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Transnational links in rhino poaching and the black-market price of rhino horns

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Rhino poaching in South Africa and India's major range states have been remarkably similar over time. Organised criminal syndicates manage an illegal supply chain of rhino horns from poachers, middlemen and corrupt authorities to East Asian black-markets. In this paper, we use rhino poaching data from South Africa and India to examine the plausibility of transnational links and coordination in their supplies of rhino horns. We develop an innovative model of oligopolistic collusion in supply and find empirical evidence to support the theory, while controlling for rhino horn demand features, corruption, governance quality, and conservation policy. Furthermore, we propose an inventory management model of a criminal syndicate that controls the horn supply chain. The method retraces and forecasts black-market prices and has potential applicability in estimating supply or demand elasticities. This paper is the first to suggest an oligopolistic feature of the poaching industry. It highlights the need to reorient conservation policy to account for possible coordination of rhino horn supplies between range states.

Key words: conservation economics, environmental and ecological economics, natural resource management, wildlife.

1. Introduction

Rhino poaching has been emerging as a major conservation crisis. Charismatic megafauna species like rhinos and elephants are targeted for their body parts and sold illegally. In the last couple of decades, the demand for rhino horns has been increasing substantially (Crookes and Blignaut 2015), and so has the supply as suggested by the growing poaching incidents (Sas-Rolfes 2012). Economics can be used to shed light on market demand and supply characteristics of rhino horns. However, such studies are limited due to the lack of data on black-market prices, demand, and supply. Trade in rhino horns was banned in 1977 by the Convention on International Trade in Endangered Species (CITES 2017). Milner-Gulland (1993) uses linear regression to estimate price and income elasticities for rhino horns using consumer data prior to the CITES ban. However, data on black-market prices, supply and consumption are largely unavailable postban. Economic analysis must therefore circumvent this lack of data in order to ascertain a black-market's characteristics. A deeper understanding of such characteristics is useful for conservation policy. The ability to derive unknown prices using

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limited data could decipher trends in demand and supply, and thereby direct conservation efforts towards reducing demand or supply when prices are expected to increase.

Economic analysis of markets relies on a modelling framework with certain assumptions. Crookes and Blignaut (2015) develop a system dynamics model of market demand to estimate demand elasticities for rhino horns using data on legal trophy hunting. Their study asks whether trade legalisation might improve rhino conservation. They examine the effect of legalising trade on rhino populations and behaviour of consumers and suppliers. Milner-Gulland finds that consumers are price inelastic but highly income elastic, indicating that rhino horns are luxuries and demand reduction is necessary for conservation. Crookes and Blignaut find that conventional demand reduction strategies that influence the price of rhino horn are unlikely to reduce poaching; instead, less conventional strategies like consumer behaviour modification through education might be more effective in reducing demand compared to legalising horn trade. In this study, we will focus instead on the illegal aspects of poaching wherein black-markets for rhino horns are prevalent.

Apart from assessing the effect of market demand on rhino poaching, other studies have examined the various reasons behind poaching in particular national parks. For instance, Poudyal *et al.* (2009) and Lopes (2014) find significant effects of sociopolitical unrest on increasing rhino poaching in the Chitwan Park in Nepal and the Kaziranga Park in India. They account for demand by using East Asian income in their regressions. A number of studies and reports have highlighted reasons behind the increase in rhino poaching in South Africa or India (Baura and Talukdar 2008; Milliken and Shaw 2012; Hübschle *et al.* 2016); however, not much attention has been paid to the similarity of rhino poaching patterns between the major rhino range states of South Africa and India (Lopes 2014). Conservation organizations allude to the rhino poaching crisis spreading from South Africa to India (WWF 2013). Moreover, with rhino poaching increasing in India conservation organizations have cautioned Indian authorities to step up antipoaching measures in light of the increasing South African poaching (Emslie *et al.* 2016). Apart from anecdotal evidence pointing to a link between South African and Indian rhino poaching while examining the relationship between sociopolitical unrest and rhino poaching in India, Lopes (2014) assumes South African rhino poaching to be an indicator for that in India. We rigorously confirm the validity of that assumption by developing an economic model of collusion and corroborating it with empirics.

