An Economic Assessment of Wildlife Farming and Conservation

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Abstract: *The supply-side approach to conservation, as recommended by economists, prescribes the provision of cheap substitutes for wildlife commodities in an effort to lower the price of such commodities and reduce harvesting pressure. We developed a theoretical economic model to examine whether wildlife farming or ranching indeed contributes to conservation. We first present the naïve economic model that lends support to the supply-side approach. This model is incomplete because it fails to capture the fact that most wildlife markets are not perfectly competitive (instead, models are characterized by a small number of suppliers who have a certain degree of market power), which also implies that it fails to incorporate strategic interaction between suppliers. We then present an alternative model of the (illegal) wildlife trade that reflects imperfect competition and strategic interaction, and demonstrate that wildlife farming may stimulate harvesting (or poaching) rather than discourage it. By applying the model to the case of rhinoceros poaching and ranching, we demonstrate the potentially ambiguous outcomes of rhinoceros-ranching initiatives—wild rhinoceros stocks may recover or suffer from additional depletion, depending on key parameters and the type of competition on output markets. We also show that this type of ambiguity may be eliminated when policy makers restrict quantities of farmed output through a quota system; in that case, introducing wildlife farming will unambiguously promote conservation. In the absence of such accompanying regulation, however, policy makers should be careful when stimulating wildlife farming and be aware of potentially adverse consequences.*

Key Words: captive breeding, poaching, rhinoceros conservation, rhinoceros dehorning, wildlife ranching, wildlife trade

Una Evaluación Económica de la Crianza y Conservación de Fauna Silvestre

Resumen: *La estrategia de abastecimiento para la conservación, recomendada por economistas, propone el suministro de sustitutos baratos de los artículos de consumo provenientes de vida silvestre en un esfuerzo por disminuir el precio de tales artículos y reducir la presión de captura. Desarrollamos un modelo económico teórico para examinar si la crianza de fauna silvestre realmente contribuye a la conservación. Primero presentamos el modelo económico simple que soporta a la estrategia de abastecimiento. Este modelo está incompleto porque no considera el hecho de que la mayoría de los mercados de vida silvestre no son perfectamente competitivos (dichos mercados se caracterizan por un número pequeño de proveedores que tienen cierto grado de fuerza de mercado), lo que también implica que no incorporan interacciones estratégicas entre proveedores. Luego presentamos un modelo alternativo del comercio (ilegal) de vida silvestre que refleja la competencia imperfecta y la interacción estratégica y que demuestra que la crianza de fauna silvestre puede estimular la captura (o cacería ilegal) en lugar de disuadirla. Aplicando el modelo al caso de la crianza y caza ilegal de rinocerontes, demostramos los resultados potencialmente ambiguos de las iniciativas de crianza de rinocerontes—las existencias de rinocerontes silvestres se pueden recuperar o sufrir mayor reducción dependiendo de los parámetros clave y del tipo de competencia en los mercados resultantes. También mostramos que este tipo de ambigüedad puede ser eliminado cuando tomadores de decisiones restringen la producción en cautiverio por medio de un sistema de cuotas—en ese caso la introducción de crianza de fauna silvestre promoverá la conservación sin ambigüedades. Sin embargo, en ausencia de tal reglamentación acompañante*

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los tomadores de decisiones deberán tener cuidado al estimular la crianza de fauna silvestre y estar alertas de consecuencias potencialmente adversas.

Palabras Clave: cacería furtiva, comercio de vida silvestre, conservación del rinoceronte, crianza de fauna silvestre, descornado de rinocerontes, reproducción en cautiverio

Introduction

An important threat to the survival of many wildlife species in developing countries is harvesting of wildlife for meat or other commodities such as bones, skins, horns, tusks, and bladders. To protect species from overhunting, various (complementary) conservation measures are used. The key insights to safeguard endangered species from excessive hunting pressure are based on simple economics—conservation efforts should be geared toward reducing the benefits of harvesting or increasing its cost. Information campaigns, for example, are aimed at lowering consumer demand by stigmatizing the consumption of certain wildlife goods (e.g., ivory consumption in Europe and the United States). As a result, demand shrinks and prices fall, eroding the profitability of harvesting effort and lowering hunting pressure. Enforcement by antipoaching units, in contrast, raises the cost of poaching by introducing an expected fine or penalty. In certain countries, such as Zimbabwe, Nepal, and Kenya, penalties can be as severe as being shot to death (Messer 2002).

Both approaches—raising costs and reducing benefits—have been effective with varying degrees of success. Raising consumer awareness and altering human preferences, however, are difficult and time-consuming and often have only limited impact. Monitoring and enforcement are obvious solutions, but they are expensive. And expense is a serious consideration in light of tight budget constraints and fiscal deficits in many developing countries. It is no surprise, then, that there is a constant search for new and more cost-effective ways to enhance conservation.

One rather new, market-based approach to restrict harvesting appears to be gaining momentum; we call it the "supply-side approach" to wildlife conservation. Interestingly, its main supporters are economists, not conservation biologists. Supply-side conservation aims to provide a cheap substitute for the wildlife commodity in question, depressing the commodities' market price, which lowers hunting incentives and forces harvesters to search for alternative employment. Supply-siders recommend "flooding" the market for wildlife goods with farmed varieties (Brown & Layton 2001) or with other substitutes such as stockpiled goods (Kremer & Morcom 2000) or chemical substitutes (Mills et al. 1995). For example, Viagra has affected the trade in velvet from reindeer antlers, harp seals, and hooded seal penises—all commodities prescribed as aphrodisiacs in traditional Asian medicine (von Hippel & von Hippel 2002).

There have been proposals to begin farming wildlife for specific commodities—bears for bile, tigers for bones and other organs, rhinoceros for their horns—as well as to farm animals for more generic output such as bushmeat (Clayton et al. 2001). Supply-side conservation has also been recommended to curb the buoyant illegal trade in live endangered species such as seahorses, birds, and reptiles (Commonwealth of Australia 1998). A key element common to all approaches is that segments of the (international) trade in wildlife commodities is legalized so that the legal trade can crowd out the illegal trade.

Despite its logic and appeal, many conservationists are reluctant to adopt the supply-side approach without further analysis. We argue that they are correct and evaluated the prospects of supply-side policies for conservation. We argue that the basic premises of the supply-side model ignore important elements of conservation, and demonstrate that this model may at times be counterproductive, triggering extra harvesting and further deterioration of wild stocks.

