilibrium (30 years, as opposed to 8 years, at 4%). The ability to draw out his sales over a longer period of time allows the speculator to supply less, and thereby charge a higher price, in each period. However, the optimal period of time until private stocks are exhausted under the subsidy scheme falls dramatically as interest rates rise. Ultimately, the difference in optimal time to depletion between the subsidy scheme and the dumping equilibrium disappears altogether (e.g., the optimal time to depletion is 7 years under both approaches at 24%).

Based on these results, we conclude that betting on extinction can be a profitable strategy if the speculator is sufficiently patient. Even though a stable zero-profit bioeconomic equilibrium above the MVP would exist in the absence of speculator's intervention, extinction is a legitimate possibility when the speculator's perverse incentives are accounted for.

When stockpilers care about conservation of rhinos and are willing to forego some profits to achieve that objective, it has been argued that ex situ stocks of rhino horn may be used to promote rhino conservation (Brown and Layton 1998, 2001; Fernandez and Swanson 1996). We demonstrate the exact opposite: private stocks and profit maximizing investors may trigger rhino extinction. Our finding suggests that stored commodity could be a liability for conservation rather than an asset, when used strategically by the stockpile owner. This result reenforces Kremer and Morcom (2000), who argue in the context of non-strategic interaction that stable or rising wild stocks ''may be vulnerable to a switch to an extinction equilibrium'' (p. 231). Explicitly incorporating stores and speculators thus reverses the insights of traditional renewable resource models, and suggest the rhino population is far from safe.

This brings us to a pair of interesting and perhaps counterintuitive results. In our model, extinction of the endangered species is more likely the higher its intrinsic growth rate. The reason is that a high intrinsic growth rate undermines the potential optimality of the near-extinction strategy: cull a population today and they are back tomorrow, waiting to be culled again at considerable cost. This finding contrasts sharply with conventional bioeconomic models, where rapid growth typically enhances species' abundance (Clark 1990). In such models, a high growth rate implies that the marginal return to leaving a unit of the species *in situ* is high, suggesting that the species is an attractive asset in the decision maker's portfolio (Swanson 1994). The current model is different because speculators do not reap the benefits from investing in rhino conservation. Indeed, quite the opposite is true. From the speculator's perspective, living and growing rhino populations foster competition and are considered a nuisance (Rondeau 2001). More rapid recovery of the wild stock from any arbitrary S^* undermines the profitability of the 'near extinction strategy' because re-entry occurs sooner. Therefore, the additional benefits of lowering S^* below $\underline{S}$ are larger as the intrinsic growth rate is increased, which makes extinction more likely.

A similar story holds with respect to the discount rate. Conventional wisdom implies that high discount rates discourage investments in wild stocks and thus promote extinction (Clark 1990). Not so when we account for the incentives of speculators. We find that the extinction probability decreases for higher discount rates. The reasons are twofold. First, when discount rates are very low, betting on extinction might pay because the gains in future benefits more than compensate for the required current subsidies (Table 1). Under the dumping strategy the benefits are realized up front, which is favored with high discount rates. In contrast, with subsidizing to extinction, the costs are immediate and the benefits are realized in the future. In other words, ''extinction'' compares favorably to ''dumping'' when discount rates are low. In addition, low interest rates are detrimental for conservation because they undermine the relative profitability of the near-extinction version of the subsidy scheme. Because the optimal depletion time of the private stockpile increases as interest rates fall, re-entry by poachers before the private stock is drawn becomes more of an issue (for any S^*). To circumvent this possibility, the speculator would need to lower the time path of prices, which would tend to reduce the PDV associated with the near-extinction scheme. The speculator therefore has an incentive to drive stocks below MVP to avoid costly future competition, thereby ensuring extinction.

IV. CAVEATS AND EXTENSIONS

While instructive, the analysis we have presented so far does rely on two restrictive assumptions: that the speculator does not acquire the harvest for which he offers bribes; and that the speculator does not face competition from other potential stockpilers. As we noted above, the first of these assumption diminishes the case for stockpiling. Nevertheless, one can easily imagine a model whereby the speculator acquires harvests for a period of time. In such a model, the control variable y, representing sales from the stockpile, would be replaced with a variable representing net sales. A plausible implication of such an adjustment to the model would be that there is a period of time wherein the optimal level for this new control variable would be negative, representing a period of net acquisitions. That said, the fundamental insights of the story told in this paper seem likely to go through: for appropriate combinations of exogenous parameters (initial levels of R and S, cost and demand parameters, and interest rate), it will pay to drive the population of the species to the point where extinction is inevitable, after which the speculator can enjoy supra-normal profits based on his position as the sole vendor of an exhaustible resource.