We firstly examine the possibility of collusion between suppliers from the two major rhino range states. We develop a model of an oligopolistic industry, hypothesise that South Africa is a collusive quantity-leader, and then empirically test for quantity-leadership by suppliers of South African rhino horns and quantity-following by suppliers of Indian rhino horns.

This collusive imperfect market structure has not been considered in the literature. Given the lack of black-market horn prices, we devise a reduced-form regression framework in which equilibrium prices become implicit via the equating of demand and supply. Regressions will test the hypothesised collusive relationship between South Africa and India. Similar to other studies, we account for the effects of demand on poaching (Milner-Gulland 1993; Poudyal *et al*. 2009; Lopes 2014; Crookes and Blignaut 2015). We also estimate income elasticities and compare them to others' estimates. Secondly, this paper considers the effect of institutional quality on poaching – an aspect that has received little attention in the economics literature despite the evidence of institutional weaknesses exacerbating poaching (Milliken and Shaw 2012; Hübschle *et al*. 2016). To this end, we use World Bank indices on institutional quality (Kaufmann and Kraay 2017). Thirdly, we develop a novel methodology to retrace unknown black-market prices using data on illegal poaching. This methodology is useful for conservation policy-makers in that the estimated horn prices can act as signals of demand and supply characteristics of black-markets.

2. Background

According to the World Wildlife Fund (WWF 2015), rhino horns are illegally procured from South Africa and India and proceed to black-markets in China and Vietnam where they are used in traditional medication. Figure 1a shows a schematic of transnational flows of horns from Southern Africa and India to East Asia.

Figure 1b shows the patterns of poaching in South Africa (primary left axis) and India (secondary right axis) from 1994 to 2016. Rhino poaching in these countries suggests remarkably similar patterns, especially over the last two decades. The CITES ban on horn trade has proven ineffective as poaching continues unabated with increases in demand (Messer 2010). Figure 1b suggests that supply (poaching) of rhino horns has been keeping pace with demand. Evidence points to sophisticated organised crime in rhino poaching. Criminal syndicates manage a clandestine supply chain of rhino horns from poachers to middlemen to black-markets (Baura and Talukdar 2008; Emslie *et al*. 2016; Hübschle *et al*. 2016). Institutional corruption plays a large role in the illegal trade of endangered species. Such corruption facilitates the flow of rhino horns from source to final consumer via the criminal syndicate network (Milliken and Shaw 2012; Hübschle *et al*. 2016). Relatedly, Collins *et al*. (2015) emphasise the need for strong institutional structures with extensive monitoring and enforcement to increase endangered populations to sustainable levels.

Missios (2004) argues that when endangered species are targeted for sale in foreign markets, traditional wildlife models characterised by perfect

