Banking on Extinction:
Endangered Species and Speculation

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Abstract: Many wildlife commodities such as tiger bones, bear bladders, ivory and rhino horn have been stockpiled in large quantities by speculators who expect that future price increases justify foregoing the interest income associated with current sales. When supply from private stores competes with supply from "wild populations" (in nature) and when speculators are able to collude, it may be optimal to coordinate on an extinction strategy. We analyze the behavior of a speculator who has access to a large initial store, and find that it is optimal to either deter poachers' entry by depressing prices (carefully timing own supply) or by depressing wild stocks. Which strategy maximizes profits critically depends on the initial wildlife stock and initial speculative stores. We apply the model to the case of black rhino conservation, and conclude it is likely that "banking on extinction" is profitable if current speculators are able to collude. Contrary to conventional wisdom, we also find that extinction is favored by such factors as low discount rates or high growth rates.

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1. Introduction and motivation

An increasing number of wildlife species are in some danger of extinction because of over-harvesting, habitat destruction, pollution, or a combination of these factors. Ecologists recognize that small populations run the risk of going extinct because of environmental or demographic stochasticity, and have introduced the concept of the minimum viable population (MVP) to indicate what safety margins should be respected to maintain "acceptable" extinction probabilities for a certain time horizon. Such 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 "bank on extinction."

"Banking on extinction" may be defined as the behavior of private parties investing in private stores of renewable resources (including endangered species), hoping that the combination of ill-defined (or enforced) property rights and high prices on consumer markets will deplete *in situ* stocks in the immediate future. With common stocks depleted, such investors may enjoy considerable market power and, by carefully restricting supply henceforth, may earn monopoly rents. The notion of speculating on extinction is not the product of an estranged academic's imagination, but something that may be observed in real life. Meecham (1997, p.134), for example, describes an encounter with a Japanese gentleman "... *who is breeding a pure strain of Hokkaido brown bear taken from the wild [...] He talks with pride about how he will have the one and only last pure strain of Hokkaido brown bear... His investment pays off big time.*" Other examples of threatened wildlife species killed in the wild for commercial reasons but that could also be grown in captivity include tigers, rare birds and rhinos. Often times, products from such species are believed to have important medicinal value (tiger bones, bear bladders, rhino horn), explaining why prices increase a lot when supply is restricted and why gaining market power is profitable for private investors.

But investing in private stocks of valuable species or commodities thereof is only the first step. Under certain conditions, it may be rational (profitable) for speculators to *actively contribute* to the depletion of common stocks, speeding up or indeed triggering the extinction process. This may be achieved, for example, by subsidizing poachers harvesting from the wild, or by providing poachers with improved technology or by blocking conservation efforts. The black rhino, tigers, and certain bear species are also close to extinction, and some extra effort by investors may push the species over the brink. Anecdotal evidence supports the main idea put forward in this paper. Meecham (1997, p.134), again, 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, p.231), citing anecdotal evidence in the *New York Times*, suggest large-scale killing of wild rhinos (even dehorned ones) increases the value of *ex situ* stocks.

The main idea put forward in this paper is not new and has been tried to put into practice a few times in history.[1] One example, discussed by Muller (1990) and Quammen (2000), concerns the attempt by the Dutch in the 17th century to extirpate all but a few nutmeg trees. The remaining trees were located in the safest locations of the Dutch empire (e.g., Ambon), while trees in less tightly controlled areas were simply exterminated. Quammen (2000, p.30) writes "within a few decades, three fourths of the nutmeg trees in the Moluccas (and therefore in the world) had been destroyed, so as to preserve the monopoly and keep prices artificially high." People bought nutmeg from the Dutch East India Company, or they did not buy nutmeg at all.[2]

We analyze the potential profitability of “banking on extinction”.[3] 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 spill over to more general settings. A straightforward extension is the case where wildlife species are grown in captivity by investors (such as bears, farmed and “milked” for the bile from their gall bladder in Asia), but one may also imagine how salmon fish farms actively (and at a cost) oppose habitat restoration of wild salmons. They key element is that output from private and common stocks are substitutes on markets where demand curves are downward sloping.