We considered the particular market structure of certain parts of the (endangered) wildlife goods trade and focused on the wildlife trade characterized by imperfect competition and few active traders. The trade for certain wildlife commodities is run by criminal networks that are involved in smuggling and trading wildlife goods and in trafficking of arms, drugs, and people across borders. Support for this assertion comes from three distinct sources: (1) studies conducted for conservation organizations such as World Wildlife Fund and TRAFFIC, (2) law enforcement authorities, and (3) academic work (e.g., Galster et al. 1994; Commonwealth of Australia 1998; Le Duc 1999; Galster & Eliot 2000; Cook et al. 2002). Within a criminal network, introducing competition from farms might trigger various strategic responses from incumbent traders, including one that is detrimental to conservation. The nature of the emerging competition between traders and farmers will determine the exact outcome that is, essentially, unknown a priori in many cases.

We focused exclusively on situations in which farmed commodities compete with poached output from the wilds in an effort to discourage poaching. We did not consider the ethical aspect of raising species, such as captive bears for their bile; the private profitability of wildlife farming; or the potentially important role of wildlife farming to restock empty habitats. We also did not consider the impact of wildlife farming on the conservation of wildlife when the trade in wildlife commodities is characterized by perfect competition, which is arguably the context for many wildlife commodities, including bushmeat and certain reptile skins. Our focus is on farming endangered species that are currently protected and, when harvested, are traded illegally by criminal networks. We therefore use the terms harvesting, hunting, and poaching interchangeably.

Wildlife Farming and Conservation

Growing and breeding wildlife in captivity takes various forms. Although the terminology associated with captive propagation can at times be confusing and contradictory, the term "captive breeding" usually refers to zoos and efforts to breed wild animals for conservation. "Wildlife farming" typically refers to intensive management and husbandry of wild stock, and "wildlife ranching" usually refers to less-intensive management in semifree ranching contexts and applies to rhinoceros breeding. Sometimes ranching involves raising eggs or juveniles collected from the wilds (such as with crocodile ranching), but this is not always the case. Our focus is on farming and ranching supported by commercial captive propagation, resulting in a flow of output that can be sold on wildlife commodity markets and how these operations interact with supplies from the wilds. We use the words *farming* and *ranching* interchangeably.

There are opposing views on the impact of wildlife farming on conservation. A plethora of perspectives is contained in a recent volume by the IUCN/SSC (2001). There are several arguments why commercial farming may contribute to the conservation of wild stocks. Farmed supplies may simply discourage harvesting from the wilds through its depressing effect on prices. In addition, in certain cases farmed animals can be used to restock depleted populations in the wild (unless such individuals carry contagious diseases). When demand for wildlife commodities is growing rapidly (e.g., certain food items and traditional Chinese medicine), meeting demand with supplies from the wild without destroying the wild stock may be impossible. It has also been argued that captive populations may provide a genetic safety net for wild populations and that a share of the revenues from farming or ranching may be used to fund conservation of wild stocks. Finally, when harvested from the wild, many animals in the pet trade die during transport to consumer markets. Breeding such pets closer to consumers can prevent many unnecessary deaths.

There are downsides to farming as well. When harvesting from the wild is banned, introducing a legal flow of farmed output may facilitate the "laundering" of illegal output from the wild through, for example, false paperwork. Dobson and Poole (1992) use an argument along these lines to encourage the retention of the ivory trade ban. The availability of farmer wildlife may confuse consumers by sending a signal that the wild species is no longer endangered, or it may reduce the stigma associated with consuming certain wildlife commodities. This inadvertently inflates demand (and prices). When wildlife farms or ranches are restocked from the wild (effectively transforming a common good into a private), farming can result in more intense hunting pressure for animals as an intermediate input into farming systems. On the other hand, when farms and ranches are closed systems and completely separate from wild stocks, they may remove the incentive to protect the wild resources altogether—why invest in the conservation of wild resources when farmed substitutes are readily available? Farming may also undermine the profitability of use programs through its impact on prices, compromising farm viability and decreasing the scope of conservation through sustainable use.

With so many conflicting arguments, it is no surprise that the debate about the desirability of wildlife farming is unsettled and remains a controversial topic. Real-life examples are scarce and cannot guide decision making. For example, Meacham (1997) argues that the laundering effect has caused the (near) extinction of the wild crocodile in Thailand. In contrast, widespread bear farming in China in the 1990s stabilized Chinese prices for bear bile (Mills et al. 1995), whereas such prices have increased substantially elsewhere in Asia (providing an incentive to expand harvests from the wilds there). Crocodilians provide one exception for which adequate data are available. Ross (2001) argues that countries with crocodile-farming systems that have severed all direct and economic interest of commercial operators from the wild population are typically associated with poorly known and depleted crocodilian populations. In light of these conflicting arguments and findings, it is perhaps no surprise that Parry-Jones (2001) concludes that "captive breeding's actual conservation impact on wild populations has yet to be documented."

The Supply-Side View

One of the main reasons why people believe wildlife farming will contribute to conservation of wildlife is through its depressing effect on prices for wildlife goods. Supply-side conservation typically rests on the (implicit) assumption that the market for wildlife commodities is characterized by perfect competition; that is, there are many hunters or poachers, each taking the price of the wildlife commodity as a given and beyond their control. Moreover, poachers do not have property rights to the resource. Although they may recognize that excessive harvesting today curtails the scope for hunting tomorrow, they also are cognizant of the fact that any wildlife left unharvested today (an investment decision) will not be available to them for future use but instead will be taken by another poacher. This implies that no poacher is willing