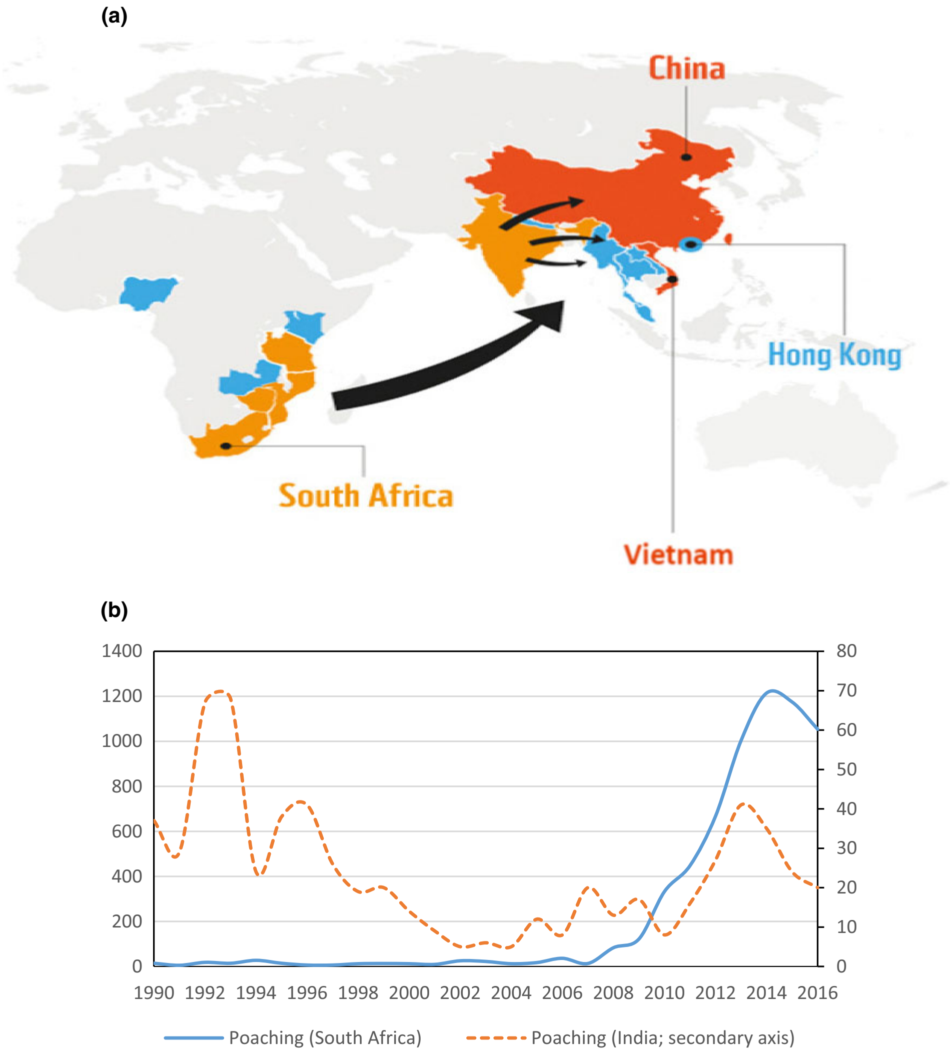

Figure 1 (a) Rhino horn source countries (South Africa and India), and final destination or consumer countries (China and Vietnam). Source: WWF (2015). (b) Patterns of rhino poaching (South Africa – left axis; India (Assam) – right axis). Source: see Table 1. [Colour figure can be viewed at wileyonlinelibrary.com]

competition or monopoly might not realistically portray the poaching industry. This is because such poaching is limited to those with resources and connections to transport and sell internationally without being caught easily – aspects that might describe coordinated organised crime. Missios (2004) uses game theory to examine how imperfect competition among suppliers who can impact markets might be a more appropriate modelling choice. We consider whether a collusive oligopoly explains the relationship between South African and Indian rhino horn suppliers.

This paper has two main research objectives. The first is to explain the plausible relationship between rhino poaching in South Africa and India as major sources of horn supply. To formulate this relationship, we develop an economic model of oligopolistic collusion via quantity-leadership in Section 3. We validate the collusive model by using a reduced-form regression framework within which unknown black-market horn prices are implicit; thereby circumventing the issue of unavailable black-market prices. We further relate the quantum of rhino horns supplied from South Africa and India to demand from East Asian black-markets. Our results indicate that there is significant evidence of oligopolistic supply collusion between South Africa and India, China and Vietnam are major consumers of rhino horns with characteristics of luxury goods, poaching is positively associated with corruption and institutional instability, and negatively associated with improvements in conservation policy. The second objective is to retrace black-market prices through an inventory management model of a syndicate that controls rhino horn supply chains. The calibration of this model utilises the regression results to estimate demand and supply patterns. In Section 3, we first describe the available data on rhino poaching, East Asian horn demand measured by GDPs per capita of China and Vietnam, World Bank indices on institutional quality and poaching fines as measuring conservation policy. We then develop our economic model of collusion via quantity-leadership that forms the basis of reduced-form regressions. We will use the regression results to estimate parameters of the inventory management model. We then discuss the empirical results, policy implications and future research on this topic.

