Oxford Review of Economic Policy, Volume 28, Number 1, 2012, pp. 180–192

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 forgoing 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 analyse the behaviour of a speculator who has access to a large initial store, and finds that it is optimal to deter poachers' entry either 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 favoured by such factors as low discount rates or high growth rates.

Key words: rhino horn, storage, conservation, hoarding

JEL classification: D43, Q27, Q28, Q57

I. Introduction and motivation

A number of wildlife species are in some danger of extinction because of over-harvesting, habitat destruction, pollution, or a combination of these factors. In recent years, analysts have become interested in the interaction between conservation of *in situ* wildlife species and the existence of *ex situ* stocks of wildlife commodities. Writing about basking sharks, for example, *The Economist* (2002, p. 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'. Meecham (1997, p. 134) 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

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doi:10.1093/oxrep/grs006

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pure strain of Hokkaido brown bear. . . . His investment pays off big time'. Often 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.

Under certain conditions, it may be profitable for a speculator to *contribute actively* to the depletion of common stocks, speeding up or, indeed, triggering the extinction process. Anecdotal evidence supports this point: Meecham (1997, p. 134), again, writes that

> massive 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 Atlantic blue fin tuna provides a more recent example. One firm (the Mitsubishi Corporation) controls a large share of the market, and there has been speculation that these tuna are being frozen in anticipation of future price rises. Concerns about potential extinction have led to suggestions that trade in tuna be banned under the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), a move which Japan (the world's largest consuming country) has indicated it would ignore. Evidently, stockpiling tuna may well pay substantial dividends.[1]

The economic forces underlying these examples are simple enough. As species become rarer, supplies from the wilds will dwindle and prices go up, which can invite additional pressure on extant populations. In other words, extinction may be an incentive-driven process, via the price mechanism. These forces are exacerbated when a significant market player holds significant stockpiles of wildlife commodities. This is related to, but different from, the physical 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. While these factors are undoubtedly of some importance, we believe another factor is potentially important—strategic behaviour. Certain agents may have an incentive to drive species to oblivion, and 'bank on extinction'. We define 'banking on extinction' as the behaviour 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. In this manner, an erstwhile renewable resource (the endangered animal species) is converted to a non-renewable, storable resource (the animal body parts). This set-up is akin to a cartel-and-fringe design, with poachers as the competitive fringe. By promoting the depletion of wild populations in the short

[1] The Yale Center for the Study of Globalization notes that a major force behind this alarming trend is consumer demand in Japan; indeed, Japan has threatened to ignore any listing of tuna under CITES. See http://yaleglobal.yale.edu/content/adieu-atlantic-blue-fin-tuna for details.

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run, the speculator eradicates potential competition from the fringe and so becomes a monopolist in the long run.[2]

We analyse the potential profitability of banking on extinction. Two possible solution paths emerge from this discussion. Under one, the speculator draws down his private stock before poachers start to harvest, operating as a traditional non-renewable resource monopolist that is constrained by potential entry. Under the second, the speculator actively participates in the market as a buyer, building up his stores while at the same time encouraging poachers to harvest so rapidly as to drive the species below MVP, thereby dooming it to extinction. Shortly thereafter, the species becomes economically unattractive to harvest, so the speculator can operate as a monopolist who harvests a non-renewable resource. Which of these paths is more profitable depends on the initial levels of private and natural stocks.

The potential for a speculator to employ this banking on extinction strategy is particularly worrisome in cases where the extinct species is similar to surviving species. Consider, for example, the black rhino. Legalizing trade in black rhino horns 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 would likely facilitate the laundering of white rhino horn and could therefore provide an impetus to white rhino poaching. To avoid this unhappy outcome, a revision to the convention that retains the trade ban as long as one of the two species survives would seem prudent.

Our paper commences with a simple model, which we describe in section II. Here we discuss the key ingredients of the conceptual framework. In section III we sketch out the approach taken to solve the model (formal details are available on request). While the hypothetical potential for banking on extinction is potentially interesting from an academic perspective, its policy relevance depends on the practical significance of the strategy. On this point we offer some empirical evidence, in the form of a simulation analysis. This simulation study is loosely based on information from the case of the black rhino. These simulation results are presented in section IV. We then offer some policy recommendations in section V and concluding remarks in section VI.