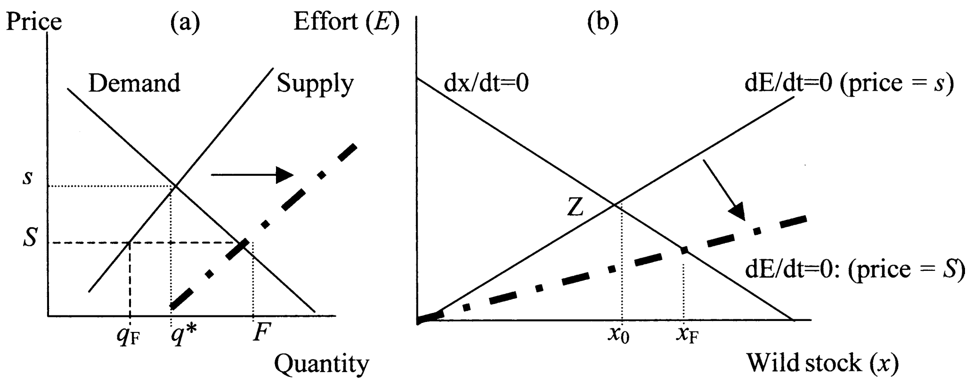

Figure 1. (a) Demand and supply of wildlife commodities. Extra supply from farms lowers the price of the wildlife good from s *(price level that balances demand and supply) to* S *(new, lower market price). (b) Lower prices of the wildlife good will trigger an outflow of labor from poaching to other sectors in the economy and an increase in the equilibrium wildlife stock from* x_0 *(initial wildlife stock) to* x_F *(new equilibrium of wildlife stock)* (s, *price of wildlife commodity without wildlife farming;* S, *price with wildlife farming;* F, *total demand at price* S*;* q_F, *supply from wilds at price* S*;* q^* *supply from wilds in absence of wildlife farming; dx/dt, change in wildlife stock over time interval dt; dE/dt, change in poaching effort over time interval dt; Z, open-access interior solution.)*

to forego current harvesting to enhance future production and, in economic jargon, poachers discount the future at a very high or infinite rate. In short, they act as static optimizers.

There are various specifications of the basic poaching model outlined in the Appendix, and alternative specifications have been used to analyze the demise of many different species resulting from hunting in the past (e.g., Wilen 1976, seals; Björndal & Conrad 1987, herring; Amundsen et al. 1995, minke whales; Bulte & van Kooten 1999, elephants; and Bulte et al. 2003, Tasmanian tigers). One convenient specification is to define poaching as an economic activity that yields a certain return per unit of labor (or effort) based on the (1) price of wildlife commodities and (2) size of the wild stock. These are two variables beyond the control of the individual poacher. Because there are no property rights, no one can be excluded from harvesting the species. This implies that labor (effort) will spill into this activity as long as the returns to poaching are higher than the returns to labor elsewhere in the economy. Conversely, labor will flow out of the poaching sector when the reverse is true. In an interior equilibrium, therefore, the return to labor in poaching must be equal to the return to labor in some other sector, and hunting effort does not change over time. In equilibrium (Fig. 1), wildlife replenishment also equals aggregate off-take so that the wildlife population does not change over time.

Effects of aggregate supply and demand on the output market for the wildlife good (Fig. 1a) and equilibrium conditions for hunting effort and the wildlife population in question (Fig. 1b) (see the Appendix for details on derivation) are obviously interconnected. The solid upward sloping line in Fig. 1b depicts all combinations of the wildlife stock (x) and aggregate poaching effort (E) that, for a certain wildlife commodity price, s, yield an unchanging effort level: $dE/dt = 0$, where dE/dt measures the change in effort (dE) over a small time interval (dt). When $dE/dt = 0$, or effort is unchanging, the marginal poacher recovers only the opportunity cost of his effort and earns zero profits. The solid downward sloping line depicts all combinations of x and E, where harvesting is equal to growth such that the wildlife population is unchanging over time: $dx/dt = 0$. The intersection of these two lines is the unique and stable equilibrium of the open-access system, and we denote it with Z.

In Fig. 1b at equilibrium Z, the marginal poacher earns zero rent, given wildlife price s. Figure 1a describes how this price comes about according to the supply-sider view.

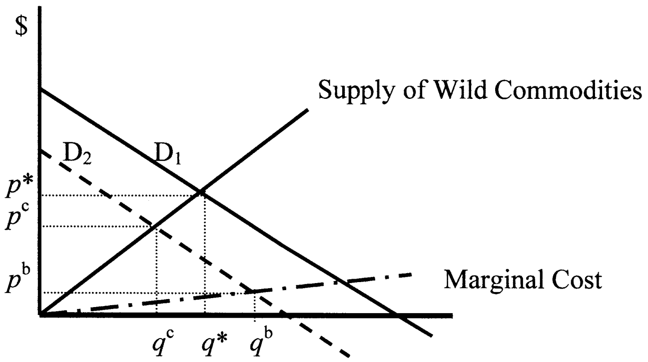

Figure 2. Captive breeding equilibria with imperfect competition. Farmed output shifts the residual demand curve inward (from D_1 to D_2). In response, depending on the type of competition, traders of products from the wilds may supply Cournot (q^c) or Bertrand (q^b) quantity (i.e., respond by supplying less or more; q^*, supply from wilds in absence of wildlife farming).

Price s is the unique price level that exactly balances demand for the wildlife commodity and supply from the wild (at production/consumption level q^* which, in equilibrium, must be exactly equal to replenishment of the wild stock at population level x_0 in Fig.1b). Assuming perfect competition in this market, the supply curve is defined by the marginal cost of harvesting (or the foregone returns to labor elsewhere in the economy). For the functional specification in the Appendix this amounts to a linear upward sloping line as drawn in Fig. 1a (given any wildlife stock x).

Introducing wildlife farming essentially adds production capacity to the market. For each price, there is some additional supply. For Fig. 1a this implies that the supply curve shifts out and is represented by the thick dashed line. Assuming that the downward-sloping demand curve is unaffected, a new and lower market price S emerges. Following the drop in prices, some poachers will choose to switch to another occupation, and supply from the wild will fall from q^* to q_F. The remainder of the market (or $F-q_F$ in Fig. 1a) will be supplied henceforth by farms.

The consequences for the wildlife population of decreasing the price (Fig. 1b) for the poached commodity from s to S rotates the $dE/dt = 0$ isocline downward (it becomes the thick dashed line). Stated simply, the result is fewer people chasing more animals. The new equilibrium is characterized by a wild stock of x_F animals (i.e., the population makes a comeback and the captive breeding effort is considered a success in terms of its contribution to conservation). In this institutional setting, any policy that lowers the price of the wildlife commodity is good for conservation.