3. Methodology

3.1 Data

In Table 1, we lay out the data statistics and sources from the 1990s up to 2016. South Africa and India contain the three most prevalent rhinoceros species in the world. South Africa has white rhinos (*Ceratotherium simum*) and black rhinos (*Diceros bicornis*). The former is a bigger species with a larger population size. The International Union for the Conservation of Nature classifies white rhinos as 'near threatened' and black rhinos as 'critically endangered' because of the latter's sparse population. India has the greater one-horned rhinoceros (*Rhinoceros unicornis*) located in Assam's national parks – Kaziranga, Orang, Manas, Pobitora. Indian rhinos are listed as 'vulnerable', are bigger and have single horns (WWF 2015). Recording of poaching incidents on a regular basis is time-consuming and expensive because of the large size of national parks. South Africa and India have regularly reported poaching incidents – making them unique in their concurrent availability of poaching data from the 1990s, as opposed to other African range states.

Table 1 Data summary

Variable	Average	Min	Max	SD	Years
Rhino population in South Africa†	15,382	7,273	21,087	5,422	1993–2012
Rhino population in India (Assam)‡	1,795	1,183	2,544	532	1991–2014
Rhino poaching in South Africa†	236	5	1,215	405	1990–2016
Rhino poaching in India (Assam)‡	24	5	68	17	1990–2016
China GDP per capita (US$)§	2,946	731	6,894	1,933	1990–2016
Vietnam GDP per capita (US$)§	994	446	1,770	402	1990–2016
Corruption Control (India)¶	−0.396	−0.540	−0.250	0.085	1996–2016
Rule of Law (India)¶	0.098	−0.090	0.350	0.157	1996–2016
Poaching penalty (India)††	24,081	8,529	71,048	19,485	1990–2016
Political stability (South Africa)¶	−0.164	−0.540	0.220	0.186	1996–2016

Note: †Population and poaching reported for all South African parks including white and black rhinos (Knight and Emslie 2012; TRAFFIC 2015; Daffue 2017). ‡Population and poaching reported for all national parks in Assam (Kaziranga, Orang, Manas, Pobitora). Largest number of poaching incidents from various sources are considered to account for under-reporting (Talukdar 2006; Baura and Talukdar 2008; Assam 2015; Facts 2016; Mukta 2016; WPSI 2016). §GDP per capita in constant 2010 US$ prices (IMF 2017; WB 2017b). ¶World Bank Index (Kaufmann and Kraay 2017). ††Poaching penalty (2010 prices) (MOEF 2013; Singh 2017; WB 2017a).

3.2 Model of collusion in horn supply

In this section, we develop an economic model to explain the relationship of rhino poaching between South Africa and India. The premise of this model is an oligopolistic industry with two major suppliers having a collusive relationship in rhino horn supply. This imperfect market structure entails two firms with unequal market shares and the firm with larger market share leads by determining its quantum of supply and the follower firm responds positively to the leader's supply decision. Rhino horns from South Africa form a majority of the supply compared to other sources in East Asian black-markets (WWF 2015). Moreover, rhino horns from both South Africa and India are destined for the same black-markets. With South Africa's larger quantum of horn supply than India's, we assume the former to be the collusive leader. The validity of this assumption will be tested in the empirics. In Figure 2, we use the collusive oligopoly models of Koutsoyiannis (1981) to depict two suppliers in which South Africa has a larger market share than India, that is Demand_SA (demand curve for South African horns) lies to the right of Demand_IN.

The two colluding firms may agree that the one with a larger market share is the quantity-setting leader. With only a single price observed at any given