2. 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. Other agents are poachers. Poachers harvest the resource under conditions of open access, 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 bribes is the possibility that they will lead to sufficiently rapid harvesting as to doom the resource to extinction. Following extinction, the speculator acts as a monopolist, extracting from his stockpile 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 the usual equation of motion:

$$\dot{R}_t = -y_t. \tag{1}$$

For the basic problem, wild animals and supply by speculators are perfect substitutes.[4]

We assume that an individual poacher's cost of harvesting, $c(x,S)$, is a declining function of the natural stock of the resource, S, and an increasing function of harvesting level, x. The marginal cost of harvest is positive, and may be constant or increasing. Poachers' revenues may come from two sources: market-based revenues and speculator subsidies (i.e., bribes). We use $p(Q)$ to denote the inverse market demand, where Q is aggregate deliveries to market, which come from aggregate poacher harvests, X, and any sales from the speculator's stockpile ($Q = X + y$). The per-unit subsidy 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 subsidy):

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

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 harvesting levels adjust at each instant so as to make the typical poacher's costs equal to its revenues:

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

Between eqs. (2) and (3), we infer that equilibrium harvests lead to a condition where each poacher operates where marginal cost equals average cost (which equals minimum efficient scale in the event that marginal costs are nor constant). Whether marginal costs are constant or increasing in harvest, the level of average cost that equals marginal cost is uniquely determined by stock size. We shall denote this common level of marginal and average cost as $c_a(S)$.

In either case, the number of poachers adjusts to force average revenue to equal average cost at the individual poacher's optimal harvest level. Accordingly, 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 shall write as $X^*(S,y,b)$ in the pursuant discussion. 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 the function $X^*(S,y,b)$ is implicitly defined by

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

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

We assumed above that an increase in natural 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 neo-classical framework. Under this interpretation, an increase in natural stock would shift the individual poacher's marginal cost and average cost curves down, and thereby lower unit cost at minimum efficient scale. Accordingly, we shall assume that $c_a'(S) < 0$. It follows from eq. (4) that $\partial X^*/\partial S > 0$ for $S \geq \hat{S}$.

The natural stock of the resource adjusts over time in the usual fashion, with the rate of change equal to gross additions to biomass less total harvest. Gross additions depend on the current stock of the resource, as described by the recruitment function $g(S)$, so that the inter-temporal rate of change in natural stock is described by

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

We assume that there is a critical mass, $\underline{S} > 0$, such that $g(\underline{S}) = 0$ and $g'(\underline{S}) > 0$. There is also a larger value of stock, $\bar{S}$, which we shall refer to as the carrying capacity of the resource in the pursuant discussion, with $g(\bar{S}) = 0$ and $g'(\bar{S}) > 0$. For levels of the resource between the critical mass and the carrying capacity, recruitment is strictly positive. In much of the discussion below we shall assume that g is strictly concave between $\underline{S}$ and $\bar{S}$. One of the main points we will develop is the possibility that the speculator may strictly 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.

In addition to the myopic behavior associated with open-access harvests, it is conceivable that a cohort of poachers stores some of their harvest, in an attempt to capitalize on future extinction (Gaudet, Moreaux and Salant, 2002). We return to this possibility later, but assume for the time being that there are sufficient barriers to entry into speculative markets as to insulate the speculator from future competition. Such barriers might be formed by set-up costs or asymmetric information, entry deterrence by the incumbent (not modeled here, but see Mason and Polasky 1994), but also by moral or ethical considerations (the illegality of the trade implies most people will resist entering this business even if it implies foregoing monetary gains—akin to limited entry in drugs trading). In this regard, we offer a discussion of the polar extreme case from Kremer and Morcom (2000), who model all agents as atomistic.

The speculator's problem is to maximize the present value of net benefits over time by choice of subsidy and extraction rates:[5]

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

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

$$H = p(X+y)y - bX + g\,[g(S) - X] - my + l\,[p + b - c_a(S)]\,, \tag{6}$$

where γ and μ are the co-state variables on natural stock and private stockpiles, respectively, and ? is the Lagrangean multiplier on the poacher participation condition.

2.1 Solving the speculator's problem

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:

$$\partial H / \partial y = p - m + p'[y + l] + (\partial X / \partial y)[(y + l)p' - b - g]; \tag{7}$$

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

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):

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

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

To better understand the implications of these equations, let us first consider equation (7). There are two possibilities to consider: either $X \geq 0$ such that the zero profit condition is binding, or the zero-profit condition does not bind and $X = 0$. When the zero-profit condition binds, i.e., $p + b = c_a(S)$, then $p+b$ is fixed at any particular instant since S is fixed at any point in time. Accordingly, any changes in y and X must exactly offset so as to leave the sum of price and subsidy unchanged; $\partial X/\partial y = -1$ in this range. It follows that equation (7) reduces to

$$\partial H / \partial y = p + b - \mu + \gamma = \sigma \qquad (7')$$

where s(t) defines a switching function. As indicated above, the middle expression in equation (7′) is invariant with respect to y as long as the zero-profit condition binds. Whenever $s(t) < 0$ the optimal value of y is nil, and whenever $s(t) > 0$ the optimal value of y is the largest possible level—a so-called bang-bang solution. Here, "largest possible level" is defined in the context of the case we are focusing on, namely where $p + b = c_a(S)$ so that poachers are *exactly indifferent* between entering but are crowded out at the margin: $X = 0$.[6] If a poacher did try to enter, the extra supply would drive down prices, triggering negative profits and instantaneous exit. Thus, either poachers or the speculator are inactive when the zero profit condition binds: $y = 0$ or $X = 0$.[7]

If $X = 0$ and $p + b < c_a(S)$, then it follows that $\partial X/\partial y = 0 = \lambda$. In this case, equation (7) reduces to:

$$\partial H / \partial y = p(y) + p'(y)y - m\,. \qquad (7'')$$

The speculator's optimal harvest would then set the right-hand side of equation (7″) equal to zero, which yields the traditional Hotelling result: the speculator extracts from his stores such that marginal revenue is set equal to the shadow price of remaining reserves (which as we show below rises over time at the rate of interest).