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. Other agents are poachers. Poachers harvest the resource under conditions of open access, so that instantaneous profits are always competed away. One important distinction between our model and the traditional open-access model is that the speculator can induce poachers to harvest more

[2] Bulte *et al.* (2003*b*) develop a similar idea, but their model was based on the unrealistic assumption of a speculator 'bribing' poachers to expand their supply. We revisit the issue of incentive-driven extinction as a purposeful strategy by developing a more realistic model in which speculators purchase commodities on the black market. This not only allows them to accumulate their private stocks, but, as a side benefit, raises prices on the (black) market, accentuating existing incentives to engage in poaching (possibly driving the wild population to extinction). It is easy to demonstrate that a purchasing strategy must be more attractive—for the speculator—than following a bribing strategy.

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rapidly by adding his demand to market demand. The motivation for undertaking such behaviour is the possibility that it 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 as R, the rate of net sales (sales less purchases) as y, the speculator's stockpile evolves according to the equation of motion:

$$\dot{R} = -y. \tag{1}$$

We assume that wild animals and supply by speculators are perfect substitutes.[3] Aggregate deliveries to market, Q, therefore equal aggregate poacher harvests, X, plus net deliveries from the speculator's stockpile:

$$Q = X + y. \tag{2}$$

We show below that market clearing implies that Q is fixed in a particular time period. This means that, when $y < 0$, the speculator induces more poacher harvests while increasing his own stockpile. Poachers' revenues are determined by $p(Q)$, the inverse market demand (i.e. marginal willingness to pay) by private individuals aside from the speculator. We regard $p(Q)$ as net of any anticipated penalties that might be imposed upon private individuals, for example because of the possibility of confiscation, fines, or other sanctions. Unit harvest costs are denoted by $c_a(S)$, with $c_a'(S) < 0$.[4]

The number of poachers adjusts to force average revenue to equal average cost at the individual poacher's optimal harvest level. The equilibrium condition for poachers,

$$p(Q) = p(X^* + y) = c_a(S), \tag{3}$$

therefore implicitly determines equilibrium net deliveries as a function of the natural stock, Q(S), or the equilibrium instantaneous aggregate harvest as a function of the

[3] 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.

[4] The unit cost is derived based on individual poachers' costs along with profit-maximizing and market-clearing conditions. Specifically, 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. Individual poacher's harvests are profit-maximizing, so that marginal cost is equated to average revenue. 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, which implies that price equals average cost. Between these two observations, 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 not 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; this common level of marginal and average cost is $c_a(S)$. Given our earlier assumption that an increase in natural stock leads to lower costs for a given level of harvest, an increase in natural stock lowers unit cost at minimum efficient scale, i.e. $c_a'(S) < 0$. Finally, one might think of costs as implicitly including potential penalties associated with detection. With this interpretation, expected penalties would be akin to a tax on producers. As is well known, the same market outcome obtains whether a tax is imposed on buyers or on sellers. In our application, it is more convenient to model the 'tax' as being paid by buyers.

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natural stock and net speculator sales, $X^*(S,y)$. In this case, it follows from equation (3) that $\partial X^*/\partial S > 0$ and $\partial X^*/\partial y = -1$. Two other possibilities exist. The first is when the speculator crowds out consumers, such that $X^* = -y$ and $Q = 0$. In this case, the speculator pays the unit cost $c_a(S)$ for purchases, with his demand being determined by his maximization problem (described below). The second possibility is when the speculator crowds out poachers so that $Q = y$ and $X^* = 0$. This case, which occurs when $p(y) < c_a(S)$), yields $\partial X^*/\partial S = \partial X^*/\partial y = 0$. The response function $X^*(S,y)$ is therefore piecewise continuous.

