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Analysis

Theoretical analysis of a simple permit system for selling synthetic wildlife goods

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ABSTRACT

We present an economic model of a market for wildlife products. We use it to study theoretically the potential impact on the poaching of wildlife animals if a legal market for synthetic wildlife products is created. We show that allowing for a legal trade in synthetic substitutes in general has two opposing effects on poaching level: a *price effect* that reduces poaching by lowering the revenue generated from poaching; and a *laundering effect* that encourages poaching by making it easier for poachers to sell their products. When demand for wildlife goods is inelastic, the price effect is bigger, while the laundering effect is smaller; hence, establishing a legal market for synthetic substitutes is more likely to reduce poaching when demand is less sensitive to price changes. Measures that make it more difficult for poachers to launder their products reduce the laundering effect and enhance the conservation value of producing synthetic substitutes.

1. Introduction

With many wild species threatened by overexploitation for the purpose of trading in their harvested products, there is much interest in identifying appropriate measures to mitigate the effects of illegal and unsustainable wildlife trade ('t Sas-Rolfes et al., 2019). Among the measures considered—and increasingly implemented—are so-called 'supply-side' (expansion) approaches, which seek to reduce wild-harvesting pressure by introducing cheap substitutes, typically produced through wildlife farming (Damania and Bulte, 2007; Harfoot et al., 2018). However, many critics consider this approach to be controversial or risky. For some, commercial captive breeding and trade of wild animals raises serious animal welfare concerns (Baker et al., 2013). Others claim that wildlife farming still draws on wild stocks and has been linked to the decline of certain species in Southeast Asia (Brooks et al., 2010). This has prompted policy advisors and scholars to develop frameworks to assess the conditions under which such supply-side approaches might succeed as a conservation tool (Cooney et al., 2015; Phelps et al., 2014).

Recent rapid advances in technology have added a new candidate for supply expansion interventions: substitute products produced by synthetic biology. The prospect of fabricating and selling products such as synthetic rhino horns (Mi et al., 2019) and elephant ivory (Fischer et al., 2019) as substitutes for genuine products harvested from these threatened species has generated much media interest and stirred up a heated debate in the conservation community (Nuwer, 2019). On one side are innovative scientists and biotech companies such as Pembient that propose to manufacture synthetic products that are biologically or chemically equivalent to the real thing. They contend that the availability of synthetic substitutes at much lower prices than wild harvested products would reduce the demand for the latter, diminish their value, and reduce the amount of poaching that has adversely affected wild populations of threatened species (Corbyn, 2015; Mi et al., 2019). On the other side of the debate are various wildlife NGOs such as Save the Rhino, WildAid, and the Wildlife Justice Commission, that staunchly oppose the manufacture and sale of synthetic products. With some theoretical support from the economic literature (Fischer, 2004), these groups fear that, rather than reducing poaching levels, the availability of synthetic products would stimulate greater demand for wild-harvested products and provide a cover for the illegal trade of those products (i.e., 'laundering'), thereby leading to even more poaching (Save the Rhino, 2015; Nuwer, 2019).

The concerns of these NGOs echo the objections against other supply expansion interventions— those that oppose legal sales of synthetic products appear to find law enforcement concerns most persuasive, taking their cue from officials who report attempts at laundering (Zhou, 2014). However, synthetic products offer two distinct potential advantages over other conventional supply expansion approaches. First,

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they avoid the potential direct harms to the welfare of individual organisms inherent in farming and other harvesting practices. Second, since production levels are unconstrained by biology, this allows for the adoption of genuine 'market flooding' strategies that avoid any direct negative impacts on the numbers of live animals or plants. This could be especially advantageous in the case of species that are slow growing and difficult to farm (e.g., pangolins—see Challender et al., 2019).

To date, there has been limited rigorous analysis and examination of the potential impact of synthetic products on the market for wild-harvested products using the principles and tools of economics. Chen (2017) took a step in addressing this lacuna and considered how a monopoly producer of synthetic rhino horns that consumers cannot distinguish from real horns would behave if its sole objective is to maximize profit. However, this analysis does not explicitly account for the abovementioned concerns of wildlife NGOs. Therefore, there is currently a lack of firm theoretical understanding of how the introduction of synthetic wildlife products into the market could affect poaching levels of the species in question.

Given that this is a topic of great interest and concern to mainstream conservation bodies (Redford et al., 2014) and also currently under discussion among the parties to CITES, the Convention on International Trade in Endangered Species in Wild Fauna and Flora (Kinderlerer, 2018), we submit that such deliberations should be informed by perspectives beyond the narrow interests of law enforcement officials. To contribute toward this need, we present a theoretical model of a market for a wildlife good and consider plausible consequences if producers of an essentially indistinguishable synthetic substitute product are allowed to enter into the market. We assume that the sale of the synthetic product is legal only if the seller obtains a permit from the government at some cost. As mentioned earlier, wildlife NGOs worry that a legal market for a synthetic substitute could end up facilitating illegal trades in the wildlife good by providing a means for poachers to launder their merchandises—especially since it may be difficult or extremely costly for law enforcement agencies to distinguish between the synthetic and the real products. Therefore, we consider the worst-case scenario in which any seller—whether a poacher or a synthetic good producer—can obtain a sales permit as long as they incur the cost of getting one. Because the impact of the synthetic product on poaching levels depends on how easy it is for illegal sellers to disguise their wares as such products—among several other factors such as the price of those synthetic goods—analyzing the case in which poachers and producers of the synthetic good have the same ability to gain legal market access gives us a lower-bound assessment—i.e., the most pessimistic point-of-view—of the conservation effects of introducing synthetic substitutes into the market.

The analysis of the model presented here shows that allowing synthetic substitutes in general leads to two opposing effects on the level of poaching: a *price effect* that tends to reduce poaching by lowering the revenue from selling harvested wildlife goods; and a *laundering effect* that tends to promote more poaching by making it easier and less costly for illegal suppliers to sell their products. Whether poaching overall will increase or decrease in response to the availability of the synthetic substitutes depends on which of these effects is stronger. In particular, the price effect becomes greater as consumer demand becomes less price elastic; hence—even when illegal suppliers cannot be restricted from obtaining permits—allowing producers of the synthetic substitute into the market is more likely to reduce poaching when demand is relatively insensitive to price changes. In the case of products for which consumer demand is thought to be price-inelastic (e.g., rhino horn—see Milner-Gulland, 1993; Brown and Layton, 2001), the results of our analysis suggest that legalizing the trade of synthetic substitutes could be an effective way to curb the level of poaching.

The exposition is organized as follows. First, we present the theoretical model of the wildlife product market, lay out the assumptions employed in the analysis, and present some technical results to demonstrate that the model is well-formulated in the sense that a unique equilibrium of the market always exists. Next, we show how the impact of introducing a synthetic substitute into the market can be decomposed into two opposing components—the aforementioned price and laundering effects—and how their relative magnitude depends on how sensitive consumer demand is to price changes. Finally, we discuss some policy implications of the results presented here and discuss how the model can be modified to examine other related issues and concerns regarding the wildlife trade.

2. The model

The market under consideration consists of a set of buyers and two sets of wildlife product suppliers: the "poachers[1]" who supply the natural product; and the "biotech" firms that produce the synthetic product. We will first examine the market when there are no biotech firms (which can arise when they are restricted by regulation from entering the market).

2.1. The market without synthetic goods

Buyers

The number of (potential) buyers in the market is $N_B > 0$, where we assume N_B is continuous for convenience. Each buyer buys at most one unit of the product, and a buyer's valuation of (or willingness-to-pay for) the wildlife product is denoted by $v > 0$. The distribution of v among the buyers is given by the cumulative distribution function $F_B(\cdot)$, i.e., the number of buyers with valuation v below some value x is $N_B F_B(x)$.[2]

Sellers (poachers)

Now, consider the supply side of the market. The number of (potential) poachers is $N_W > 0$, where N_W is assumed to be continuous. We assume for the sake of simplicity that each poacher supplies either nothing or one unit of the wildlife good. A poacher's cost of supplying the good is denoted by c_W. Because the poachers can differ from one another in their cost of supplying the wildlife good (due, for instance, to heterogeneity in hunting ability or opportunity costs), we describe the population of poachers by the distribution of this supply cost c_W among the poachers. Let $F_W(\cdot)$ denote the cumulative distribution function of c_W among the poachers, i.e., $N_W F_W(x)$ is the number of poachers with supply cost c_W below value x. In what follows, we will refer to a poacher with cost c_W as a type-c_W poacher or seller.

Law enforcement

Assume that it is illegal to sell the wildlife product and that when a poacher tries to sell his[3] good there is some given probability $\mu \in [0, 1)$ that he will be caught by law enforcement agencies. A poacher who gets arrested incurs a penalty cost of $\phi \geq 0$[4] and loses his product.