Next, we turn to a discussion of the optimal subsidy. Again we consider the two cases: $X = 0$ or $X \geq 0$. Assuming $X = 0$ and $p + b < c_a(S)$, all the terms in equation (8) fall out, so that the speculator is indifferent between all levels of b. In this case it is (weakly) optimal to pay no subsidy, and so we will assume $b^* = 0$ in such instances. When $X = 0$ and $p + b = c_a(S)$, then the marginal impact of a subsidy on poachers' harvests will be positive. Recall that $y > 0$ in this case, and so the agency strictly prefers b

= 0 over all other subsidies; $b > 0$ would not yield an equilibrium outcome. Thus, $b^* = 0$ when y > 0.

In the second case where $X>0$, we know that $p+ b = c_a(S)$. Total differentiation then implies that $\partial X/\partial b = -1/p'$. Inserting into equation (8), recalling that $y = 0$ when $X > 0$, and collecting terms, we then have:

$$\partial H / \partial b = - X + (b+g) / p' = 0. \tag{8'}$$

The co-state variable γ reflects the marginal impact of a small increase in the natural stock upon the speculator's value. Because such an increase lowers c_a it must have a negative impact upon the speculator––it might be interpreted as a nuisance value. Either the speculator must wait longer for the natural stocks to be eliminated or else he must extract faster (so as to use up his reserves before poachers start to produce). In the latter case the stream of prices he will receive must be smaller, so that the discounted value of his profit flow will be smaller.

For any value of X, it is possible that γ is smaller than (i.e., more negative than) Xp'. If so, the optimal subsidy (assuming $y(t) = 0$ and $R(t) > 0$) is

$$b^* = Xp' - \gamma > 0. \tag{11}$$

If not, the optimal subsidy is nil. If the nuisance value of the wild stock $|\gamma|$ is sufficiently high, subsidizing the harvest of the species to extinction is profitable. 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 any current sales (i.e., $y = 0$) and will instead subsidize poachers. The reason for doing this is to either drive the wild stock below $\hat{S}$ but above $\underline{S}$ to obtain a temporary monopoly, or to drive the wild stock to extinction ($S < \underline{S}$) to obtain a permanent monopoly.

At the other extreme, if the competition by poachers does *not* create sufficient losses for the speculator to warrant offering a subsidy, the speculator may temporarily drive poachers out of the market by driving price down—as argued above. Along such an optimal path, the speculator might initially drive out poachers by choosing a level of private supply such that $p + b < c_a(S)$ holds (and $y(t)$ is governed by (7″)), possibly followed by a phase during which speculators fend off potential entrants by choosing supplies such that $p + b = c_a(S)$ just holds (and $y(t)$ is governed by (7′)).

In sum, speculators may deter poachers' entry by depressing prices (carefully timing own supply) or by depressing wild stocks (through subsidizing to extinction or otherwise). Which strategy maximizes profits critically depends on the initial wildlife stock and initial speculative stores. Note that this optimal path 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. Specifically, Kremer and Morcom find that public and private stocks may both decrease or move in opposite fashion—depending on the size of the wild stock. Assuming collusion among speculators with fixed initial stocks thus sets the stage for a completely different dynamic path, albeit one that could lead to an identical possible steady state—depletion of both private and wild stocks.

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

$$\dot{m} = rm; \tag{12}$$

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

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 equation (12) along with equation (7″) indicates that the speculator's marginal revenue should rise at the rate of interest. When the zero profit condition binds, 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, the speculator chooses to drive out poachers by depressing stocks (granting subsidies)— recall that profits are maximized by either choosing b>0, X>0 and y=0, or by choosing b=0, X=0, y>0. For X>0 we must have $\partial X/\partial S = c_a'/p' > 0$ and $y = 0$. It follows that equation (13) reduces to

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

Plugging in the optimal subsidy value from equation (11), we have

$$\dot{g} = g[r - g'(S)] + Xc_a'. \qquad (14')$$

We implicitly define $\tilde{S}$ by $g'(\tilde{S}) = r$. For values of $S > \tilde{S}$, or "thick" wildlife stocks, the square-bracketed expression on the right side of equation (14′) is positive, so the first term is negative. Because the second term is also negative, we know that $\dot{g} < 0$ until the stock has been reduced to level $S = \tilde{S}$ after which $\dot{g} > 0$ is feasible. Two possibilities arise. (i) If the second term on the RHS of (14′) is sufficiently large, the nuisance value of the remaining wild stock continues to increase over time and the optimal bribe as defined by (11) must increase. If this keeps up then eventually the wild stock is subsidized to extinction. (ii) If the second term on the RHS is sufficiently small, the subsidy scheme will be phased out or aborted while a viable population of the wild stock remains. In this case, removing the subsidies triggers immediate exit by poachers setting the stage for a subsequent phase where the speculator can behave as a monopolist.