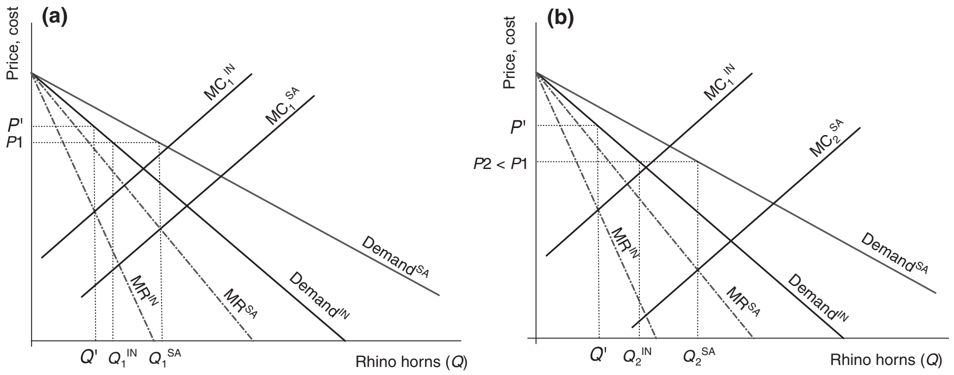

Figure 2 Oligopolistic collusion in poaching between suppliers from South Africa and India. (a) Horn supply with quantity-leadership of South Africa. (b) Increase in supply (poaching) from South Africa leads to increase in poaching in India. $Q_2^{\mathrm{SA}} > Q_1^{\mathrm{SA}} \rightarrow Q_2^{\mathrm{IN}} > Q_1^{\mathrm{IN}}$.

time in the black-market one may assume that suppliers do not compete on price. In Panel (a), the quantity-leader (South Africa) maximises profits by setting marginal revenue equal to marginal cost to choose a quantity of Q_1^{SA} (i.e. wild stocks poached) which yields price $P1$ on Demand_SA. The same price $P1$ applies to rhino horns procured from India, which results in Q_1^{IN} wild stocks poached. To maximise profits, the Indian supplier would like to sell quantity $Q' \left(<Q_1^{\mathrm{IN}}\right)$ where $\mathrm{MR}^{\mathrm{IN}} = \mathrm{MC}^{\mathrm{IN}}$ and choose price P' ($>P1$). However, in this collusive setup the follower would avoid doing so because a higher price for Indian rhino horns would drive consumers to switch to South African rhino horns. With the supply of horns being the choice variable in this model, we note what occurs when the supply (poaching) from South Africa increases, *ceteris paribus*. In Panel (b) of Figure 2, this decision results in a quantity of $Q_2^{\mathrm{SA}} \left(> Q_1^{\mathrm{SA}}\right)$ and a reduction in price from $P1$ to $P2$. With this price, the follower chooses output $Q_2^{\mathrm{IN}} \left(> Q_1^{\mathrm{IN}}\right)$ and responds in consonance with the quantity-leader's decision to either increase or decrease supply. We formalise the South African quantity-leadership argument using general forms for demand and supply functions.

$Q_{\mathrm{SA}}^{D}(P_{\mathrm{SA}}, M)$:	Inverse demand for South African rhino horns. P_{SA} is black-market price. M is East Asian income.
$Q_{\mathrm{IN}}^{D}(P_{\mathrm{SA}}, M)$:	Inverse demand for Indian rhino horns.
$Q_{\mathrm{SA}}^{S}(P_{\mathrm{SA}}, C_{\mathrm{SA}})$:	Inverse supply of South African rhino horns. C_{SA} is cost of poaching.
$Q_{\mathrm{IN}}^{S}\left(P_{\mathrm{SA}}, C_{\mathrm{IN}}, Q_{\mathrm{SA}}^{S}\right)$:	Inverse supply of Indian rhino horns. C_{IN} is cost of poaching in India. Q_{SA}^{S} denotes the quantity-leadership link.

South African supplier maximises its own profits to derive quantity-price pair: $\left(Q_{\mathrm{SA}}^{*}, P_{\mathrm{SA}}^{*}\right)$. The follower substitutes this price into its own inverse demand function: $Q_{\mathrm{IN}}^{D}\left(P_{\mathrm{SA}}^{*}, M\right)$. This is inverted to derive demand for Indian rhino horns, $P_{\mathrm{SA}}^{*}\left(Q_{\mathrm{IN}}^{D}, M\right)$, which is further substituted into supply function,

$Q_{\mathrm{IN}}^{\mathrm{S}}\left(P_{\mathrm{SA}}^{*}(\cdot), C_{\mathrm{IN}}, Q_{\mathrm{SA}}^{\mathrm{S}}\right)$. This derives reduced-form of supply for Indian rhino horns in Equation (1):

$$Q_{\mathrm{IN}}^{*}\left(P_{\mathrm{SA}}^{*}\left(Q_{\mathrm{IN}}^{D}, M\right), C_{\mathrm{IN}}, Q_{\mathrm{SA}}^{\mathrm{S}}\right). \tag{1}$$