Market equilibrium

If a buyer's valuation v exceeds the price of the product p, then the buyer would choose to purchase the good; if $v < p$, then the buyer would not purchase the good; if $v = p$, then the buyer is indifferent

[1] For the sake of simplicity, we use the term 'poachers' to collectively represent all actors in the illegal supply chain, acknowledging that in reality the constituent actors perform different roles, with varying levels of market power.

[2] The assumption that a buyer can buy at most one unit of the good is imposed purely for ease of exposition. The model could be extended to the case where each buyer can purchase multiple units of the good (and the buyer's willingness-to-pay for an additional unit may vary with the amount purchased); this, however, would not substantively change the main implications of the model.

[3] Because the illegal wildlife trade is dominated by men (McElwee, 2012), we only use the masculine pronouns in our exposition.

[4] Penalties for poaching could include prison sentences in addition to fines. Moreover, people who are arrested for poaching may incur significant legal costs. For simplicity, we ignore distinctions between the various types of costs that could arise from being arrested, and lump all of them into the penalty cost ϕ.

between the two options, and either one is optimal for the buyer. Given price p, the total demand for the good is thus $N_B(1 - F_B(p))$.

If a type-c_W poacher chooses to supply the good, then his expected revenue—taking into account the risk of getting caught by law enforcement agencies—given product price p is $(1 - \mu)p - \mu\phi$. Whether a type-c_W poacher would choose to supply the good depends on the comparison between c_W and $(1 - \mu)p - \mu\phi$: it would be optimal for the poacher to supply the good only if the expected revenue is at least the cost of supply. Therefore, given that only the fraction $1 - \mu$ of the goods for sale will get past law enforcement and reach the market, the aggregate supply of the good at price p is $(1 - \mu)N_WF_W((1 - \mu)p - \mu\phi)$.

In equilibrium, the market price must equate demand and supply, i.e., an equilibrium price p^* satisfies

$$N_B(1 - F_B(p^*)) = (1 - \mu)N_W F_W((1 - \mu)p^* - \mu\phi). \tag{1}$$

For simplicity, it will be assumed throughout this exposition that $F_B(\cdot)$ and $F_W(\cdot)$ are continuous and that: $F_W(0) = F_B(0) = 0$; $F_B(\cdot)$ is strictly increasing over $[0, \overline{p}]$ for some $\overline{p} > 0$; $F_B(\overline{p}) = 1$; and $F_W((1 - \mu)\overline{p} - \mu\phi) > 0$.

Theorem 1. An equilibrium price exists and is unique.

Proof. Consider the function $f(p) \equiv N_B(1 - F_B(p)) - (1 - \mu)N_WF_W((1 - \mu)p - \mu\phi)$. Given the stated assumptions for the model, $f(0) > 0$ and $f(\overline{p}) < 0$. By continuity, there must exist a $p^* \in (0, \overline{p})$ such that $f(p^*) = 0$. Since $f(\cdot)$ is strictly decreasing over $[0, \overline{p}]$, p^* must be unique. Q.E.D.

2.2. The market with synthetic goods

Now, suppose we have a competitive biotech sector that produces a synthetic version of the wildlife product that is indistinguishable from the real or natural product. Further, we will assume for simplicity that the synthetic good is a perfect substitute for the natural good so that a buyer derives the same value from either product. It has been noted that a synthetic substitute—even if biochemically identical to the real product—may be considered by consumers to be less valuable or desirable than the natural wildlife good (Ball, 2015). We explain later on in the *Discussion and Conclusion* section that our main results concerning the conservation value of synthetic substitutes are strengthened if we assume instead that the synthetic good is an imperfect and inferior substitute for the natural wildlife good.

Sellers (biotech firms)

There are $N_S > 0$ synthetic good producers (or biotech firms), where we assume N_S is continuous for convenience. To keep the analysis simple, we assume without loss of generality that each biotech firm can produce nothing or one unit of the synthetic good. The cost of producing the synthetic product is denoted by c_S. To allow for the possibility that the biotech firms can differ in their cost of producing the synthetic good, we will describe the biotech sector by how the biotech firms' cost c_S is distributed: let $F_S(\cdot)$ be the cumulative distribution function of c_S in the biotech sector. This means that the number of biotech firms in the model with production cost c_S less than some given value x is $N_SF_S(x)$. Because the proponents of developing synthetic wildlife substitutes are ultimately interested in displacing the natural products in markets for wildlife goods through lower prices (Mi et al., 2019)—which can only happen through lower supply cost—we will therefore assume that the cost of producing the synthetic good overall is lower than the cost of supplying the natural good: $F_S(x) \geq F_W(x)$ for all $x \geq 0$.

Law enforcement

As before, supplying the natural product is considered illegal. Suppose, however, that it is legal to sell the synthetic product as long as the seller has a permit for doing so. More specifically, the rules governing the market are as follows.

- A seller must obtain a permit at cost $\gamma \geq 0$ in order to transact legally.
- The certification or permit system is "soft" in that, because the synthetic product cannot be distinguished from the real product by assumption, any seller (poacher or biotech firm) can obtain a permit as long as the cost γ is paid.
- If a seller (poacher or biotech firm) tries to sell a product without a permit, then the seller has probability μ of getting caught; in that event, the seller incurs a penalty cost of ϕ.

In what follows, we will assume for convenience and without loss of generality that every biotech firm will obtain a permit in order to make a sale, i.e., no biotech firm will transact illegally.

We note that the assumption that the certification system is soft—i.e., poachers have the same ability and incur the same cost as biotech firms to obtain permits—is highly unrealistic. In practice, government and law enforcement agencies would undoubtedly impose certain measures or restrictions on sellers to make it more difficult for poachers to obtain permits for selling real wildlife products.[5] Put differently, we would expect in reality the cost of obtaining a sales permit for poachers to be higher—if the certification system is well designed, significantly higher—than the cost of acquiring a permit for biotech firms.

Hence, assuming in our analysis that poachers and biotech firms have the same cost of obtaining permits allows us to analyze the worst-case scenario in which it is "as easy as possible" for the poachers to launder their products in the wildlife market. An immediate implication of this assumption is the following: any condition under which the introduction of the biotech sector benefits wildlife by reducing poaching levels with a soft certification system must also lead to outcomes in which having the biotech sector decreases poaching when the certification system is more stringent (for the poachers). In other words, our analysis allows us to identify the minimal conditions that are required for the existence of synthetic substitutes to benefit wildlife conservation.

Market equilibrium

Because the synthetic and real products are perfect substitutes and indistinguishable from one another by assumption, there is only one price in this market, and the total demand for the products given price p is $N_B(1 - F_B(p))$.

If all the biotech firms would obtain a permit if they choose to produce, then it is optimal for a type-c_S firm to supply the synthetic good given price p if $p - \gamma > c_S$ (if $p - \gamma = c_S$, the firm is indifferent between producing and not producing, and could go either way). The supply of synthetic goods at price p is therefore $N_SF_S(p - \gamma)$.

The supply decision of a poacher is not as straightforward since the poacher has to choose whether to obtain a permit or not if he decides to supply the (real) good. Obtaining a permit yields revenue $p - \gamma$, while trying to sell the good without a permit gives an expected revenue of $(1 - \mu)p - \mu\phi$. Because $p - \gamma \gtreqless (1 - \mu)p - \mu\phi$ as $p \gtreqless \frac{\gamma}{\mu} - \phi$, let us define $p_c \equiv \frac{\gamma}{\mu} - \phi$. The price p_c is a threshold price such that it is more profitable to sell the good with a permit if the product price is above the threshold, and it is more profitable in expectation to sell the good without a permit if the price is below the threshold. Hence, the supply of the natural good at price p is $N_WF_W(p - \gamma)$ if $p > p_c$, and $(1 - \mu)N_WF_W((1 - \mu)p - \mu\phi)$ if $p < p_c$. At $p = p_c$, due to indifference, the supply of the real good is anywhere between $(1 - \mu)N_WF_W((1 - \mu)p - \mu\phi)$ and $N_WF_W(p - \gamma)$.