The length of this monopoly interval and the maximum price the speculator can charge during this phase depends on initial stock values and on the magnitude of the prior cull.

The only alternative option is the case where the speculator chooses y>0, b=0 and X=0, depleting his stores in early periods. In this case, short-term movement of γ depends on whether the zero profit condition is binding or not – although clearly $\gamma \rightarrow 0$ as the speculator depletes his stores. If the zero profit condition does not bind, then equation (13) reduces to

$$\dot{\gamma} = [r - g'(S)]\gamma \tag{15}$$

If $S < \tilde{S}$, then γ becomes more negative over time. But since X=0, S gets bigger (assuming $S>\underline{S}$) and $\dot{g}$ changes sign after $S > \tilde{S}$. If the initial wild stock was sufficiently low such that, at any time during the phase in which speculators deplete their stores, poachers would not choose to enter even at high prices, then the speculator can freely operate as a monopolist until his stores are depleted. In this case, γ=0 in all periods.

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. When the zero profit condition binds, then equation (13) reduces to

$$\dot{\gamma} = [r - g'(S)]\gamma + c_a'[\gamma / p' - y] \tag{15′}$$

The growth rate of γ now depends on an additional term. From equation (7′), we know that $\gamma > -p$. From this we find that the second term on the right hand side of (15′) is negative when marginal revenue (MR) from the speculator's sales is positive. Therefore, $\gamma \rightarrow 0$ more slowly once the zero profit condition binds, as long as $MR > 0$. If $MR < 0$, then the speed at which $\gamma \rightarrow 0$ is ambiguous relative to the case in which the zero profit condition does not bind. If MR is sufficiently negative, then $\gamma \rightarrow 0$ faster after poachers become indifferent to entering.

2.2 Implications for conservation

What does this analysis imply for the conservation of endangered wildlife species? Assume the existence of a certain species that is harvested for a tradable and storable commodity. If stockpilers collude and have access to a "large" initial stock of the wildlife commodity in their private freezers, they have two different strategies at their disposal to maximize profits. First, private stocks may be exploited without subsidizing poachers to drive the natural stock down. We term this the "dumping equilibrium" in the pursuant discussion. Second, speculators may subsidize poachers. Depending on the size of the optimal bribe (determined endogenously—a function of *in situ* and *ex situ* resource stocks), wildlife stocks can be subsidized to extinction ($S^* < \underline{S}$) or "near-extinction" ($\underline{S} < S^* < S_0$, where S^* is the *in situ* rhino stock when the subsidy is withdrawn and S_0 is the initial population).[8] If wild animals are hunted to extinction, the speculator will be a monopolist henceforth. The "near extinction" strategy is more subtle. Poachers are bribed to "substantially" reduce the wild stock (the optimal reduction in stock size is endogenously determined). After the subsidy scheme is lifted, all poachers exit and the speculator gains a temporary monopoly. Eventually, as the wild population recovers, re-entry by poachers will take place and the speculator's maximization problem starts anew, unless the speculator depletes his private stores during the monopoly/stock recovery phase. The near extinction strategy entails lower subsidy costs than the extinction strategy as fewer animals have to be killed in early periods, but might pose restrictions on the timing of supply from private stocks because of the threat of future re-entry by poachers.

A key difference between the two scenarios thus follows from the different "backstop prices" that the speculator faces.[9] If the speculator is a monopolist, the maximum price he can charge is determined by the willingness to pay of consumers. In contrast, with potential competition associated with supplies from the wilds, the maximum price is determined by the zero-profit supply conditions for harvesting wild stocks. The speculator responds to the threat of potential entry by tailoring his supplies such that poachers are either driven out (that is: would earn negative profits when entering) or are indifferent between entering and not entering. This strategy typically corresponds with larger supply and, hence, lower prices. Eventually, when he runs out of supplies, prices rise and poachers enter.

3. Empirical illustration: banking on black rhino extinction

We now explore the profitability of banking on rhino extinction by analyzing whether the gain in speculator's profits due to extinction is sufficient to cover the subsidy costs. We use Brown and Layton's (1998, 2001) data on rhino poaching and horn trading, which demonstrated that *ex situ* stocks of rhino horn may be used to promote rhino conservation.[10] We demonstrate the exact opposite: private stocks and rational investors may trigger rhino extinction.