We believe that this model is misleading in at least two ways. First, as mentioned in the section on Wildlife Farming and Conservation, the assumption that aggregate demand is unaffected by wildlife farming is probably false. The introduction of a farmed (legal) substitute may stimulate demand because it reduces the stigma (if any) associated with consumption of the wild thing; it may act as a stepping stone toward the real thing for new users. We do not deal with this important issue but it could be easily incorporated in our analysis by shifting the demand curve in Fig. 1a upward. (Interested readers should refer to Fischer [2004] for more information.) Second, and perhaps less obvious, the assumption of perfect competition on the wildlife goods market is violated in practice. As we have argued, it is well documented that the marketing channel associated with the wildlife trade, linking consumer demand to poaching effort, can be qualified only as imperfectly competitive. Only a few (often criminal) groups are involved in the smuggling and trafficking of the commodity across borders. We analyzed the implications of this insight in the next section.

An Alternative View: Imperfect Competition and the Wildlife Trade

In a perfectly competitive market the marginal production cost curve defines the supply curve. The key element is that poachers take prices as given. Supply is determined by a large number of poachers, and individuals cannot influence market prices.

The perfectly competitive market form is the basic workhorse in economic science. This model is used so often not because it is an accurate description of most markets in reality; instead, it is simply a convenient model with which to work. Abandoning the perfect competitive framework can have far-reaching consequences.

The trade in some wildlife commodities is one example of an imperfectly competitive industry that is controlled by a relatively small number of criminal organizations or networks. These groups, then, have the ability to a certain extent to set market prices by manipulating their own supplies. In economic jargon, these groups are said to have market power. These traders are the crucial hinge between poachers and consumers, often illegally trafficking their commodity across borders and typically earning supernormal profits. The market structure of the wildlife commodity trade resembles an hourglass: there are few traders in the middle but many poachers and consumers at opposing ends of the marketing chain.

How does this market structure affect our supply-side analysis? We argue that the assumption of open-access harvesting is essentially correct—there are many poachers who take prices as given and typically do not have formal property rights to the resource they are harvesting. The model in Fig. 1b, therefore, follows. Fig. 1a, however, is too gross a simplification of reality and must be amended because it completely ignores the role of the traders in the middle. We demonstrate that failure to capture market power may result in bad policy recommendations.

For the sake of argument, first consider the extreme and clearly unrealistic case of a single wildlife trader for a wildlife good. Assume all rhinoceros horns (or other commodity) are trafficked by a single organization that has monopoly power when selling to consumers. How much horn would such a trader sell? It is well established that a profit-maximizing monopolist supplies less than a large number of perfectly competitive suppliers would, raising prices and increasing profits. This is a crucial point for the analysis that follows—when traders have market power the supply curve is no longer the same as the marginal cost curve. This holds both for the extreme case of a monopolist and for the more moderate version in which a small group of traders competes on the output market—the so-called oligopoly setting. If traders have market power there will be a markup of price over marginal costs, the extent of which is determined by the intensity of competition. The markup is largest in the case of a monopolist and gradually approaches zero as the number of traders increases. Although the oligopoly setting is a more apt description of the wildlife trade than the monopoly assumption, the latter is easier to work with, so we present the main insight through this market structure. It is important to realize that the results follow, albeit in a somewhat diluted form, for the oligopoly case (Tirole 1988). An appendix showing this result is available from the authors.

We propose an alternative model. First, the monopolistic trader chooses the quantity of output q^* that maximizes his or her own profits. The trader takes into account that (1) demand for wildlife goods is downward sloping, such that expanding supply implies a lower price for all the units sold and (2) the marginal production cost is upward sloping because supply can be expanded only by attracting more people to the poaching business at increasing cost. After establishing the optimal output level, the trader chooses the transfer price s^* offered to poachers. Transfer price s^* is the price level at which aggregate supply by poachers is equal to the quantity that the trader wants to sell to consumers. Hence, the poachers take s^* as a given and produce the desired quantity q^*, which is sold to consumers who pay the (black) market monopoly price p^*. Market price p^* obviously exceeds transfer price s^*, such that the monopolist earns positive profits.

How robust are our earlier results on the beneficial impact of captive breeding on stock conservation with respect to this new institutional context? The effect of wildlife farming is ambiguous, a priori.

The logic is as follows (the full mathematical model is available from the authors on request). In Fig. 2 curve D_1 represents the demand curve the trader faces in the absence of competition from captive-bred animals. The supply curve under imperfect competition will therefore lie above the marginal cost curve (Fig. 2). In equilibrium a supply of q^* animals will be poached from the wild, commanding a market price p^*.

The introduction of legal supplies from captive-bred animals lowers the residual demand for the illegal commodities—represented by an inward shift in demand from D_1 to D_2. This shift reflects the new reality that the "trader" (or the traders in an oligopoly) now has to share the market with farmers. But the story does not stop here. It turns out there are two distinct possibilities.

If the trader(s) responds "passively" to this increased competition and continues to operate on their original supply curve(s), poaching levels fall to q^c and price declines to p^c. Supply from the wild declines, with the difference made up by farmed output (Fig. 2; the new market price p^c is lower than the old one). In equilibrium, there must be thicker wild stocks, and captive breeding is a conservation success. But this is but one possible outcome.

If, on the other hand, competition is intense, the trader(s) may compete more aggressively and lower the markup. This can be envisaged by rotating the supply curve in Fig. 2 clockwise. In the extreme case of highly aggressive competition, the price may fall back to marginal cost, such that the marginal cost curve again represents the supply curve (as in the case of perfect competition). In other words, competition has dissipated profits for the trader, and an even lower price p^b materializes, with quantity of poaching q^b. Because $q^b > q^*$, this outcome can only be interpreted as a conservation failure. Intermediate outcomes between the monopolist's initial supply curve and the marginal cost curve are of course also feasible, which implies that the conservation effect is ambiguous. In a more general oligopoly model, the position of the postfarming supply curve will also depend on the number of traders in the market.

Formally, whether traders continue to operate on their original supply curves or move to a new supply curve depends on whether competition occurs through quantity adjustment (i.e., a Cournot equilibrium, hence the superscript *c* in Fig. 2) or through price setting (called a Bertrand equilibrium, hence the superscript *b*). The latter will occur when competition among players is highly aggressive, whereas the former is more likely to occur when competition is less intense (e.g., Tirole 1988)—a matter of the attitudes of the players. It is unclear a priori what mode of competition will emerge, and it is unclear whether captive breeding will enhance or undermine conservation efforts. Farmers and traders would strictly prefer to compete less aggressively (i.e., Cournot manner) if they could commit to such a strategy (benefiting from higher prices and de facto reaping greater market power rewards). It has been demonstrated, however, that lack of commitment devices implies that ambiguities remain, making these greater benefits impossible (Shapiro 1980).