Combining the supply decisions of both the biotech firms and the poachers gives us the total supply of goods at price p:

[5] Authorities could, for instance, make use of genetic databases that allow investigators to match wildlife products with tissues from poached animals—see Harper et al. (2018) for a system that was developed for African rhinos.

$$N_S F_S(p-\gamma) + \begin{cases} N_W F_W(p-\gamma) & \text{if} \quad p > p_c \\ n \in [(1-\mu)N_W F_W((1-\mu)p-\mu\phi), N_W F_W \\ (p-\gamma)] & \text{if} \quad p = p_c \\ (1-\mu)N_W F_W((1-\mu)p-\mu\phi) & \text{if} \quad p < p_c \end{cases}.$$

An equilibrium price p^{**} equates aggregate demand and aggregate supply:

$$N_B(1-F_B(p^{**}))$$

$$= N_S F_S(p^{**}-\gamma) + \begin{cases} N_W F_W(p^{**}-\gamma) & \text{if} \quad p^{**} > p_c \\ n \in [(1-\mu)N_W F_W((1-\mu)p^{**}-\mu\phi), N_W F_W(p^{**}-\gamma)] & \text{if} \quad p^{**} = p_c \\ (1-\mu)N_W F_W((1-\mu)p^{**}-\mu\phi) & \text{if} \quad p^{**} < p_c \end{cases}. \quad (2)$$

For ease of exposition, assume that $F_S(\cdot)$ is continuous and that $F_S(0) = 0$.

Theorem 2. An equilibrium price exists and is unique.

Proof. Consider the correspondence

$$G(p) \equiv N_B(1-F_B(p)) - N_S F_S(p-\gamma) - \begin{cases} N_W F_W(p-\gamma) & \text{if} \quad p > p_c \\ [(1-\mu)N_W F_W((1-\mu)p-\mu\phi), N_W F_W \\ (p-\gamma)] & \text{if} \quad p = p_c \\ (1-\mu)N_W F_W((1-\mu)p-\mu\phi) & \text{if} \quad p < p_c \end{cases}.$$

Given the stated assumptions for the model and Kakutani's fixed point theorem, there must exist a $p^{**} \in (0, \overline{p})$ such that $0 \in G(p^{**})$. Uniqueness follows from the monotonicity of $F_B(\cdot)$, $F_W(\cdot)$, and $F_S(\cdot)$. Q.E.D.

3. Analysis and policy implications

Let us now examine how the existence of the biotech sector that produces the synthetic good affects the amount of poaching under the soft certification system. We will assume that γ is not prohibitively high in the sense that, in the market equilibrium with the biotech sector, some biotech firms would choose to produce the synthetic good. Formally, this assumption is given by $F_S(p^{**} - \gamma) > 0$. A key observation we can make at the outset is that—compared to the market without the synthetic substitutes—the equilibrium price in the market with the biotech sector is lower. The intuition for this is straightforward: with the biotech firms in the market, there is a larger supply of products at any price, and this puts downward pressure on price.

Observation 1: *The equilibrium price with the biotech sector in the market is lower than the equilibrium price without the biotech sector:* $p^* > p^{**}$.

Proof. Suppose not—suppose $p^* \leq p^{**}$. First, note that the total supply of goods at price p^{**} is at least $N_S F_S(p^{**} - \gamma) + (1 - \mu) N_W \max\{F_W((1 - \mu)p^{**} - \mu\phi), F_W(p^{**} - \gamma)\}$. Therefore, we have

$$\begin{aligned} N_B(1-F_B(p^{**})) &\geq N_S F_S(p^{**}-\gamma) + (1-\mu)N_W \\ &\quad \max\{F_W((1-\mu)p^{**}-\mu\phi), F_W(p^{**}-\gamma)\} \\ &> (1-\mu)N_W \max\{F_W((1-\mu)p^{**}-\mu\phi), F_W(p^{**}-\gamma)\} \\ &\geq (1-\mu)N_W F_W((1-\mu)p^{*}-\mu\phi) \\ &= N_B(1-F_B(p^{*})), \end{aligned}$$

where the second line follows from the assumption $N_S F_S(p^{**} - \gamma) > 0$, the third line follows from the hypothesis that $p^* \leq p^{**}$, and the last line follows from the definition of p^* as the equilibrium price in the market without the synthetic goods. These, together, imply that $N_B(1 - F_B(p^{**})) > N_B(1 - F_B(p^*))$, which is impossible since $F_B(\cdot)$ is strictly increasing over $[0, \overline{p}]$ by assumption. This is the desired contradiction. Q.E.D.

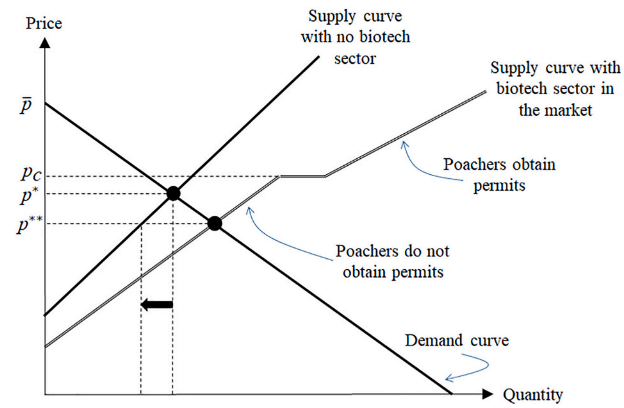

Fig. 1. If the certification cost γ is too high so that no poacher would choose to obtain a permit in equilibrium ($p^{**} < p_c$), then allowing the biotech firms to enter the market under a soft certification mechanism would unambiguously reduce the amount of poaching.

At first blush, we might expect that the soft certification mechanism, by allowing any poacher to obtain a supply permit as long as he pays the cost γ, would increase the amount of poaching relative to the market without the biotech sector since the permit system gives the poachers an avenue to bypass law enforcement agencies. This, however, is not necessarily true.

First, just because the permit system is available does not mean that the poachers would utilize it in equilibrium—it all depends on how the cost of acquiring a permit compares to the expected cost of supplying the wildlife good without a permit. If the cost of a permit is too high so that few poachers would obtain one—this occurs when the price of the wildlife good is below the threshold price p_c—then allowing the biotech firms to enter the market would unambiguously reduce the amount of poaching. This follows because the availability of the synthetic goods, by driving down market price, would make poaching less lucrative given that the poachers do not acquire permits (see Fig. 1).

Note in Fig. 1 that the supply curve with the biotech sector in the market has a jump at price p_c. This is because for prices below p_c, poachers do not acquire permits, and the fraction of natural wildlife products that reach the market is $1 - \mu$; for prices above p_c, poachers will obtain permits in order to sell their products legally, and all natural products that are poached will reach the market. At price p_c, poachers are indifferent between acquiring permits and not obtaining them; hence, depending on which option the poachers choose, the fraction of natural products that reach the market at that price is anywhere between $1 - \mu$ and 1.

Consider now the case where γ, the cost of getting a supply permit, is relatively low so that the poachers would choose to acquire a permit in the market equilibrium when the biotech firms are present, i.e., the equilibrium price with the synthetic good producers in the market exceeds p_c (see Fig. 2).

Unlike the situation depicted in Fig. 1, in this scenario the introduction of the biotech sector—along with the soft certification system—has two (rather than one) effects on the poaching sector: there is a decrease in the equilibrium price (let us refer to this as the *price effect*); and the poachers are able to use the permit system to sell their wares legally rather than "go underground" (let us refer to this as the *laundering effect*).

In terms of the impact on poaching levels, the price effect and the

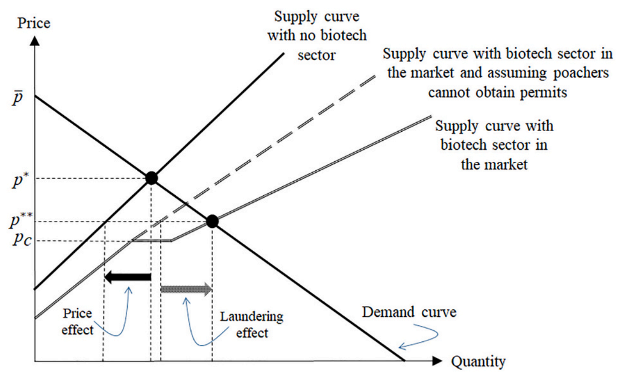

Fig. 2. If the certification cost γ is low enough so that the poachers would choose to acquire a permit in equilibrium ($p^{**} > p_c$), then allowing the biotech firms to enter the market under a soft certification mechanism has two opposing effects on the amount of poaching: the price effect, which tends to reduce poaching; and the laundering effect, which tends to increase poaching.

laundering effect work in opposite directions. All else being equal, the price effect decreases the amount of poaching since a lower equilibrium price means less revenue from selling the wildlife product.

On the other hand, the laundering effect—assuming all else fixed—raises the amount of poaching because a supply permit allows a poacher to avoid getting caught by law enforcement agencies and increases the probability of making a sale. More rigorously, we can quantify the laundering effect by comparing the supply of wildlife goods (both synthetic and real) at the market equilibrium price p^{**} to what the supply of wildlife goods (again, both synthetic and real) would have been at price p^{**} if there is a way to prohibit any poachers from acquiring sales permits. (The dashed line in Fig. 2 represents what the supply curve of wildlife goods would look like if there are biotech firms in the market and all poachers can be prevented from obtaining permits.)