Private parties, mainly in Asian countries, have stored large quantities of rhino horn over the past few decades. The only reason to hold (speculative) stocks is the expectation that prices will rise rapidly enough to compensate for the interest income foregone (Hotelling 1931). In the recent past, speculators have been proven right; 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, speculators hold larger quantities of black rhino horn *ex situ* than wild stocks carry *in situ*.

Presumably speculators expected the extinction of the black rhino (conservationists claimed extinction was imminent), in which case their stocks would immensely increase in value. Recently, however, there is mounting evidence that illegal rhino harvesting has reached a steady state. The near free fall in abundance has been halted and, indeed, has locally been reversed (as is consistent with traditional open access models; see Conrad 1995). Black rhino populations appear to have stabilized since the early 1990s (Dublin and Wilson 1998), which would have severe repercussions for horn speculators. Given constant prices, the dynamic conditions for optimal selling and storing are violated, and should trigger an immediate response. In light with the results in section 2 we distinguish between the dumping and subsidy strategy to maximize profits, assuming speculators are able to collude. Details of the empirical model used to derive our results (e.g., growth function, inverse demand function, harvest costs and production function) are presented in the Appendix.

3.1 Profits and costs from "Banking on extinction"

Asian speculators hold approximately 20,000 kilograms of rhino horn (Brown and Layton 1998, 2001). We assume speculators can collude as a monopolist when they pursue the extinction strategy. Assuming perfect collusion (granted, a strong assumption), the net discounted benefits of selling from existing stores are readily computed. In Table 1 we present the net present value (NPV) of the subsidy strategy (second column), and the dumping equilibrium (third column), and the net gains from the former over the latter. The table also presents information on (1) the optimal time to depletion of private stockpiles, given in parentheses, and (2) the rhino population level when the subsidy is withdrawn, S^*. For $S^* < \underline{S}$, extinction is the result.

<Insert Table 1 about here>

The NPV of the subsidy scheme represents the discounted flow of monopoly profits, less aggregate subsidies. This subsidy cost might be considerable—for *r*=8%, for example, the total “bribe” that is required to deplete the wild stock to levels just below the minimum viable stock $\underline{S}$ (or 100 animals) amounts to \$2.40 million, assuming an initial stock of 2600 rhinos. Subsidizing the near extinction cull that is optimal for r=12% (S^*=235 rhinos) costs the speculator some \$2.24. Despite these high costs it is clear from the first column that, for “low” discount rates of 4% and 8%, subsidizing to extinction generates profits in excess of the “near extinction” strategy. 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—the speculator times his supplies such that he runs out exactly when the poachers re-enter. Future re-entry by poachers will then force him to shorten his optimal supply path, selling more at lower prices throughout. By subsidizing to absolute extinction, this restriction does not exist.

The dumping NPV summarizes similar statistics for the case where speculators face competition from poachers harvesting the wild stock. When speculators supply from private stores, they depress prices and temporarily drive some poachers out of the business, letting rhino populations recover and thereby setting the stage for the return of poachers—recall that the wild stock is an important determinant of average and marginal harvest costs, and thereby the zero-profit entry level. As private stores are depleted, the natural stock rises to a level where it becomes profitable for poachers to harvest wild animals.

In the fourth column, labeled “Net gains of banking on extinction”, we deduct the dumping profits (column 2) from the subsidy profits (column 1) to obtain an estimate of the net profits of the banking strategy. The information on NPV thus suggests that gaining a (temporary) monopoly is profitable for a wide range of discount rates (up to some 22%). As a subset of this strategy, gaining a permanent monopoly (banking on extinction) is profitable for a more narrow but still plausible 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 subsidy outlays, depressing the return to the "subsidy strategy".

Finally, the numbers in parentheses below the gross profits of the two sales strategies refer to the optimal depletion time of the private stock. Under monopoly conditions, depletion occurs faster when the discount rate is increased – in accordance with Hotelling's basic model. This is not true for the model with competition, where the speculator's behavior is constrained by other motives—the desire to lower prices in order to drive out poachers. We also find that that depletion occurs much faster when the speculator faces competition from poachers. When the speculator competes with poachers on output markets, he is forced to sell his stocks earlier and at lower prices throughout. This unambiguously translates into lower revenues for the speculator relative to the extinction strategy, which may or may not be compensated for by the savings on bribes (depending on the interest rate—see above).

Based on these initial results, we conclude that banking on extinction represents a profitable strategy if private stockholders are able to collude. Hence, while the current zero-profit bioeconomic equilibrium (which would have been stable in the absence of speculator's intervention) is likely in excess of traditional MVP measures, we find that it might represent nothing but a stepping-stone to oblivion when accounting for the perverse incentives speculators may have. This finding re-enforces the theoretical result by Kremer and Morcom, who also argued that stable (or, indeed, 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.