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

$$\dot{S} = g(S) - X^*(S, y). \tag{4}$$

We assume there is a critical mass or MVP, $\underline{S} > 0$, such that $g(\underline{S}) = 0$ and $g'(\underline{S}) > 0$; $g(S) < 0$ for values of S less than $\underline{S}$. There is also a larger value of stock, $\bar{S}$, at which $g(\bar{S}) = 0$ and $g'(\bar{S}) < 0$; this is the carrying capacity of the resource. For levels of the resource between the critical mass and the carrying capacity, recruitment is a strictly positive, concave function of stock. One of the main points we develop is the possibility that the speculator may strictly prefer a time-path of purchases that forces the natural stock below S, even though stock would not fall so low in the absence of such behaviour.[5]

While the assumption of myopic behaviour associated with open-access harvests is convenient to work with, it is possible that in reality a cohort of forward-looking poachers stores some of their harvest, in an attempt to capitalize on future extinction.[6] To facilitate our discussion, we assume 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 (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 forgoing monetary gains, akin to limited entry in drugs trading. Alternatively, the pre-existing stock of commodities owned by the speculator may be a decisive factor. An extinction strategy would increase the value of this extant stockpile, potentially making the extinction strategy a profitable undertaking for the speculator (but not for poachers with zero initial stocks). The assumption of a monopolistic speculator implies 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. However, 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. The downward-sloping demand function the speculator faces can

[5] Implicitly, we are assuming that conservation efforts (enforcement, investments in population or habitat, etc.) do not intensify as the stock approaches MVP. This seems like a natural policy response to impending extinction. We discuss this point in the concluding section.

[6] The solution to the dynamic problem of the speculator below does not rule out upward price jumps, hence there appears to be scope for agents to arbitrage gains by 'entering' the market post-extinction. Gaudet *et al.* (2002) and Karp and Newbery (1993) consider similar scenarios.

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equally well be thought of as residual demand in the context of a cartel and fringe model. Indeed, the main message of this paper could be reinforced in such a setting.

The speculator's flow pay-offs from transactions are positive if the speculator sells and negative if he purchases. Treating the speculator as the Stackelberg leader in the 'game' with poachers, his optimization problem is to maximize the present value of net benefits over time by choice of sales and purchase rates:

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

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

$$H = p(X^* + y)y + y[g(S) - X^*] - \mu y, \tag{5}$$

where γ and μ are the co-state variables on natural stock and private stockpiles, respectively.

III. Solving the speculator's problem

There are two possible outcomes to consider. First, the speculator may pursue a *banking on extinction strategy*, in which he first adds to his stockpile (driving up prices, encouraging extra poaching which helps drive the resource to extinction), followed by a phase in which he sells his stockpile as a monopolist. Especially if the speculator has access to a 'large' initial stock of the wildlife commodity, it may pay to hunt the wild stock to a level below MVP so that extinction becomes inevitable. As mentioned above, in addition to the benefits from unfettered market power, the speculator may enjoy an additional bonus from following the banking strategy. Insofar as current (international) trade in the species' commodities is banned by CITES, the trade ban might be lifted after extinction (as CITES only regulates trade in endangered species—not extinct ones: see Bulte *et al.* (2003*a*)). Relaxation of a trade ban would lead to increased demand, raising profits from banking.

Second, the speculator may forgo the banking option and, instead, follow a *dumping strategy*. This implies divesting the stockpile while competing with poachers—a classical cartel-and-fringe set-up. The speculator will not drive poachers out of business, unless he decides to dump his stockpile on the market at once, which would be the optimal thing to do if price rises too slowly to make holding the stockpile a worthwhile investment. Keeping poachers out of business over a longer interval is not an optimal long-run strategy because this involves selling off larger quantities of the stockpile at a lower price. The dumping strategy may or may not coincide with extinction of the wild stock; if extinction does occur, this outcome is due to poaching pressures (open access harvesting) and has nothing to do with the speculator.

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The choice of whether to pursue the banking strategy is a numerical one, and requires comparison between the present value of net benefits to the speculator under the banking and dumping strategies. In both cases, value is determined by the initial level of wild stocks and the initial level of private stores. The main point of the paper is that for appropriate combinations of these two initial levels, it pays the speculator to pursue a banking strategy, taking actions that lead to extinction of the wild stock. This choice does not require the initial natural stock to be lower than the MVP, but of course banking is more attractive as wild stocks are closer to MVP as this would lower extinction costs. We now turn to a numerical example to examine whether banking on extinction may be a real threat for some species.