But there is an exception to this rule, and we believe that this exception could be important for "conservation through wildlife farming" efforts in the future. In a duopoly context (i.e., with one farmer and one trader), Kreps and Schienkman (1983) have shown that the type of competition—Cournot or Bertrand—that emerges on the output market can be manipulated by artificially restricting the output level of one of the trading partners. When the government constrains the output level of one of the suppliers, it is in the best interest of the unconstrained supplier to respond by competing in a Cournot fashion—by setting quantities. The mathematical proof of this result is straightforward and available from the authors on request. But this has an important implication. Although restricting the output level of the trader is difficult and expensive, this is not true for controlling the farmer. The farmer's production can presumably be monitored at relatively low cost, and the government can force the farmer to comply at the risk of legal sanctions. This suggests that the ambiguities surrounding unconstrained captive breeding can at times be resolved by managing the farmer's output instead. Thus far, however, we have not seen this issue discussed.

There are various ways for the government to restrict farmers' output. When farmers are heterogeneous (i.e., have different production costs) and when the government cannot differentiate between high- and low-cost farmers, market-based regulatory instruments such as taxes and tradable quota are most efficient because these instruments achieve production levels at lowest cost (most of the production takes place by low-cost farms). Other types of intervention, such as command and control regulation, aggregate quota systems, and subsidies, typically entail efficiency losses. Experiences with fisheries management have taught us that the implementation of a tax system to regulate resource management is often politically infeasible. Quota systems, then, are the most likely candidates to regulate farmers in practice. Although tradable quota are most efficient (independent of whether they are auctioned off or "grandfathered"), a system of nontradable quota may be considered (which is administratively more straightforward) when efficiency concerns are relatively minor or when farmers are relatively homogenous. For more information on managing natural resources, see Hartwick and Olewiler (1986).

It may be hard to sell the idea that restricting the profits of legal firms ensures that illegal ones behave in a certain fashion. But a few observations are in order: (1) if the tradable quotas are auctioned, the money can be used to finance additional enforcement—hurting illegal firms. And (2) by restricting supply in the farming or ranching sector, firms in this sector are capable of generating supernormal profits. They might not object to this type of regulation. Moreover (3) by advocating a cap on the production level of legal firms, we do not specify how stringent the regulation should be. In other words, the aggregate quota can be quite large—given any initial level, a cap precludes a wasteful and risky race to the bottom. But, of course, the higher the level of the cap, the more that residual demand for the illegal commodity falls.

The key insights of this section can be summarized as follows. When the government allows captive breeding to conserve wild stocks, the outcome could be the exact opposite of what is desired—extra poaching pressure and smaller wild stocks. Evidence suggests that there is imperfect competition in the wildlife commodity market; hence, the mode of competition between suppliers is undetermined a priori. It is unclear whether competition will be intense or not, implying that it is unclear whether supplies from the wild will contract or expand. However, if the government does not only allow captive breeding or wildlife farming but at the same time restricts the farmer's output level below the output level that maximizes the farmer's profits, (1) farmer and trader competition is restricted and resembles the Cournot outcome and (2) farming lowers poaching and raises wild stocks.

An Application to Rhinoceros Conservation

Here we demonstrate our key results by applying the model to the case of rhinoceros conservation. Recently, proposals have been put forward to conserve wild stocks by supplying the market with horns from farmed rhinoceros, dehorned on a sustainable basis (e.g., Brown & Layton 2001). We focus on the black rhinoceros (*Diceros bicornis*) for which reasonable data are available. The population has plummeted from an estimated 100,000 animals in 1960 to a current stock of approximately 3000 animals. Poaching for rhinoceros horn has been identified as the chief threat to the species (Dublin & Wilson 1998). We explored the effects of competition from captive-bred substitutes on population levels in the wild under the two modes of competition—passive (Cournot) and aggressive (Bertrand) competition.

We calibrated and simulated the model with data provided by Milner-Gulland and Leader-Williams (1992). Because of the lack of data, we have incorporated a few simplifications consistent with the theoretical model. Our quantitative results are therefore at best a tentative approximation at this stage. Specifically, we adopted the following four simplifying assumptions. First, rhinoceros growth is described by a logistic growth function, as opposed to the skewed growth function common in the ecological literature: $g(x) = 0.16x(1 - x/k)$, where $x =$ rhinoceros stocks and $k = 100{,}000$ animals. Second, the parameter for poaching costs is set such that the no-farming model yields a steady state of 2600 animals (the rhinoceros population in the early and mid 1990s). Third, with respect to farming costs, we assume that the only costs of farming are based on dehorning and approximately

\$1000 per rhinoceros. Fourth, the (inverse) demand function for rhinoceros horn is assumed to be linear and has been derived by fitting a regression line through the price-quantity data that are available, yielding $p(q) = a - bq = 6182 - 2.13q$, where p is the price of rhinoceros horn, q is the number of rhinoceros supplied, and every rhinoceros carries 3 kg of horn. In the absence of data on substitutability, we arbitrarily set the elasticity of substitution between farmed and poached horns at $\gamma = 0.75$ (see Sensitivity Analysis for additional analysis). The inverse demand function used in the numerical analysis therefore reads as $p(q) = 6182 - 2.13q_T - \gamma q_F$, where q_T is supplies from traders and q_F is supplies from farmers. The coefficient γ measures the impact of farmed supplies on the price of commodities obtained from the wild. When $\gamma = b$, the wild and farmed goods are perfect substitutes. Expanding legal supplies will have the same effect on prices as expanding illegal supplies. For most species, however, $\gamma < b$ holds, reflecting that consumers will perceive the wild and farmed commodity as "somewhat different." This may happen, for example, because consumers believe product from the wild is more potent. For γ close to b, there will be strong interaction and rivalry between the two sectors. Conversely when $\gamma = 0$, farmed products have no effect on the price of wild supplies, so there is little strategic interaction between the sectors. Full details of the simulation model are available from the authors.