3.2 Growth rates, interest rates and species extinction

This brings us to an interesting and perhaps counterintuitive result. In our model, the extinction probability of the rhino is an *increasing* function of its intrinsic growth rate. The reason is that a high intrinsic growth rate undermines the potential of the near-extinction strategy to be competitive—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. 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 marginal benefits of ongoing reductions of S^* all the way down to $\underline{S}$ increase, as does the probability of extinction.

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 opposite result. The reasons are twofold. First, when discount rates are very low, banking 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 strategy.’ Lowering the discount rate implies that the optimal depletion time of the private stockpile increases (again, see Table 1), which increases the probability that re-entry by poachers occurs before the private stock is drawn down (for any S^*). To avoid costly competition in the future, the speculator therefore has an incentive to invest in extinction.

3.3 Caveats: hospital stocks, white rhinos and stability

In this section we explore the consequences of relaxing three restrictive assumptions. First, we consider what happens if some of the rhino horn stockpilers are no speculators but consumers. Brown and Layton indicate that clinics and medical corporations have stockpiled large quantities of rhino horn in the past, and it may be doubted that these agents have done this for speculative purposes (let alone that they are willing to join a cartel). What happens if we lower our estimate of the total stock that the cartel holds (to R_0=10,000 kg) and assume that the remaining stocks are simply used for own consumption? Assuming that the demand curve has not shifted, it is readily verified that the incentive for banking on extinction has been reduced. Specifically, upon comparing the net present value of profits for the extinction and co-existence case, we find that subsidizing dominates dumping for discount rates smaller than 19% (as opposed to 22% earlier). Further reducing the cartel’s stock to a mere 5,000 kg implies this critical discount rate falls to 13%. Subsidizing the wild stock to extinction ($S^*<\underline{S}$) is optimal for discount rates below 5% (as opposed to 9% earlier). We conclude the scope for banking on extinction is reduced as the private stock gets smaller, but it does not vanish for realistic values.

Second, in the above analysis we have considered the case of black rhino conservation and exploitation in isolation. In reality, another species produces a near-perfect substitute for black rhino horn—the more common and docile white rhino. Brown and Layton indicate there may be some 8,400 white rhinos in Africa. If we add white and black rhinos to a single large stock of some 11,000 rhinos, does co-ordination on extinction still pay off? Obviously, the required subsidy to topple the aggregate rhino into oblivion increases considerably when white rhinos enter the picture. The additional costs in terms of extra subsidies involved with a single large cull from 11,000 to 2,600 rhinos, amounts to almost $2 million. (Note that the per unit harvest costs are lower now that we assume a larger stock that is subject to exploitation—a consequence of the Schaefer production function.) Again, we conclude that the incentive to bank on extinction is diluted by accommodating this concern, but it does not disappear (note that adding the required $2 million does not change the main conclusions in Table 1).

Third, the theoretical and numerical analysis are based on the assumption that a single cartel forms that is capable of earning monopoly rents after wild stocks have been depleted. It is an open question whether such a cartel will be stable as individual stockpilers have incentives to free ride on the price-raising efforts of other cartel members. A more general model could therefore be based on a differential game where a finite number of stockpilers competes on output markets—earning lower profits than a monopolist would. Depending on the nature of certain parameters, the open-loop solution to such an oligopoly model might be time consistent or not (see Withagen et al. 1992, Groot et al. 2002). In case the open-loop solution is not time-consistent, analytically deriving equilibrium strategies might be extremely complex. We don't explore this caveat any further, but note it is an interesting topic for future research.

Ultimately, whether the black rhino is likely to be the victim of a speculative attack is of course an empirical matter—the current analysis illustrates that such a doom-scenario should not be ruled out on forehand.

Before closing we would like to emphasize that we have deliberately biased the numerical analysis against extinction by assuming that poachers sell their harvest on the market and collect their bribe from the speculator. In reality, speculators would likely purchase the commodity from poachers at above-market prices, thus converting public into private stocks (see Kremer and Morcom, who also noted—but did not analyze—the case of a "George Soros of poaching"). Allowing for this possibility can only increase the profits of the banking on extinction scheme.

4. Conclusions and recommendations

Wildlife commodities harvested in nature and those sold from either private stores of 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 wards may be bribed or conservation efforts may be blocked. After extinction of wild stocks, speculators can act as monopolists and earn monopoly rents. Our theoretical model outlines conditions under which this is likely to happen. Our empirical study of rhino horn storage indicates that current *ex situ* stockpiles are sufficiently large that profit-maximizing individuals may have an incentive to subsidize the slaughter of rhinos until the wild stock collapses.