How the introduction of the synthetic good—along with a soft certification mechanism—would affect the level of poaching overall depends on which of these effects—the price effect and the laundering effect—is stronger. Specifically, if the price effect dominates, then allowing the biotech firms to enter the market under a soft certification system would reduce the overall level of poaching activity (relative to the market without a biotech sector).

Observation 2: *Allowing synthetic good producers in the market can reduce poaching, even with a soft certification mechanism.*

Note that if the soft certification mechanism is replaced with an ideal mechanism that can restrict any poacher from obtaining a permit, then there would be no laundering effect whatsoever, and allowing the biotech firms in the market would unambiguously reduce the amount of poaching.

On the other hand, if the laundering effect is stronger than the price effect, then having the biotech sector in the market would increase the amount of poaching under the soft certification mechanism. This leads to the following observation.

Observation 3: *If in equilibrium poachers acquire permits, then poaching level may be higher with the biotech sector in the market, though not necessarily.*

One significant factor that determines how strong the price effect is relative to the laundering effect—and hence whether allowing the biotech firms to produce the synthetic substitute would increase or decrease the level of poaching—is how responsive consumer demand is to price changes. The magnitude of the price effect is determined by how much the equilibrium price declines when the biotech sector is allowed into the market. Therefore, if consumer demand is highly sensitive to price changes—i.e., demand is very elastic—then the drop in equilibrium price resulting from introducing the biotech sector would be small; this means that the laundering effect is more likely to

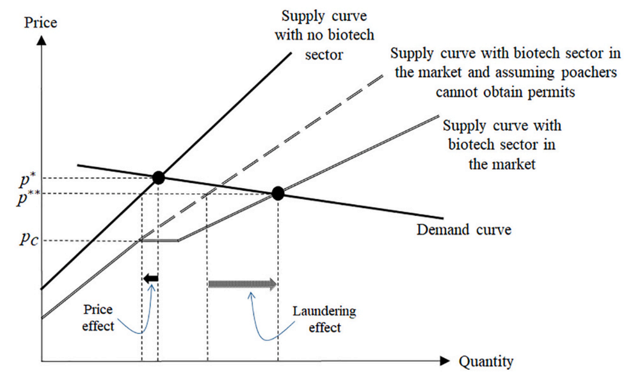

Fig. 3. Assuming the certification cost γ is sufficiently low, the price effect on poaching resulting from allowing the biotech firms in the market is small when demand is sensitive to price changes.

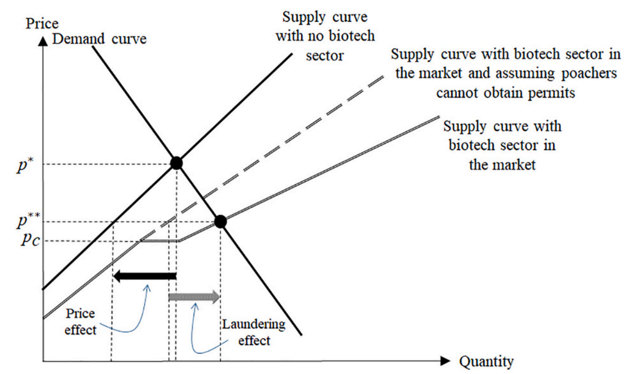

Fig. 4. Assuming the certification cost γ is sufficiently low, the price effect on poaching resulting from allowing the biotech firms in the market is large when demand is not sensitive to price changes.

dominate the price effect, yielding a market equilibrium with more poaching (see Fig. 3).

However, if demand is quite inelastic—i.e., not so sensitive to changes in price—then letting the biotech firms into the market would bring about a relatively large price drop. A big price change means a strong price effect, which in turn implies that the availability of the synthetic substitute is more likely to result in lower poaching levels (see Fig. 4).

Observation 4: *If consumer demand is highly inelastic (resp., elastic), then allowing the biotech sector in the market is more likely to result in lower (resp., higher) poaching level.*

A more formal analysis of this result is given in the Appendix.

3.1. Numerical example

To give a better sense of the implications of our model, we consider the rhino horn market in China,[6] for which we have some recent indicative data. Based on 't Sas-Rolfes (2012), the estimated market equilibrium outcome in 2011 consists of 2.5 tons of rhino horns traded at a price of $65,000/kg. From Brown and Layton (2001), the demand elasticity of rhino horns is –0.47. Assuming the market demand curve has constant price elasticity and that the market outcome in 2011 is a

[6] The main driver of prices in the Chinese market appears to be consumer demand for carved ornaments and trinkets (Gao et al., 2016; Moneron et al., 2017; Stoner et al., 2017), for which we can imagine that an indistinguishable synthetic substitute would be competitive.

point on this curve, the market demand is $D(p) = 414670p^{-0.47}$. (For ease of computation, we use the demand function $D(p) = 414670p^{-0.5}$ in our calculations.)

The average East Asian horn price more recently is around $26,000/kg (WJC, 2017; UNODC, 2020). Assuming this drop in price since 2011 was caused by a shift of the supply curve outwards,[7] our estimated demand curve tells us that an equilibrium price of $26,000 would yield an equilibrium quantity of 2572 kg.

We assume that poachers' cost of supplying the real wildlife product is uniformly distributed over some interval $[\underline{c}, \overline{c}]$. For our calculations, we chose $\underline{c} = \$5,000$, which is in line with the findings in Haas and Ferreira (2016) and UNODC (2020).

For ϕ, the penalty cost of poaching, we chose $25,000. This figure was derived as follows. In China, the penalty for trafficking in rhino horn includes prison time (and fines). Assuming that a trafficker who is arrested gets a 10-year sentence—and given that the per capita income from wages and salaries in China in 2019 is around $2500 (National Bureau of Statistics of China, 2020)—the foregone earnings from imprisonment is $25,000. We use this figure to be a rough estimate of the cost of being arrested for poaching and trafficking.

Given the stated assumptions above and supposing the supply curve of real rhino horns includes the outcome (2572 kg, $26,000), the supply curve of poachers as a function of their cost c_W is $\frac{643(c_W - 5000)}{750(7 - 17\mu)}$. Note that this is the amount of horns that are not confiscated by law enforcement—these are the wildlife products that actually reach the consumers. The total amount of horns poached as a function of poacher cost c_W is greater and given by $\frac{643(c_W - 5000)}{750(7 - 17\mu)(1 - \mu)}$.

Based on figures in UNODC (2020), the amount of rhino horns seized by authorities between 2014 and 2017 is around 700 kg. Using this information and our estimated poachers' supply curve yields a value of around 0.2 for the probability of apprehension μ.

For the biotech firms, because high quality synthetic rhino horns are still in the development stage, it is difficult to determine what their cost structure will be. Given that the cost of producing synthetic substitutes in the diamond industry has dropped dramatically in the last ten years with the advent of new technologies (Bain and Company, 2018), we use that industry as a guide and assume for our model that the biotech firms' costs are one-tenth of those of the poachers. More specifically, we assume that c_S is $500. We set $N_S = 1,000$ so that the biotech sector collectively can produce at most 1000 kg of synthetic products.[8]

Using this model specification, we examine how the market equilibrium—specifically, the price and amount of poaching—is affected by the permit cost γ when the biotech sector is added to the market (see Fig. 5). We note that the parameter values were chosen so that, in the absence of the biotech sector, the market equilibrium price and quantity are $26,000 and 2572 kg,[9] respectively.

In this example, when the permit cost γ is too high ($10,000 or more), no poacher would choose to acquire a permit in equilibrium. On the other hand, when γ is lower than $10,000, the poachers would prefer to obtain permits in order to sell their goods legally. In either case, having the biotech firms in the market reduces the equilibrium price and amount of poaching relative to the market outcome without the biotech sector.

For the sake of comparison, let us suppose that the probability of apprehension μ is lower and equal to 0.1 instead; all other parameter values and specifications remain the same. Fig. 6 below shows what happen to the equilibrium price and poaching amount with the biotech firms in the market given this change. Because the probability that a poacher will get arrested for supplying the real wildlife good is so low in this case, no poacher would choose to acquire a permit to masquerade as a biotech firm. Therefore, the laundering effect is completely absent, and the availability of the synthetic substitutes would unambiguously reduce the equilibrium horn price and the amount of poaching.

For one more example, suppose the probability of apprehension μ is back at 0.2, but the penalty cost for getting arrested for poaching, ϕ, decreases from $25,000 to $20,000. All other aspects of the model remain as before. With this change, the supply curve of poachers as a function of their cost c_W is $\frac{643(c_W - 5000)}{250(21 - 46\mu)}$. How the equilibrium price and amount of poaching change as the permit cost γ varies is shown in Fig. 7. Just as in the previous examples, making the synthetic products available in the market decreases the product price and reduces the equilibrium amount of poaching.