The second issue is not so easily resolved. Adapting the model to allow for a competitive fringe would seem like a relatively straightforward task. Within such a model, we conjecture that there would again be conditions under which the speculator has an incentive to induce the species to be harvested to the point where extinction is inevitable. After that, it seems most likely that the speculator would be forced to withhold his sales until the fringes' stockpiles are exhausted, at which time he could commence selling.[8] In general, one could imagine a model where a small number of large stockpile holders compete on output markets, each earning lower profits than a monopolist would. As each of these agents would recognize his ability to influence market price, the model would entail non-cooperative interaction among the agents, so that the analysis would require solving a differential game. While such a scenario is undoubtedly more realistic than our model of monopoly behavior, it is far more complicated than the model we analyzed; indeed, analytically deriving equilibrium strategies can be extremely complex (Withagen, Groot, and de Zeeuw 1992 Mason and Polasky 1997; Groot, Withagen, and de Zeeuw 2002). Moreover, the fundamental economic ingredients remain: when speculators have some ability to influence market price and can induce more rapid harvesting by poachers by offering bribes, it can pay them to drive the natural stock to extinction.

Our basic model could also be extended by allowing some agents to hold stockpiles for their own private use. Indeed, Brown and

[8] While the fringe is actively selling, price must rise at the rate of interest; while the speculator sells, marginal revenue rises at the rate of interest. Unless demand is iso-elastic the latter leads to a slower increase in prices, inducing fringe members to liquidate any remaining stocks. It would therefore seem that the speculator is forced to wait until the fringes' stockpiles are completely exhausted.

Layton indicate that clinics and medical corporations have stockpiled large quantities of rhino horn in the past, and it seems implausible that these agents have stockpiled for speculative purposes (recall that rhino horns have medicinal uses). Simulations patterned after such an extension suggest that while the scope for betting on extinction is reduced as the speculator's share of privately held stocks gets smaller, it does not vanish for realistic values.[9] Similarly, increasing the initial level of the natural stock lowers the incentive to bet on extinction, but does not eliminate it for reasonable parameter values.[10]

As a final point, we note that harvesting to extinction need not require any market power at all. Perhaps the promise of future scarcity rents would be enough to induce competitive firms to sharply increase current harvest, thereby dooming the species to extinction. Indeed, this is one of the themes in Kremer and Morcom (2000). What Kremer and Morcom do not consider is the possibility that heterogeneous behavior might emerge, whereby some firms harvest for sales while others harvest to stockpile, and the implications of such heterogeneity. A sketch of such a model might be along these lines: Suppose that firms face upward-sloping marginal-cost curves and that entry is sticky, so that temporary profits are possible. At time zero existing firms make a discrete decision to stockpile or not; if they elect to stockpile they pay a (sunk) set-up cost. Then the evolution of natural stock would depend on the rate of entry, exogenous demand and cost parameters, and the number of firms that choose to stockpile. The more firms that choose to stockpile, the better it is to choose to stockpile; if enough firms elect to stockpile then all firms could earn positive profit flows associated with the Hotelling scarcity rents. On the other hand, if too few firms elect to stockpile it doesn't pay anyone to stockpile. Accordingly, two equilibrium paths could exist: one leading to the traditional bioeconomic steady state, and one with speculation and extinction; which path is selected depends on both history and expectations (Krugman 1991).

V. CONCLUSIONS AND RECOMMENDATIONS

Wildlife commodities harvested in nature and those sold from either private stores or farms (captive breeding) compete on output markets. When private supply is concentrated in the hands of a few speculators, such investors may find it in their interest to promote extinction of wild stocks, either by subsidizing poachers, as modeled in this paper, or by providing them with improved technology. Alternatively, game wardens may be bribed or conservation efforts may be blocked. After extinction of wild stocks, speculators can act as monopolists and earn monopoly rents. Our results indicate that there are conditions under which "betting on extinction" can pose a real threat to conservation of certain rare species.

The policy implications of the model run counter to some existing insights. While Kremer and Morcom (2000) and Brown and Layton (1997, 2001) consider *ex situ* stockpiles of wildlife commodities to be assets that could be strategically used to enhance conservation, we point out that they are potentially dangerous liabilities when in the hands of profit-maximizing individuals. Therefore, from a conservationist perspective it makes sense to promote the transfer from such stocks from private to public parties, either through confiscation or purchase. Finally, in an interesting twist to the analysis above, we note that there are conceivable

[9] Specifically, we altered the simulations by lowering the speculator's initial stockpile to 10,000 kg. The results from such a simulation show that subsidizing dominates dumping for discount rates below 19% (as opposed to 22% for the simulations reported earlier). Further reducing the cartel's stock to 5,000 kg implies this critical discount rate falls to 13%.

[10] In this variation of the simulation analysis, we raised the initial stock to 11,000. One interpretation of this change is that black and white rhinos are aggregated into one stock (Brown and Layton indicate a population of 8,400 white rhinos exists). The extra costs involved with harvesting the aggregated rhino stock (reducing the new initial stock of 11,000 animals to the old initial stock of 2,600 animals) amount to $ 2.1 million. While this extra cost surely reduces the incentive to bank on extinction, it is clear that the incentive does not disappear.

cases where the interests of conservationists and speculators run parallel. Speculators only care about restricting supplies from the wild, and presumably are equally happy with a well-enforced harvest (or trade) ban as with extinction. When public agencies can commit to strict conservation, the incentive to bet on extinction evaporates.[11]

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[11] This discussion is based on the presumption that it is socially preferable to prevent extinction. In a model with a growth function qualitatively identical to ours, Cropper (1988) demonstrates that it can be socially preferable to allow extinction under certain conditions.