"Banking on extinction" might pose a real threat to conservation of certain rare species providing valuable and storable commodities. Of course it is an open question to what extent the numerical results of the rhino case spill over to the conservation of other species. We speculate that for some species they might. For example, bear bile prices have increased to incredible levels in response to increasing scarcity of bear gall bladders—Mills et al. (1995) mention that prices paid in South Korea went up to $210,000 per kilogram. Chinese investors keep nearly 10,000 bears on so-called bile farms, where bile is drained from live bears through devices surgically implanted in their gall bladders. It may be profitable for these investors to coordinate on extinction of wild stocks as this would increase their market power and moreover relax existing international trade restrictions (most of the world's bear species are listed on Appendix 1 of CITES—the Convention on International Trade in Endangered Species of Wild Fauna and Flora). Bear (or tiger) farming implies that speculators "own" a renewable resource, rather than an exhaustible stockpile of a commodity such as rhino horn or ivory. This implies that they are able to enjoy monopoly rents for a longer, indeed potentially infinite, period, which enhances the profitability of banking on extinction.

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 would like to note that there are conceivable 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 bank on extinction evaporates.

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Appendix

We interpret the recent stabilization of rhino abundance as sign that the dynamic system has reached a new steady state—one in which (*i*) poachers earn zero profits and (*ii*) where replenishment of the rhino population exactly equals illegal offtake. Assuming that open access harvesting has reduced the rhino population to such a bioeconomic equilibrium, we use the observation that S^*=2,500 rhinos to solve for (1) equilibrium growth and harvests $G(S^*)=h^*$, (2) equilibrium effort levels $E^*=h^*/qS^*$, and (3) the costs per unit of poaching effort $c=P(h^*)h^*/E^*$. Storage costs are negligible when compared to the value of rhino horn and are hence ignored in what follows. Throughout we assume that one rhino carries 3 kg of horn.

Following Brown and Layton, we first define a conventional logistic growth function $F(S) = 0.16S[1-(S/100{,}000)^7]$, where S is measured in rhinos. Since we are interested in studying extinction and near-extinction of rhinos, we explicitly introduce the minimum viable population (MVP) concept. We "shift down" the growth function as defined above by a constant M so that it intersects the horizontal axis ($F(S)$=0) at stock levels somewhat greater than zero (and somewhat smaller than K). Assume that 100 rhinos is a reasonable estimate for the minimum viable population (see Primack 1998), and define $M=G(S=100)=48$. Including an MVP of 100 animals with negative (positive) growth of the undisturbed rhino population whenever S < (>) 100, thus implies rewriting the growth function as follows: $G(S)=F(S)-48$.

Returning to the issue of the open access zero-profit equilibrium, we find that equilibrium growth and harvest is equal to about 375 rhinos. Milner-Gulland and Leader-Williams (1992) estimated q = 2.6

$\times 10^{-4}$, hence equilibrium poaching effort is $E^*=h^*/qS^*=577$ units.

Finally, we need to determine the per-unit cost of poaching effort, c. To derive this, we first require the demand for rhino horn. Data on supply and rhino horn prices are difficult to obtain since the trade has moved underground in the late 1970s. Demand is likely to be inelastic over some range of output values and elastic over another, but existing price studies do not measure that, suggesting instead that demand is inelastic throughout (Milner-Gulland 1993, Brown and Layton 1997, 2001).[11] Of course, the monopolist's optimal supply path does not have an optimal solution when demand is inelastic as the marginal value of supply would always be negative (e.g., Dasgupta and Heal 1979). While very little information exists about the "backstop price" of rhino horn (i.e, the price where demand is reduced to zero), some data are available for 'intermediate' output levels. Specifically, according to Brown and Layton, 8,000 kilograms were traded at \$168/kg and 3,000 kilograms were traded at \$1,351/kg. Using these observations, we parameterized the inverse demand curve $P(Q) = be^{-aQ}$, where b = \$4,719 is the backstop price and $a = 0.00042$ is a parameter measuring the curvature and slope of the demand curve. Given the demand for rhino horn and a steady state supply of h^*, we determine that $P(h^*)$ = \$2945. Following Brown and Layton, we assume that poachers receive a price equal to $P(h^*)/2.67$, so that the cost of organizing a poaching trip is readily computed: $c=P(h^*)h^*/E^*$ = \$707. This number is somewhat larger than cost estimates provided for rhino hunting in Zambia by Milner-Gulland and Leader-Williams (1992), but may be interpreted as an aggregate cost, combining both the "true effort" cost and an expected fine or penalty (treated separately by Milner-Gulland and Leader-Williams).