We emphasize that we present the above numerical examples for purely illustrative purposes to show how the model works and some of the qualitative implications of our model. The exact numerical figures derived in the examples above should be treated with caution since we have made significant simplifying assumptions and had to rely on the limited rhino horn trading data available in our calculations. For instance, we did not analyze in detail the different levels of the supply chain involved in rhino horn trafficking, nor did we consider the possibility of speculative traders who stockpile rhino horns for the purpose of selling them for profit at a later date. These are important extensions of the model that should be examined in detail in future research.

3.2. Strengthening the certification system

So far in our analysis, we have assumed the “worst case” in which poachers have the same ability as biotech firms to acquire permits for selling wildlife goods. In this subsection, we will consider what happens to the equilibrium amount of poaching when poachers' cost of acquiring permits differs from that of biotech companies (which could arise because, for example, poachers need to incur some expenses in faking the provenance of their products).

As before, let γ denote biotech firms' cost of obtaining permits, and let γ' denote poachers' cost of acquiring permits. Whether a poacher should obtain a permit to sell his product or transact illegally again depends on whether or not the market price of the product p exceeds a threshold price, where the threshold is now defined by $p_c{}' \equiv \frac{\gamma'}{\mu} - \phi$. At price p, the total supply of wildlife product in the market with the biotech sector is thus

$$N_S F_S(p-\gamma) + \begin{cases} N_W F_W(p-\gamma') & \text{if } p > p_c{}' \\ n \in [(1-\mu)N_W F_W((1-\mu)p - \mu\phi), N_W F_W(p-\gamma')] & \text{if } p = p_c{}'. \\ (1-\mu)N_W F_W((1-\mu)p - \mu\phi) & \text{if } p < p_c{}' \end{cases}$$

As usual, the equilibrium of the market is defined by the condition that total demand has to equal total supply.

Now, let us consider what happens to the market equilibrium when poachers' cost of obtaining permits increases from γ' to some higher level $\gamma'' > \gamma'$, which could result, for instance, from better enforcement of the certification system. Let p' denote the equilibrium price when the poachers' cost of acquiring permits is γ', and let p'' denote the equilibrium price when their cost of acquiring permits is γ''. To rule out trivial cases, assume that $p' > p_c'$ so that poachers would obtain permits in equilibrium when their cost of doing so is γ'.

When poachers' cost of acquiring permits increases from γ' to γ'', the

[7] A shift of the demand curve downwards would also cause a drop in price. However, this would be accompanied by a decline in horn quantities, which would be inconsistent with the finding that the number of rhinos poached in 2016 was greater than the number poached in 2011. While it is possible that both the demand curve and the supply curve have shifted down in the last few years—with the supply curve shifting relatively more—in the absence of any empirical evidence to ascertain this, we make the simplest assumption that only the supply curve had shifted.

[8] We imposed a relatively low production constraint on the biotech sector to avoid trivialities; if the biotech sector's capacity were set too high, the market price would be driven so low that no real wildlife product would be supplied by poachers.

[9] This is the amount that actually reaches the market to the buyers. The total amount of poaching corresponding to this quantity of consumption is 3340 kg.

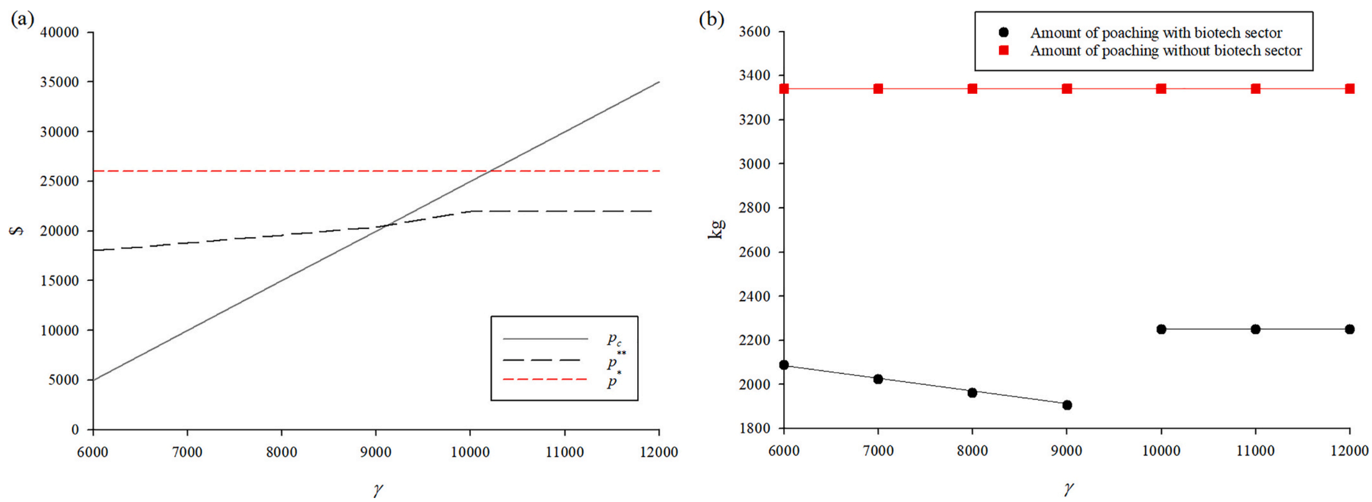

Fig. 5. (a) The equilibrium price p^{**} in the market with the biotech sector as it varies with respect to the permit cost γ. (b) The equilibrium amount of poaching in the market with the biotech sector as it varies with respect to the permit cost. For γ greater than $9000, no poacher would obtain a permit. Hence, there is a "jump" in the level of poaching for γ between $9000 and $10,000, because poachers without permits need to acquire a greater amount of real horns in order to account for the amount that will be confiscated by law enforcement agencies.

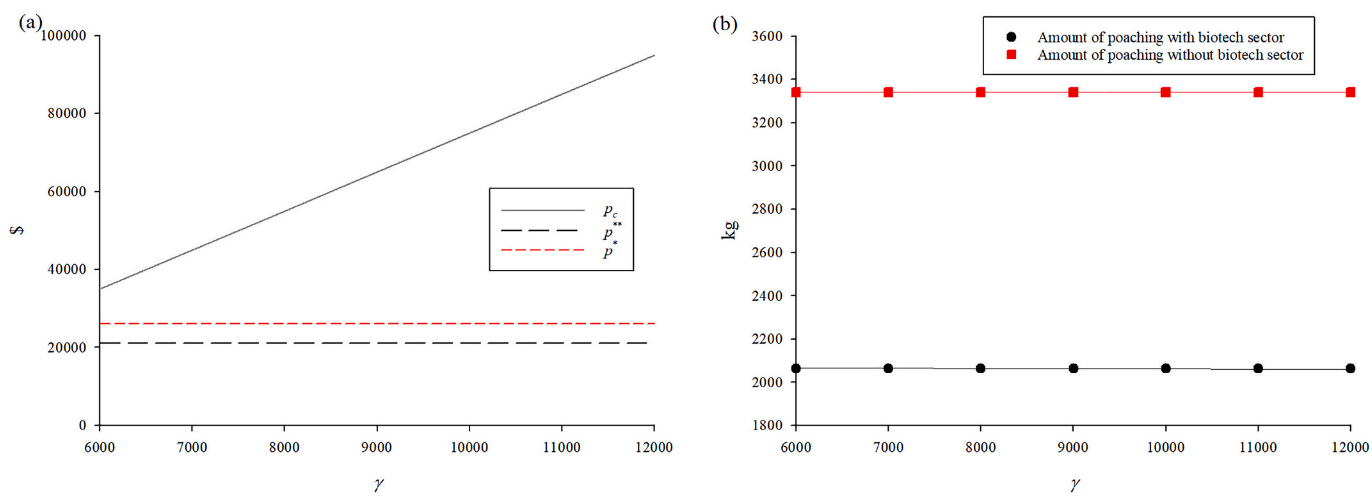

Fig. 6. The probability of apprehension μ is 0.1. (a) The equilibrium price p^{**} in the market with the biotech sector as it varies with respect to the permit cost γ. (b) The equilibrium amount of poaching in the market with the biotech sector as it varies with respect to the permit cost.