Figure 3 illustrates the qualitative features of the equilibria with and without rhinoceros farming. The growth of the wild rhinoceros population is given by the concave function $g(x)$. The equilibrium harvest function q, implied by the previously described model, increases in stocks x and is convex-concave in x. Equilibria are defined by the intersection of the $g(x)$ and q curves, where the harvest equals the growth rate (e.g., May 1974). The number of equilibria that results depends on the position and slopes of these curves. When the harvest function intersects the growth curve from below, the equilibria are stable. When the reverse holds, the equilibria are unstable.

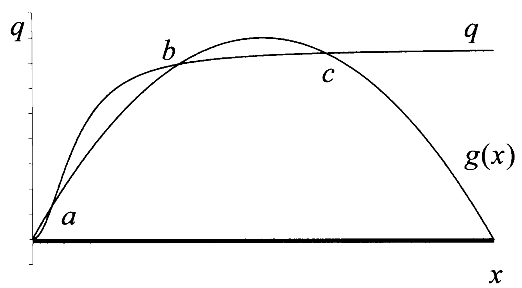

Figure 3. An example of supply from the wild with three population equilibria (a, b, c): a and c are stable and b is unstable (q, harvesting; x, wildlife stock; g(x), growth of the wildlife population).

The simulations reveal that without competition from a farmed substitute, there are three equilibria (outcomes a, b, and c [Fig. 3], of which a and c are stable and b is unstable). We now examine how these equilibria are affected by the introduction of captive-breeding efforts.

The ecological effects of Cournot competition (passive) are summarized in Figs. 4a and b. The curve in Fig. 4a portrays the wildlife population as the number of wildlife farmers increases from 1 to 30; the curve is upward sloping. That is, holding the number of traders

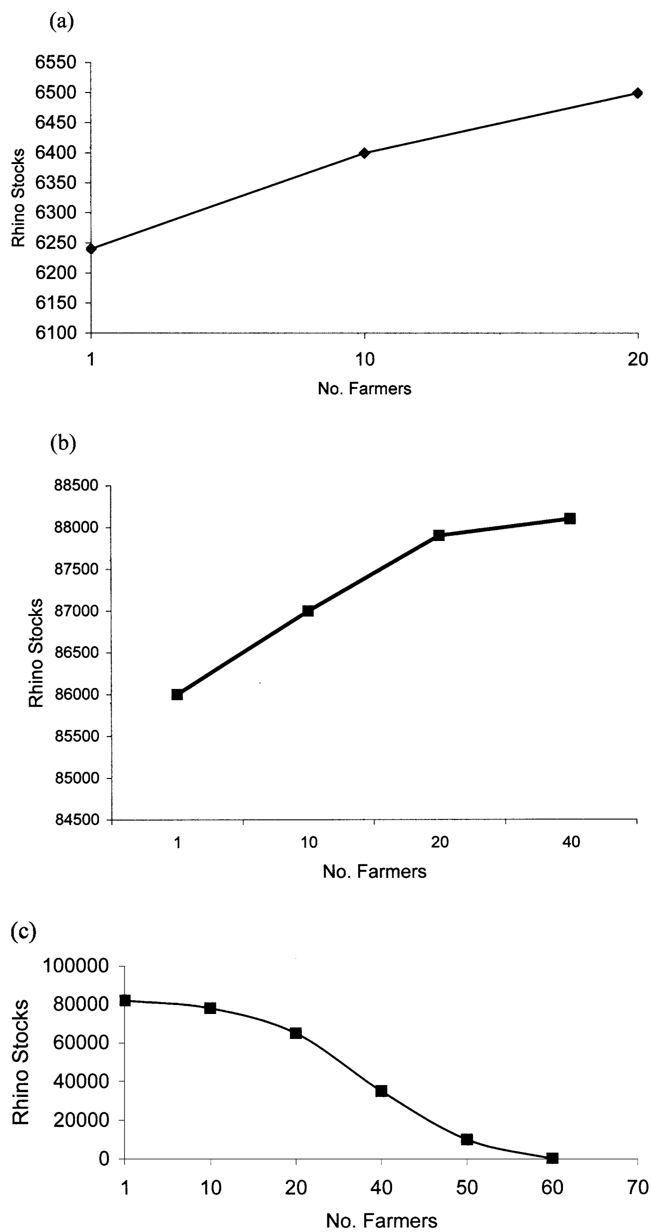

Figure 4. Effects of competition from captive breeders of rhinoceros on the population of wild rhinoceros: (a) low steady state and Cournot competition (see equilibrium a in Fig. 3), (b) high steady state (see equilibrium c in Fig. 3), and (c) Bertrand competition.

constant, increased competition from farmers increases wildlife stocks. (Another result, not shown, is that the number of rhinoceros falls as the number of traders increases and competition is more intense, given the number of farmers.) More importantly, perhaps, is that as the intensity of competition from farms increases, the low, stable equilibrium disappears when the number of farmers is greater than 20. Thus, with Cournot competition, increasing the number of farmers pushes the q curve in Fig. 3 down. This implies that equilibria a and b approach each other, merge, and eventually disappear. As a result, the rhinoceros population "jumps" (in a mathematical sense, not a biological one) to the high-abundance equilibrium (as depicted in Fig. 1b). Hence, encouraging a sufficiently large number of farmers to enter the rhinoceros farming business could result in an enormous conservation success if there is Cournot competition in the rhinoceros horn market.

In the case of the (aggressive) Bertrand competition, there is only one stable equilibrium. The curve in Fig. 4c represents the wildlife population as the number of wildlife farmers increases from 1 to 30, for any given number of traders. Increased competition from farmers induces wildlife traders to lower their price (cut their profit margins) to maintain market share. The curve therefore slopes downward. Holding the number of traders constant, increased competition from farmers lowers wildlife stocks, eventually leading to extinction as competition becomes increasingly aggressive. This is an important result: encouraging a sufficiently large number of farmers to enter the rhinoceros farming business could result in extinction of wild stocks if there is aggressive competition. Moreover as before, and again not shown, increasing the number of traders shifts each curve downward—because competition is more intense, stocks decline more rapidly.

The form of competition thus significantly affects equilibrium stocks, shifting steady states but possibly triggering discontinuous jumps from one steady state to another. These numerical results demonstrate that the behavioral underpinnings of wildlife markets should be of the utmost importance to policy makers. But without sufficient understanding of the market and the biological dimensions of the problem, it is hard to predict what outcome might emerge.