IV. Empirical illustration: banking on black rhino extinction

We now explore the profitability of banking on extinction by analysing whether the gain in speculator's profits due to extinction is sufficient to cover the purchase costs for a specific case study where speculation does exist and for which some data are available: the case of the black rhino. Our use of this case is not meant to imply the banking outcome is inevitable for this species, but rather to demonstrate that it is optimal under a certain set of empirically defensible parameters. In this application we use data provided by Milner-Gulland and Leader-Williams (1992) and Brown and Layton (1998, 2001). Assuming that stockpilers care about conservation of rhinos and are willing to forgo some profits to achieve that objective, Brown and Layton demonstrated that *ex situ* stocks of rhino horn may be used to promote rhino conservation (see also Fernandez and Swanson, 1996).[7] Here we demonstrate the opposite result: a profit-maximizing speculator that holds a sufficiently large private stock may trigger rhino extinction.

Private parties, mainly in Asian countries, have stored large quantities of rhino horn over the past few decades. Presumably, these stocks are held in the expectation that prices will rise rapidly enough to compensate for the interest income forgone (Hotelling, 1931). In the recent past, speculators have been proven right; rhino horn prices have increased tremendously since the mid-1970s and, according to one estimate, rhino horn now fetches up to US$60,000 per kilogram in Asian markets (Choi, 2010). Such price increases are more than enough to compensate for the lost interest, justifying stockpiling of rhino horns. Since the 1970s, the wild population of black rhinos has collapsed from 65,000–100,000 animals to just about 2,500 in the 1990s, after which they stabilized at a level of about 4,000–5,000 rhinos at present. Unfortunately, poaching pressure has intensified in recent years. Well-equipped, sophisticated crime syndicates have killed more than 800 African rhinos in the past 3 years (IUCN, 2011). 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's demise.

[7] 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.

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

Discount rate (%)	PVNB from banking ($m)	PVNB from dumping ($m)	Net gain from banking ($m)
5	50.03	26.43	23.60
10	34.11	22.23	11.88
40	10.9	9.8	1.1

Currently, private stockpilers hold larger quantities of black rhino horn *ex situ* than wild stocks carry *in situ*. Speculators hold approximately 20,000 kilograms of rhino horn (Brown and Layton, 1998, 2001); we assume these stocks are held by one agent.[8]

Based on this parameterization, we conducted a simulation analysis. Results from these simulations are presented in Table 1. Here we tabulate the net present value (PVNB) of the banking strategy (second column), and the dumping equilibrium (third column), and the net gains from the former over the latter (fourth column).

The PVNB of the banking scheme represents the discounted flow of monopoly profits, less purchase costs. While these costs can in principle be considerable, the first column indicates that they are more than offset by the post-extinction profit flow. This appears to hold for reasonable discount rates; in particular, it is true in our simulations at rates below 40 per cent.

The dumping PVNB 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 push poachers out of the market; this allows rhino populations to recover, thereby reducing the unit cost of harvest. Ultimately, poachers return to the market; in anticipation of this fact, the speculator exhausts his stocks at the moment entry is triggered.

In the column labelled ‘Net gains of banking on extinction’, we deduct the dumping profits (column 2) from the banking profits (column 1) to obtain an estimate of the net profits of the banking strategy. The results thus suggest that gaining a (temporary) monopoly is profitable for a wide range of discount rates. Accordingly, we conclude that banking on extinction can represent a profitable strategy if the private stockholder is not too impatient. Explicitly incorporating stores and speculators thus reverses the insights of traditional renewable resource models, and suggests the rhino population is far from safe.