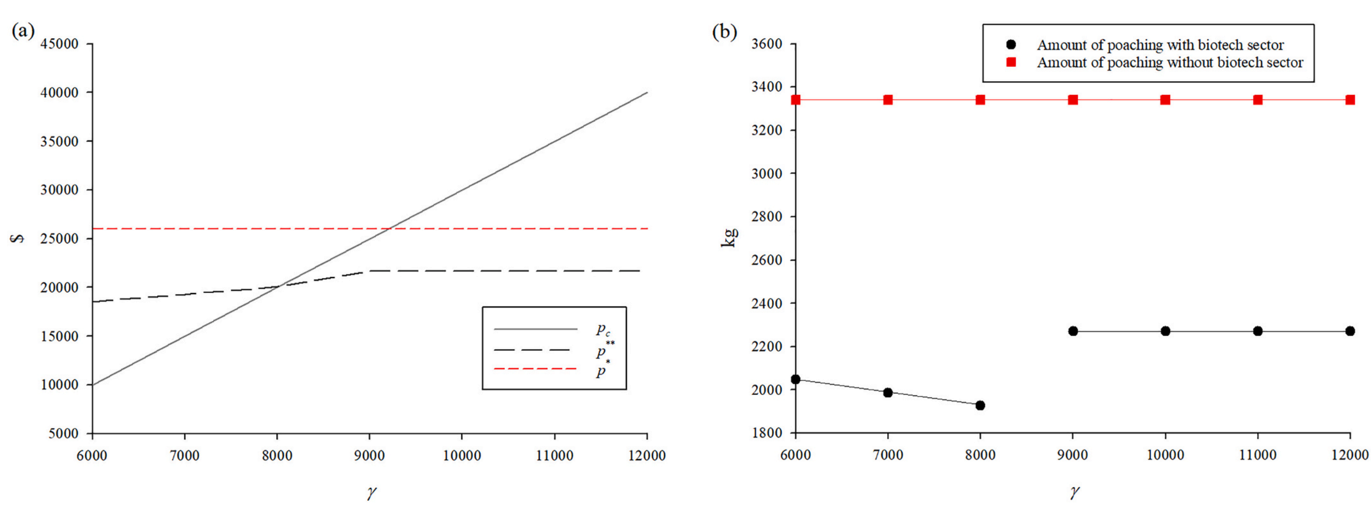

Fig. 7. The penalty cost ϕ is $20,000. (a) The equilibrium price p^{**} in the market with the biotech sector as it varies with respect to the permit cost γ. (b) The equilibrium amount of poaching in the market with the biotech sector as it varies with respect to the permit cost. There is a "jump" in the level of poaching for γ between $8000 and $9000, because poachers would not acquire permits if γ exceeds $8000.

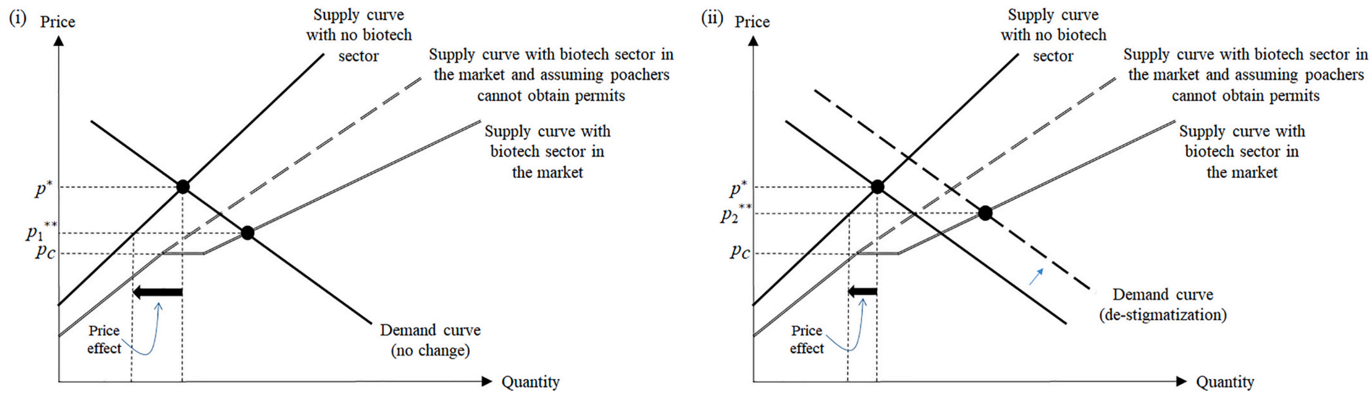

Fig. 8. (i) When the availability of the synthetic substitutes does not lead to any de-stigmatization effect, the equilibrium price drops from p^* to p_1^{**}. (ii) When the availability of the synthetic substitutes has a de-stigmatization effect on consumption, then the equilibrium price drops from p^* top_2^{**}.

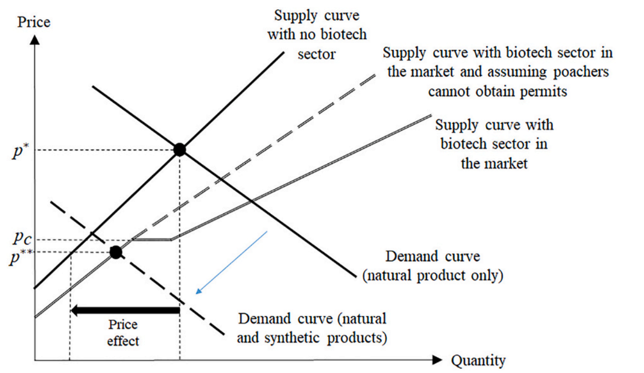

Fig. 9. If consumers view the synthetic product as significantly inferior to the natural product, then allowing the biotech firms to enter the market would shift the demand downward and cause a large decrease in price. This could potentially eliminate the laundering effect.

threshold price determining whether poachers should get permits or not increases from p_c' to $p_c'' \equiv \frac{\gamma''}{\mu} - \phi$. There are two possible cases to consider.

Case 1: $p'' < p_c''$. In this case, making it more costly for poachers to acquire permits leads to the outcome in which no poachers get them. This means the laundering effect disappears when the cost of obtaining permits is γ''.

Case 2: $p'' \geq p_c''$. In this case, the poachers will still choose to acquire permits when the cost of getting them increases. As we show in the Appendix, this, however, must lead to a reduction in the amount of poaching.

Therefore, no matter which case obtains, making it more difficult for poachers to obtain permits or get certification in the model unambiguously is better for conservation purposes.

4. Discussion and conclusion

Opponents of proposals to combat wildlife poaching by producing and selling synthetic versions of wildlife products point out that a legal market for the synthetic good could result in more poaching by providing a cover for the illicit trade in genuine harvested products. The analysis here shows that this is indeed a valid concern, but only under certain conditions. Previous studies suggest relatively price-inelastic demand or supply for rhino horn (Milner-Gulland, 1993; Brown and Layton, 2001) and elephant ivory (Do et al., 2020), and the results here tell us that in such cases introducing a synthetic substitute into the market is more likely to reduce the overall level of poaching. This finding is consistent with that of Becker et al. (2006), who demonstrate that optimal regulations depend on demand and supply elasticities.

In the exposition here, we assumed that the synthetic product is a perfect substitute for the real product. This means that the model can be applied directly—with suitable renaming of variables and parameters—to study the impact on poaching of allowing a legal trade in a (farmed) wildlife product (Di Minin et al., 2015). The results and implications of the model here therefore support the essential proposal of Biggs et al. (2013), who assert that, given inelastic demand, providing consumers with a suitable substitute—through a carefully regulated legal harvest of horns, in their opinion—is the most viable option for curbing rhino poaching. They also support the assertion of Farah and Boyce (2019) that mammoth ivory imports to China have served to assist significant reductions in both elephant ivory prices and elephant poaching.

A few caveats and comments regarding the model are in order, however. First, allowing a synthetic substitute (or farmed or other substitute) into the wildlife product market could stimulate consumer demand—by, for example, removing any stigma that may be attached to the consumption of the wildlife good (Fischer, 2004; Save the Rhino, 2015). As shown in Fig. 8, this de-stigmatization effect serves to weaken the price effect of introducing a legal substitute into the market.

Second, a synthetic product—even if engineered to be biochemically identical to the real thing—may be valued less than the natural product (whether procured from the wild or farmed) by consumers (Ball, 2015). If buyers are unable to distinguish between the synthetic and the natural products, then the uncertainty caused by having both types of products in the market would lead to a downward shift of the demand curve (Chen, 2017). This would enhance the price effect and—if the price drop is sufficiently large, which, for example, could result if the synthetic product is deemed significantly inferior to the natural product—eliminate the laundering effect (see Fig. 9). Therefore, a major difference—one that apparently has not been noted by others in the literature—between allowing a legal trade in farmed substitutes and allowing a legal trade in synthetic substitutes is that introducing synthetic products into the market is potentially more beneficial from a conservation perspective.[10]

An additional point to note about the analysis here is that, for ease of exposition, we assumed that the biotech sector is perfectly competitive, i.e., each synthetic good producer is small relative to the whole market. Depending on the technology required to develop and manufacture high quality synthetic substitutes, and how intellectual property rights of such products are allocated, this perfect competition assumption may not be reasonable. As Chen (2017) showed, when there is a monopoly producer of a synthetic substitute that is interested solely in

[10] Note that this applies to farming systems that operate independently from wild populations rather than cases in which farming revenues may support conservation efforts (such as with extensive wildlife ranching in Southern Africa—see Child et al., 2012).

profit maximization, it may prefer to restrict its supply to keep the market price high. In that case, the price effect of allowing synthetic substitutes into the market could be dampened (relative to a market with a perfectly competitive biotech sector), thereby reducing the conservation benefit of making synthetic products available. Because the model in Chen (2017) does not incorporate the laundering effect considered here, a possible topic for future research is to examine how the market for the wildlife good would be affected given a monopolistic or oligopolistic biotech sector under a soft certification mechanism.