Sensitivity Analysis

The paucity of data, in particular on the economic dimension of the problem (demand and substitution), renders our numerical results imprecise. It is therefore important to examine the robustness of our results to variations in key parameters. In the absence of data on an identifying instrument, it is possible that the estimated parameters of the rhinoceros horn demand function are flawed. It is known that, when demand is sufficiently elastic—the demand curve is sufficiently flat—the oligopolistic outcome approximates the perfect competition outcome, where firms take prices as given (from the perspective of individual suppliers, the demand curve is completely flat). Because there is insufficient information to estimate a demand function, we performed a sensitivity analysis by varying the demand parameters.

A reduction in the slope parameter of the inverse demand function implies that price declines less as the quantity supplied on the market increases (Fig. 5a). Thus, an increase in the supply of rhinoceros horns has less impact on the overall price of wild rhinoceros horns and the profitability of hunting wild rhinoceros. Because prices are less affected by increases in the supply of horns, there is an incentive to increase harvests. All else being equal, as the slope parameter of the inverse demand function declines (Fig. 3), the hunting curve q pivots upward. It follows that for any given level of competition from farmers, the low, stable steady-state equilibrium now occurs at a higher stock of wild rhinoceros (Fig. 5a), and the high, stable steady-state equilibrium occurs at a lower stock of wild rhinoceros (not shown). The qualitative results are therefore unaffected for considerable changes in the slope parameter, but it is clear that the impact on the quantitative results (i.e., the number of rhinoceros in equilibrium) may be large. We believe that this highlights the importance of gathering more price and quantity data on black markets for wildlife commodities. Access to such data will be critical when evaluating the prospects of new approaches to conservation.

Rhinoceros stocks decline more rapidly with more intense farm competition as the slope parameter falls (Fig. 5b). As the slope of the inverse demand function declines, a given increase in the supply of horn has less impact on market price. Hence, there is a stronger incentive for traders to compete more aggressively. Accordingly, wild rhinoceros stocks decline more rapidly as the slope parameter declines, and extinction becomes more likely. Again, the qualitative results are unaffected, but the demand parameter shifts the critical threshold beyond which extinction occurs.

Varying the parameter representing the substitutability of demand between wild and farmed products (γ) has consequences with Cournot competition. As the degree of substitutability between farmed and wild products diminishes, increased competition from farmed products has less impact on the demand for wild rhinoceros horn. Because the degree of competition between the rival sectors is reduced, farming has less impact on hunting levels. All else being equal, the hunting curve q pivots upward as γ declines (Fig. 3). Qualitatively, therefore, the impact of lowering γ is akin to decreasing the slope of the demand curve. Rhinoceros stocks decline in the high equilibrium as the substitutability parameter declines, and they increase in the low equilibrium (these results are not shown).

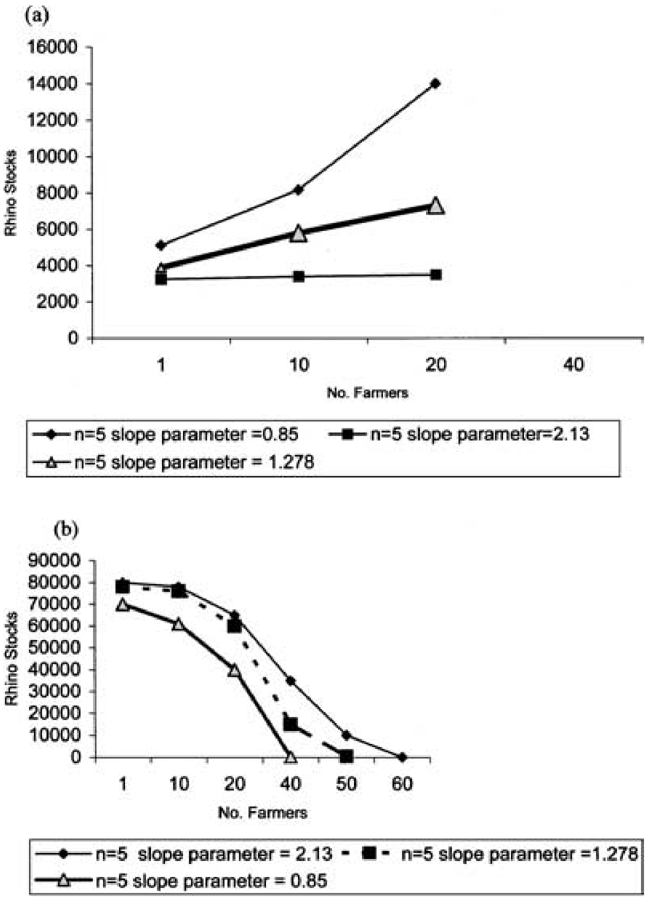

Figure 5. Effects of varying the slope parameter of the demand function, assuming five wildlife traders. (a) Cournot competition: increasing the slope parameter implies that the effect of competition by farmers becomes smaller. (b) Bertrand competition: increasing the slope parameter implies that the effect of competition by farmers becomes smaller.

Varying γ affects the price competition equilibrium (Fig. 6). Because a decline in the degree of substitutability implies that supplies from the farmed sector have less impact on the demand for wild rhinoceros products, there is less incentive for traders to compete aggressively (Fig. 6). Hence, for any given number of farmers (n in Fig. 6), a reduction in the substitutability parameter results in a higher equilibrium stock of rhinoceros. Thus, despite increased farm competition, rhinoceros numbers remain close to carrying capacity levels (Fig. 6). This represents a large qualitative change. When the degree of substitutability of farmed and poached output is sufficiently low, the potentially disastrous effects of Bertrand competition will not occur. This, of course, is intuitive. When the market perceives these commodities as separate entities, the degree of strategic interaction between different types of producers will be mitigated. On the downside, of course, there are few beneficial effects to be expected

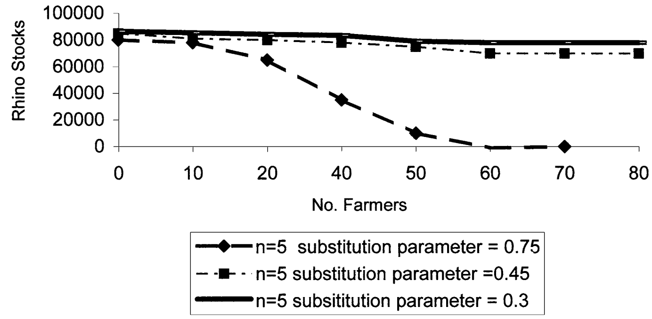

Figure 6. Effect of varying the degree of substitution between farmed output and output from the wild (Bertrand competition). If farmed and wild outputs are better substitutes, increasing the number of farmers has a larger impact on the wild rhinoceros population.

from Cournot competition when the degree of substitutability is very low.