Table 1: Numerical analysis of banking on extinction for the case of rhino poaching

Discount Rate	NPV from subsidy sche (million $)	NPV from dumping equilibrium (million $)	Net gain from subsidies (million $)
4%	42.9 (30) *Extinction:* $S^* < \underline{S}$	28.0 (8)	14.9
8%	32.0 (22) *Extinction:* $S^* < \underline{S}$	24.8 (7)	7.2
12%	25.9 (15) *Near Extinction:* $S^* = 235$	22.3 (7)	3.6
24%	17.1 (7) $S^* = S_0$	17.1 (7)	0

Profits from subsidizing poachers to ensure a (temporary) monopoly, and profits from dumping private stocks to drive out poachers by depressing prices. Numbers in parentheses refer to optimal depletion time of private stocks. S^* refers to the wild rhino stock when the subsidy scheme is optimally lifted. For S^* below minimum viable population levels ($\underline{S}$), extinction is the result.

Endnotes

1. Perhaps the best known case of such strategic behavior involving an exhaustible resource (where extinction is not an issue), is the attempt by the Hunt brothers to corner the silver market in 1979-1980 (e.g., Friedman 1992).

2. Eventually the monopoly was broken, presumably because adventuresome Frenchmen managed to smuggle nutmeg plants out of the Moluccas. Another explanation might be spreading of seeds through fruit pigeons (swallowing seeds in one place, voiding them onto some other place not controlled by the Dutch later).

3. We consider when coordination on extinction is profitable to enjoy market power rents in successive periods. Writing about elephant conservation, Bulte, Horan and Shogren (2002) consider another case for coordinating on extinction. Extinction will trigger lifting of CITES trade bans, and when stockpiled quantities are sufficiently large, the net present value of such an elimination strategy exceeds the net present value of conservation.

4. Speculator's supply may come from stockpiles of a storable commodity (such as ivory or rhino horn) or from captive animals (bears, rhinos). In reality, wild animals and the speculator's supply may be imperfect substitutes.

5. In principal, the speculator's supply decisions will be based on dynamic decision rules, as this supply comes from either harvests from a captive stock or reductions in commodity stores. For now, we ignore such dynamic components and take the captive stock of animals as exogenous and chosen freely by the speculator. These simplifying assumptions greatly simplify the exposition and do not affect the main results of this section in a qualitative way. In an empirical model below, we model all dynamic components explicitly.

6. Actually, this depends on how much the speculator can sell in a given period. If the speculator cannot sell enough to completely crowd out poachers, then the speculator will sell all of his stores in one period and the poachers will supply the rest of the market. We ignore this degenerate case.

7. The singular solution arises when s(t) vanishes identically over some time interval: $s = c_a(S) - \mu + \gamma = 0$. The singular control is $y^*(t) = -\dot{R}^*(t)$, where $R^*(t)$ denotes the optimal time path of speculative stores (assuming such a path exists). Under the singular solution, $y^*(t) < y^{max}(t)$ and so poachers would instantaneously enter and harvest from the wild stock (X>0). However, it is not possible to determine an optimal time path of speculative stores. The optimal singular path is typically determined by solving: $\dot{s} = c_a^{'}\dot{S} - \dot{m} - \dot{g} = 0$ along with the necessary conditions for the co-state variables (described below). 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 solution in what follows.

8. In terms of the theoretical model above, near-extinction can only be optimal when the wild stock has been depleted to $S < \tilde{S}$. Then the sign of the γ co-state variable may switch sign, reducing the size of the optimal bribe so that possibly $b^*=0$ for $S > \underline{S}$. For the rhino case study below, this condition holds. Since $\tilde{S}$ = 18,750 rhinos for the current growth function (assuming r=10%), this threshold value is well in excess of the current population. Near-extinction can therefore be optimal.

9. There is another potentially interesting difference between the monopoly and co-existence scenario. The monopoly strategy results in extinction of the species in question, and thus could be followed by relaxation of the current CITES trade ban on the relevant commodity. Consider the case of the black rhino. Legalizing the horn trade might attract new consumers to this market, and it would reduce the transaction costs of trading this commodity, further increasing profits for the speculator. However, because horns of black rhinos and white rhinos are hard to distinguish, legalizing the black rhino horn trade facilitates the laundering of white rhino horn and could therefore provide an impetus to white rhino poaching. To avoid this, policy makers likely retain the trade ban as long as one of the two species survives (see section 3.4 on white rhino poaching).

10. Specifically, Brown and Layton demonstrate that by supplying from stores, rhino horn prices will fall such that poachers will exit. In the meantime, conservation efforts should be geared towards ensuring a sustainable supply horn from "cropping" rhinos bred in captivity to ensure that prices stay sufficiently low to dissuade renewed entry when stocks run out. Private speculators then have no choice but to liquidate their stocks, further depressing prices.

11. Evidence suggests that demand be to an important degree driven by income (indeed, rhino horn is a luxury good, according to Milner-Gulland 1993).