Another important extension of the current model to examine in future work is to give buyers the ability to distinguish between the synthetic product and the natural good—albeit at some cost. For instance, suppliers of real wildlife goods may engage in costly market signaling activities or invest in reputation-building in order to credibly differentiate their products from those sold by the biotech firms. Buyers could also undertake various forms of information-acquisition behavior prior to making purchases so as to be better informed about the types of goods that are for sale. While incorporating these elements into the analysis should not eliminate the conservation value of synthetic substitutes—since they raise the cost of supplying and consuming the natural wildlife goods—it remains to be seen theoretically to what extent the laundering effect introduced by the availability of synthetic goods offsets their beneficial conservation impact in this context.

Further extensions to the model could examine possible interactions with two other related phenomena that have been discussed in the literature. The first—as previously mentioned—is the effects of speculative stockpiling of storable wildlife products (Kremer and Morcom, 2000) and the second is the effects of dynamic interactions between increasing rarity of wildlife species and their product prices (Holden and McDonald-Madden, 2017; Burgess et al., 2017); the latter effects will also vary with institutional context (i.e., open access versus stronger property rights over wildlife). Given these phenomena—and depending on the market structure (i.e., the extent and nature of competition)—the introduction of the synthetic product may result in strategic competitive responses that could affect market prices and harvesting rates (Damania and Bulte, 2007; Mason et al., 2012). Dynamic incentive effects that arise from speculative stockpiling and seller competition could affect a legal market for synthetic wildlife products very differently from a legal market for farmed substitutes; therefore, there may be cases for which a combination of synthetic and farmed products could be simultaneously introduced to the market as a potential measure to reduce poaching (e.g., rhino horn trade—see 't Sas-Rolfes, 2016). This is a topic that requires further analysis and investigation.

Finally, for illustrative purposes, the analysis here mainly considered the simplest and most extreme certification mechanism whereby any seller who is willing to pay the required certification cost would be able to obtain a permit to legally sell their product. In reality, if synthetic substitutes are to be legally allowed in the marketplace, government authorities would no doubt require stricter certification mechanisms that would make it difficult for poachers to obtain permits in order to minimize the laundering effect. The big, practical question here thus is what that certification mechanism should look like. This is another issue that should be addressed in the future. However, as the results here show, any certification mechanism that makes it harder for poachers to launder the real wildlife products would only enhance the conservation benefits of introducing synthetic substitutes into the market.

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Declaration of Competing Interest

None.

Appendix A

The price effect, the laundering effect, and the elasticity of demand

Here, we examine more rigorously how the elasticity of demand affects the relative magnitudes of the price and laundering effects that arise from introducing a biotech sector into the wildlife market. For ease of exposition, we consider market demand curves with constant elasticities, i.e., the total quantity demanded as a function of price p has the functional form kp^{-r}, where k and r are positive parameters. The elasticity of demand (in magnitude) is thus r.

Let us consider two demand curves, $k_1p^{-r_1}$ and $k_2p^{-r_2}$, where $r_2 > r_1$. Suppose k_1 and k_2 are such that, without a biotech sector in the market, both market demand curves yield the same equilibrium price p^*, i.e., without synthetic products available, the two markets have the same outcome in equilibrium (see Fig. A1).

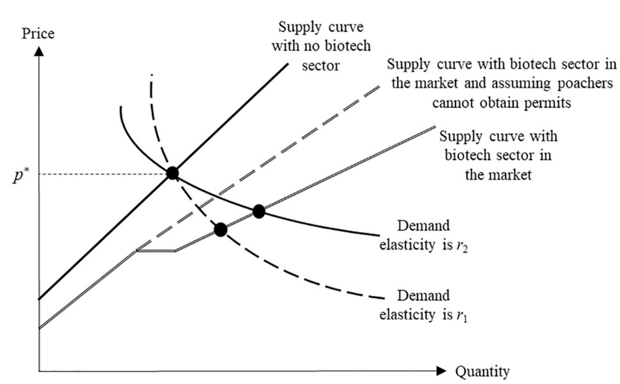

Fig. A1. How the elasticity of demand affects the equilibrium price when the biotech sector is allowed into the market.

Note from Fig. A1 that—once the biotech sector is added to the market—the new equilibrium price is higher with a higher elasticity of demand (assuming that the cost of acquiring a permit γ is low enough that poachers would obtain one in equilibrium). Hence, the price effect—the reduction in poaching resulting from a lower market price—must be greater when the elasticity of demand is lower.

Moreover, we can show that if the poaching supply curve is linear the laundering effect must be lower when the elasticity of demand is lower. To see this, recall that the laundering effect is measured by the difference between the aggregate supply with the biotech sector in the market and the aggregate supply when the biotech firms are in the market but the poachers are not able to acquire permits. Given price $p > p_c$, the aggregate supply with the biotech sector in the market (and poachers are able to obtain permits) is $N_S F_S(p - \gamma) + N_W F_W(p - \gamma)$; and the aggregate supply with the biotech firms assuming poachers cannot obtain permits is $N_S F_S(p - \gamma) + (1 - \mu)N_W F_W((1 - \mu)p - \mu\phi)$. Therefore, at price p, the magnitude of the laundering effect is $N_W F_W(p - \gamma) - (1 - \mu)N_W F_W((1 - \mu)p - \mu\phi)$.

If the distribution function of poaching costs, $F_W(\cdot)$, is linear, then $N_W F_W(p - \gamma) - (1 - \mu)N_W F_W((1 - \mu)p - \mu\phi)$ is unambiguously increasing in price p. This implies that raising the elasticity of demand—which leads to a higher equilibrium price when the biotech sector is in the market—would increase the magnitude of the laundering effect. By the same logic, reducing the elasticity of demand would decrease the laundering effect.

Numerical examples (numbers used in Figs. 5-7).

Table of numbers used in Fig. 5

γ	p_c	p^{**}	Amount poached (kg)
6000	5000	18,018	2089
7000	10,000	18,800	2024
8000	15,000	19,593	1962
9000	20,000	20,395	1904
10,000	25,000	21,944	2249
11,000	30,000	21,944	2249
12,000	35,000	21,944	2249

Table of numbers used in Fig. 6

γ	p_c	p^{**}	Amount poached (kg)
6000	35,000	21,082	2062
7000	45,000	21,082	2062
8000	55,000	21,082	2062
9000	65,000	21,082	2062
10,000	75,000	21,082	2062
11,000	85,000	21,082	2062
12,000	95,000	21,082	2062

Table of numbers used in Fig. 7

γ	p_c	p^{**}	**Amount poached (kg)**
6000	10,000	18,515	2048
7000	15,000	19,288	1986
8000	20,000	20,072	1927
9000	25,000	21,670	2271
10,000	30,000	21,670	2271
11,000	35,000	21,670	2271
12,000	40,000	21,670	2271

Increasing the cost of acquiring permits decreases the amount of poaching

Suppose poachers' cost of acquiring permits increases from γ' to γ'', with $p'' \geq p_c''$.

First, we show that $p'' \geq p'$. Since $p' > p_c'$ by assumption, the equilibrium condition determining the value of p' is given by $N_B(1 - F_B(p')) = N_S F_S(p' - \gamma) + N_W F_W(p' - \gamma')$. Because $F_W(\cdot)$ is monotonic, if on the contrary $p'' < p'$, we would get

$$\begin{aligned} N_B(1 - F_B(p')) &= N_S F_S(p' - \gamma) + N_W F_W(p' - \gamma') \\ &\geq N_S F_S(p' - \gamma) + N_W F_W(p' - \gamma'') \\ &\geq N_S F_S(p'' - \gamma) + N_W F_W(p'' - \gamma'') \\ &= N_B(1 - F_B(p'')), \end{aligned}$$

which implies that $1 - F_B(p') \geq 1 - F_B(p'')$. This, however, contradicts the strict monotonicity of $F_B(\cdot)$. Therefore, we must have $p'' \geq p'$.