Again, this finding suggests that there should be more applied research into the functioning of (black) markets and consumption of (illegal) wildlife commodities. Currently, there are conflicting signals that hamper accurate predictions in this field. Some evidence suggests farmed commodities are perceived as superior and other evidence suggests farmed output may lack the potency of the "real thing" (e.g., Mills et al. 1995; IUCN/SSC 2001). The issue is further complicated by the fact that legalization of trade may also lead to shifts in the demand curve. For instance, it is possible that legalization may lower the penalties associated with consuming banned products or reduce the stigma attached to consuming these commodities, both of which would reduce the expected costs of consumption and stimulate demand for wild commodities. The consequences of this are obvious. Higher demand will lead to higher prices and thus greater harvesting from the wild—irrespective of the form of competition.

Conclusions

Evidence suggests that the illegal trade in wild animal products is controlled by groups of criminal networks specialized in trafficking illegal commodities across borders. These traders have a substantial grip on the market for wildlife commodities and earn high profits by exercising control over supplies and prices. Thus, the illegal trade in endangered species is characterized by imperfect competition. Failure to acknowledge this fact could have detrimental consequences for wildlife.

Drawing on conventional models of imperfect competition, we show that if competition in the wildlife market is aggressive, a captive-breeding program may result in greater poaching pressure and perhaps accelerate the likelihood of extinction. Conversely, if competition is sufficiently passive, supplies from captive-bred animals could curb poaching and thus be used as a useful adjunct with other conservation policies. A priori, it is extremely difficult to predict the likely response of traders without detailed knowledge of the structural parameters of the market. We also argue, however, that policy makers can affect the nature of the competition by setting quotas for wildlife farmers (which is arguably less expensive than controlling poaching). Our main objective is not to negate the potential for captive breeding as a conservation tool, but rather to sound a note of caution on its use. The picture becomes more complex when we allow for the possibility that consumer preferences are likely unstable and that transaction costs of the illegal trade are affected when a parallel legal trade develops. Our analysis therefore suggests that simple rules of thumb might not exist in the complex world of the international trade in wildlife commodities.

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Appendix: The Supply-Side Perspective on Wildlife Farming

Assume that there are multiple sectors in the economy with varying returns to labor. Presumably this reflects different skill requirements for different sectors, otherwise such income differentials cannot be sustained and will be eroded though entry and exit decisions. Conceptually, line these sectors up from low- to high-income sectors—reflecting increasing opportunity cost of labor, or increasing marginal cost of poaching effort in the aggregate effort level. The person with the lowest skills earns the lowest wage; as the skill level increases, earning power rises. Assuming that there are no special skill requirements for hunting (i.e., labor effort in hunting is homogenous), poachers are first attracted from low-income occupations. If, because of some exogenous shock (e.g., a price or technology shock), the returns to hunting effort suddenly increase, new poachers are attracted from other increasingly profitable alternative occupations until a new equilibrium materializes.

Denote U as the net payoff from poaching for the "marginal poacher." The marginal poacher is defined as the person currently poaching who could earn most if he would switch to some other sector—the most-skilled individual that is hunting. In equilibrium, this marginal poacher must earn zero rents. That is, the return to his labor is as high in poaching as elsewhere in the economy. So-called inframarginal poachers (people with fewer skills and fewer opportunities in the rest of the economy) earn positive rents, and all others in the economy (with higher skill levels) lose money if they were to switch to the hunting sector and hence choose to stay employed elsewhere. The following differential equation captures the essence of this labor allocation process over time:

$$\mathrm{dE/dt} = \eta U = \eta[sq/E - \partial(WE^{\phi})/\partial E], \quad (1)$$

where E denotes aggregate poaching effort, η is an adjustment parameter reflecting the speed with which labor moves around in the economy in response to any profit differentials, s is the net price received by poachers per unit harvested, and q is the total quantity harvested. This implies that the return per unit of poaching effort is simply sq/E. The second term describes the returns to labor in other sectors in a stylized manner ($W > 0$ and $\phi > 1$ are cost parameters—increasing E implies that the income foregone elsewhere also goes up). We assume that these returns can be represented by a continuous function, and without loss of generality we assume that $\phi = 2$ in what follows.

Turning to production in the poaching sector, harvesting is typically described by a so-called Schaefer production function, $q = \sigma xE$, where σ is the "catchability coefficient" and x is the wildlife stock (e.g., Clark 1990). We can complement the basic poaching model by introducing population growth of the species that is harvested. Assuming a conventional logistic growth function, the dynamic system of the resource is described by the following differential equation:

$$\mathrm{dx/dt} = g(x) - q = rx(1 - x/k) - \sigma xE, \quad (2)$$

where $g(x)$ describes the biological growth of the resource, r is the intrinsic growth rate, and k is the carrying capacity. We can take Eq. 1 and Eq. 2 together in a phase plane (Fig. 1b) to analyze this simple dynamic bioeconomic model. In Fig. 1b we present this phase plane, and plot the two isoclines associated with the state variables "hunting effort E" and "population size x." These isoclines are obtained by setting the right-hand side of Eq. 1 and Eq. 2 equal to zero and solving for E as a function of x. The steady state of the dynamic system is at the intersection of the $dE/dt = 0$ isocline (or $E = [\sigma s/2W]x$) and the $dx/dt = 0$ isocline (or $E = r/\sigma[1\text{-}x/k]$) in Fig. 1. This is at point Z. This steady state is unique (as the isoclines are linear), and upon inspecting the direction of trajectories when the system is off equilibrium, it is readily verified that the steady state is stable (not shown in Fig. 1, but see Clark 1990). For point above the $dx/dt = 0$ isocline, $dx/dt < 0$ holds and for points below $dx/dt = 0$ the reverse is true. For points to the right of the $dE/dt = 0$ isocline, $dE/dt < 0$ holds. Similarly, for points to the left of $dE/dt = 0$, we know that $dE/dt > 0$.