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, which is opposite to the predictions of standard renewable resource models without storage and speculation (e.g. Clark, 1990; Swanson, 1994). The reason is that a high intrinsic growth rate lowers the profitability of dumping. It advances the date at which re-entry by poachers occurs, which requires more rapid depletion of the private stock

[8] Equivalently, one could imagine multiple speculators that collude as a monopolist in the pursuit of the banking on extinction strategy. Even if these agents interacted non-results similar to those we investigate could emerge. Such a scenario is more complicated to analyse, in that each agent ought to take other agents’ strategies into account; we would then have to solve for the equilibrium to a differential game. While such a scenario is undoubtedly more realistic than our model of monopoly behaviour, 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.

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(lowering prices in every period where the speculator is selling, and so reducing the PVNB from the dumping strategy). As a robustness check we have computed what happens when the intrinsic growth rate is doubled. This reduces the PVNB from dumping from US$26.4m to US$19.9m, and leaves the PVNB of the banking strategy unaffected (because banking requires an initial 'cull' of the herd below MVP, rendering the natural regeneration rate irrelevant). As a result, the net gain from the banking strategy, relative to dumping, increases to more than US$30m. For speculators adopting a dumping strategy, living and growing rhino populations are a nuisance.

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 (at least when populations are optimally managed; Clark, 1990). Not so when we account for the incentives of speculators. We find that the relative appeal of extinction decreases as the discount rate increases. Under the dumping strategy the benefits are realized in earlier periods, which is favoured with high discount rates. In contrast, under banking on extinction the costs are immediate and the benefits are realized in the future. In other words, 'banking' compares favourably to 'dumping' when discount rates are low.

Our analysis considered black rhino conservation and exploitation in isolation. In reality, another species produces a close substitute for black rhino horn—the more common and docile white rhino. If one included white rhinos in the analysis, would banking on extinction still pay off? While this extension is beyond the scope of our present paper, we can imagine some of its features. Including white rhinos would raise the natural stock, and so would increase the required initial costs to banking on extinction. On the other hand, this large extra harvest would raise the speculator's stockpile, with attendant benefits. There are other, subtle, changes as well: because white rhino horns are not perfect substitutes for black rhino horns one would need detailed information about cross-elasticities and the like. Furthermore, because white rhinos are more docile than black rhinos it seems unlikely the harvest costs to poachers are identical for the two species. A careful analysis would require information on all these points.

V. Policy lessons

We can use the analysis to flesh out a few policy recommendations. First, and obviously, the risk of a banking-extinction strategy can be attenuated if wild stocks remain sufficiently large. That is, if anti-poaching conservation efforts manage to steer wild populations away from MVP levels, then the costs of pursuing a banking strategy increase.

Additional lessons for policy-makers emerge. Consider the well-known Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), which aims to protect wild populations of listed species by regulating the international trade in specimens of these species. Despite its widespread acceptance, the lack of attention for economic incentives is often seen as a shortcoming of CITES. This includes the lack of an explicit attempt to deflate market demand for endangered species. However, banning trade while keeping demand unchecked creates the condition for stockpiling of wildlife commodities. Our analysis suggests that, as stocks of such commodities grow over time, they could evolve into a liability for conservation: large *ex situ* stocks increase the profitability of an extinction strategy. Moreover, because trade in *extinct* species is

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legal, owners of large stockpiles may find it worthwhile to promote an extinction strategy so as to remove the trade ban.[9] If so, CITES has inadvertently created the context in which extinction is promoted, rather than prevented. It seems prudent to regularly convert such private stocks into a conservation asset for the international community, for example via public purchase programmes or controlled auctions (e.g. Kremer and Morcom, 2000; Bulte *et al.*, 2007).

Further, to attenuate incentives to bank on extinction, the international community might invest in securing alternative sources of supply of wildlife products. If substitute products (synthetic or otherwise) were available, potential monopoly rents would be curtailed. One potential alternative source of wildlife products could be a flow of commodities from farmed wildlife species.

Next, insofar as the objective is to remove the incentive to bank on extinction, it would be particularly worthwhile to focus on lowering the backstop price of wildlife commodities, for example by using information campaigns to reduce demand. Such a campaign would be particularly efficient if it targeted those consumers with the highest marginal utility of consumption, shifting in the demand curve at higher prices.