Next, we show that the amount of poaching is lower with cost γ'' than with cost γ', i.e., $N_W F_W(p'' - \gamma'') \leq N_W F_W(p' - \gamma')$. Suppose to the contrary $N_W F_W(p'' - \gamma'') > N_W F_W(p' - \gamma')$. This yields

$$\begin{aligned} N_B(1 - F_B(p'')) &= N_S F_S(p'' - \gamma) + N_W F_W(p'' - \gamma'') \\ &> N_S F_S(p'' - \gamma) + N_W F_W(p' - \gamma') \\ &\geq N_S F_S(p' - \gamma) + N_W F_W(p' - \gamma') \\ &= N_B(1 - F_B(p')), \end{aligned}$$

where the second inequality follows from $p'' \geq p'$ and the monotonicity of $F_S(\cdot)$. This implies that $1 - F_B(p'') > 1 - F_B(p')$, which contradicts $p'' \geq p'$ and the strict monotonicity of $F_B(\cdot)$. This completes the proof.

References

't Sas-Rolfes, M., 2012. The Rhino Poaching Crisis - A Market Analysis. Available at: http://www.rhinoresourcecenter.com/pdf_files/133/1331370813.pdf.
't Sas-Rolfes, M., 2016. Rhino poaching: what is the solution? Solutions J. 7 (1), 38–45.
't Sas-Rolfes, M., et al., 2019. Illegal wildlife trade: scale, processes, and governance. Annu. Rev. Environ. Resour. 44 (1), 201–228.
Bain & Company, 2018. The Global Diamond Industry. Retrieved from: https://www.bain.com/contentassets/a53a9fa8bf5247a3b7bb0b10561510c2/bain_diamond_report_2018.pdf.
Baker, S.E., et al., 2013. Rough trade: animal welfare in the global wildlife trade. BioScience 63 (12), 928–938.
Ball, P., 2015. Material witness: the complex costs of faking it. Nat. Mater. 14 (7), 660.
Becker, G.S., Murphy, K.M., Grossman, M., 2006. The market for illegal goods: the case of drugs. J. Polit. Econ. 114 (1), 38–60.
Biggs, D., Courchamp, F., Martin, R., Possingham, H.P., 2013. Legal trade of Africa's rhino horns. Science 339 (6123), 1038–1039.
Brooks, E.G.E., Roberton, S.I., Bell, D.J., 2010. The conservation impact of commercial wildlife farming of porcupines in Vietnam. Biol. Conserv. 143 (11), 2808–2814.
Brown, G., Layton, D.F., 2001. A Market Solution for Preserving Biodiversity: The Black Rhino (pp. 32–50). Cambridge University Press, Cambridge.
Burgess, M.G., et al., 2017. Range contraction enables harvesting to extinction. Proceedings of the National Academy of Sciences 114 (15), 3945.
Challender, D.W.S., et al., 2019. Evaluating the feasibility of pangolin farming and its potential conservation impact. Glob. Ecol. Conserv. 20, e00714.
Chen, F., 2017. The economics of synthetic rhino horns. Ecol. Econ. 141, 180–189.
Child, B., et al., 2012. The economics and institutional economics of wildlife on private land in Africa. Pastoralism: Research, Policy and Practice 2 (1), 18.
Cooney, R., et al., 2015. The Trade in Wildlife: A Framework to Improve Biodiversity and Livelihood Outcomes. International Trade Centre, Geneva, Switzerland Available at: http://www.intracen.org/uploadedFiles/intracenorg/Content/Publications/2014-2015-76_Low%20Res%20PDF_Trade%20in%20Wildlife(4).pdf.
Corbyn, Z., 2015. "Can we Save the Rhino from Poachers with a 3D Printer?" May 24. Retrieved from: https://www.theguardian.com/environment/2015/may/24/artificial-3d-printed-fake-rhino-horn-poaching#maincontent.
Damania, R., Bulte, E.H., 2007. The economics of wildlife farming and endangered species conservation. Ecol. Econ. 62 (3–4), 461–472.
Di Minin, E., et al., 2015. Identification of policies for a sustainable legal trade in rhinoceros horn based on population projection and socioeconomic models. Conserv. Biol. 29, 545–555.
Do, Q.-T., et al., 2020. The price elasticity of African elephant poaching. World Bank Econ. Rev. lhaa008. https://doi.org/10.1093/wber/lhaa008.
Farah, N., Boyce, J.R., 2019. Elephants and mammoths: the effect of an imperfect legal substitute on illegal activity. Environ. Dev. Econ. 1–27.
Fischer, C., 2004. The complex interactions of markets for endangered species products. J. Environ. Econ. Manag. 48 (2), 926–953.
Fischer, D., Parks, S.C., Mannhart, J., 2019. Bio-inspired synthetic ivory as a sustainable material for piano keys'. Sustainability 11 (23), 6538 Multidisciplinary Digital Publishing Institute.
Gao, Y., et al., 2016. Rhino horn trade in China: an analysis of the art and antiques market. Biol. Conserv. 201, 343–347.
Haas, T.C., Ferreira, S.M., 2016. Combating rhino horn trafficking: the need to disrupt criminal networks. PLoS One 11 (11), e0167040.
Harfoot, M., et al., 2018. Unveiling the patterns and trends in 40 years of global trade in CITES-listed wildlife. Biol. Conserv. 223, 47–57.
Harper, Cindy, Ludwig, Anette, Clarke, Amy, Makgopela, Kagiso, Yurchenko, Andrey, Guthrie, Alan, Dobrynin, Pavel, et al., 2018. Robust forensic matching of confiscated horns to individual poached African rhinoceros. Curr. Biol. 28 (1) R13-R14.
Holden, M.H., McDonald-Madden, E., 2017. High prices for rare species can drive large populations extinct: the anthropogenic Allee effect revisited. J. Theor. Biol. 429, 170–180.
Kinderlerer, J., 2018. Study on wildlife products produced from synthetic or cultured DNA'. CITES. Available at: https://cites.org/sites/default/files/eng/com/ac-pc/ac30-pc24/AC30-14-PC24-14-R1-A5.pdf, Accessed date: 23 July 2020.
Kremer, M., Morcom, C., 2000. Elephants. Am. Econ. Rev. 90 (1), 212–234.
Mason, C.F., Bulte, E.H., Horan, R.D., 2012. Banking on extinction: endangered species and speculation. Oxf. Rev. Econ. Policy 28 (1), 180–192.
McElwee, P., 2012. The Gender Dimensions of the Illegal Trade in Wildlife. Gender and Sustainability: Lessons from Asia and Latin America. pp. 71–93.
Mi, R., Shao, Z.Z., Vollrath, F., 2019. Creating artificial rhino horns from horse hair. Sci. Rep. 9 (1), 1–6.
Milner-Gulland, E.J., 1993. An econometric analysis of consumer demand for ivory and rhino horn. Environ. Resour. Econ. 3 (1), 73–95.
Moneron, S., Okes, N., Rademeyer, J., 2017. Pendants, Powder and Pathways: Smuggling Routes and Techniques in the Illicit Trade in African Rhino Horn. TRAFFIC East/Southern Africa, Pretoria, South Africa.
National Bureau of Statistics of China, 2020. "Households' Income and Consumption Expenditure in 2019." Retrieved from. http://www.stats.gov.cn/english/PressRelease/202001/t20200119_1723719.html.
Nuwer, R., 2019. Scientists Created Fake Rhino Horn. But Should We Use It? The New York Times(November 25) Retrieved from: https://www.nytimes.com/2019/11/25/science/synthetic-rhino-horn.html.
Phelps, J., Carrasco, L.R., Webb, E.L., 2014. A framework for assessing supply-side wildlife conservation: wildlife farming and cultivation. Conserv. Biol. 28 (1), 244–257.
Redford, K.H., et al., 2014. Synthetic biology and the conservation of biodiversity. Oryx 48 (3), 330–336.
Save the Rhino, 2015. "Synthetic rhino horn: will it save the rhino?" May 11. Retrieved from: https://www.savetherhino.org/thorny-issues/synthetic-bio-fabricated-rhino-horn-will-it-save-the-rhino/.
Stoner, S., Verheij, P., Wu, M.J., 2017. Black Business: Illegal Rhino Horn Trade Dynamics in Nhi Khe, Vietnam from a Criminal Perspective: A Case Study. Wildlife Justice Commission.
UNODC, 2020. World Wildlife Crime Report. United Nations Office on Drugs and Crime.
WJC, 2017. Black Business: Illegal Rhino Horn Trade Dynamics in Nhi Khe, Vietnam from a Criminal Perspective: A Case Study. Wildlife Justice Commission.
Zhou, Z.-M., 2014. Synthetic ivory fails to stop illegal trade. Nature 507 (7490), 40.