Finally, the relative appeal of the banking strategy will be diminished by actions that reduce its present discounted value. The necessary reduction is not to zero, but to the level associated with the dumping strategy. This reduction can be realized by lowering flow profits, either by efforts aimed at lowering demand (i.e. moral suasion) or by lowering the quality of the product.[10] But the requisite reduction in value can also be obtained by increased enforcement, either raising poachers' costs, or by removing the feature of current regulations that drops trade sanctions if the species goes extinct. This latter action, which is relatively low cost, seems like an obvious place to start.

VI. Conclusions

Wildlife commodities harvested in nature and those sold from either private stockpiles or farms (captive breeding) compete on output markets. When these private stockpiles are sufficiently important, they can create an incentive to promote extinction of wild stocks. After extinction of wild stocks, the speculator earns monopoly rents. Our simulation 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 could apply to other species. We speculate that for some species they might. For example, bear bile prices have increased

[9] Bulte *et al.* (2003*a*) demonstrate that under some conditions the value of stockpiled ivory in Africa is sufficiently high to make a strategy aimed at driving the African elephant to extinction financially viable.

[10] One way to obtain this outcome is to take actions that impact the ability of the animal part to achieve its ulterior goal. If the use is medicinal in nature, one could imagine capturing the animals, sedating them, and then sprinkling some agent on the animal part. Obviously, the introduced agent would have to be benign from the animals' perspective. If the ultimate goal has to do with appearance, then disfiguring the part, for example by spray-painting it, would do the trick. This sort of action has been used to diminish the value of certain seals, thereby lowering the value of their fur coat.

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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 promote 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 in Appendix 1 of CITES). 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.

Ultimately, whether any other species is likely to be the victim of a speculative attack is an empirical matter. Our point is that such a gloomy scenario should not be regarded as empirically irrelevant. Moreover, some of the policy implications of our 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 of 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.

Appendix: Calibrating the numerical model

We interpret the recent stabilization of rhino abundance as a sign that the dynamic system has reached a new steady state, in which (i) poachers earn zero profits and (ii) where replenishment of the rhino population exactly equals harvesting. 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.

We first define a (skewed) logistic growth function $F(S) = 0.16S[1 - (S/100{,}000)^7]$, where S is measured in rhinos (see Brown and Layton, hereafter B–L). Since we are interested in studying extinction and near-extinction of rhinos, we explicitly introduce the MVP concept. We 'shift down' (or horizontally to the 'right') the growth function as defined above by a constant 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 MVP (see Primack, 1998). Including an MVP of 100 animals with negative (positive) growth of the undisturbed rhino

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population whenever $S <$ (>) 100, thus implies rewriting the growth function as follows: $G(S) = F(S) - F(S = 100) = F(\mathrm{S}) - 48$.

In equilibrium, $h^* = G(S^*) = 352$ rhinos (for $S^* = 2500$). Milner-Gulland and Leader-Williams (1992, hereafter MG–LW) estimated $q = 2.6 \times 10^{-4}$, hence equilibrium poaching effort is $E^* = h^*/qS^* = 542$ units. To determine the per-unit cost of poaching effort, c, we need to know the demand for rhino horn. Data on supply and rhino horn prices are difficult to obtain since the trade moved underground in the late 1970s. 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 B–L, 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 $h^* = 352$, it follows that $P(h^*) = \$2{,}945$. Following B–L, we assume that poachers receive a price $p(h) = P(h^*)/2.67$, so that the cost of organizing a poaching trip is readily computed when we assume zero profits: $c = p(h^*)h^*/E^* = \$709$. This number is somewhat larger than cost estimates provided for rhino hunting in Zambia by MG–LW (1992), but may be interpreted as an aggregate cost, combining both the 'true effort' cost and an expected fine or penalty (treated separately by MG–LW).

Finally, the numbers in the paper are based on the parameterized model by MG–LW (1992), where $h = qES$ (so that total costs of harvesting h animals are $\mathrm{TC} = ch/qS$). B–L, in contrast, assume that kills per expedition can be approximated by a constant, which will result in somewhat biased outcomes if the rhino stock changes over time and is an input in production.

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