Note that black-market price (P_{SA}) becomes implicit in Equation (1). If black-market price data were available, the regression empirics could rely on reduced-form Marshallian demand as a function of prices and income. Reduced-form econometric models typically eliminate one variable that enters implicitly in the regression framework.[1] Assuming equilibrium in black-markets, we account for prices implicitly in this model. We can solve for the resulting first-order derivatives of $Q_{\mathrm{IN}}^{*}(\cdot)$ and hypothesise certain relationships. The first testable hypothesis is oligopolistic collusion between the source countries, that is $\frac{\partial Q_{\mathrm{IN}}{}^{*}}{\partial Q_{\mathrm{SA}}^{\mathrm{S}}} > 0$. The second hypothesis is poaching in India is positively related to East Asian income, that is $\frac{\partial Q_{\mathrm{IN}}^{*}}{\partial M} > 0$. The third hypothesis is poaching in India is negatively related to cost of poaching, that is $\frac{\partial Q_{\mathrm{IN}}^{*}}{\partial C_{\mathrm{IN}}} < 0$. The next subsection describes the regression framework to empirically test these hypotheses with the reduced-form supply for India, $Q_{\mathrm{IN}}^{*}\left(P_{\mathrm{SA}}^{*}\left(Q_{\mathrm{IN}}^{*}, M\right), C_{\mathrm{IN}}, Q_{\mathrm{SA}}^{\mathrm{S}}\right)$.

3.3 Transnational link in rhino poaching

The economic model described the hypothesised relationship between oligopolistic suppliers of rhino horns. In Equations (2) and (3), we model rhino poaching in India, $Q_{\mathrm{IN}}^{*}(\cdot)$, as parsimonious functions of South African rhino poaching in period t and $(t-1)$. Equations (4) and (5) add independent variables of corruption, governance quality, conservation policy, and Chinese or Vietnamese demand:

$$\text{Poaching in India}_t = \beta_0 + \beta_1(\text{Poaching in South Africa}_t) + (\text{error term}_t), \tag{2}$$

$$\text{Poaching in India}_t = \beta_0 + \beta_1(\text{Poaching in South Africa}_{t-1}) + (\text{error term}_t), \tag{3}$$

$$\begin{aligned}\text{Poaching in India}_t = \beta_0 &+ \beta_1(\text{Poaching in South Africa}_t) \\ &+ \beta_2(\text{Corruption Control Index\_India}_t) \\ &+ \beta_3(\text{Rule of Law Index\_India}_t) \\ &+ \beta_4(\text{China GDP per capita}_t) \\ &+ \beta_5(\text{Poaching penalty\_India}_t) + (\text{error term}_t),\end{aligned} \tag{4}$$

[1] For instance, Strauss and Duncan (1998) derive a reduced-form labour participation regression equation as a function of labour wage rate (price), which in turn is a function of socioeconomic factors – therefore price enters a reduced-form implicitly.

$$\begin{aligned}\text{Poaching in India}_t = {} & \beta_0 + \beta_1(\text{Poaching in South Africa}_t) \\ & + \beta_2(\text{Corruption Control Index\_India}_t) \\ & + \beta_3(\text{Rule of Law Index\_India}_t) \\ & + \beta_4(\text{Vietnam GDP per capita}_t) \\ & + \beta_5(\text{Poaching penalty\_India}_t) + (\text{error term}_t). \quad (5)\end{aligned}$$

We account for conservation policy by including poaching penalties as per Indian Wildlife (Protection) Amendment Act. Antipoaching policy has become more rigorous in India over time (Singh 2017) and this variable is its representative (Lopes 2014). We include GDP per capita (2010 US$ prices) in China and Vietnam as demand measures. To account for the effect of institutional quality on poaching, we consider World Bank indices of Corruption Control and Rule of Law (Kaufmann and Kraay 2017). The indices range in values from −2.5 (weak) to 2.5 (strong). Control of Corruption Index reflects 'perceptions of the extent to which public power is exercised for private gain, including both petty and grand forms of corruption, as well as "capture" of the state by elites and private interests'. Rule of Law Index reflects 'perceptions of the extent to which agents have confidence in and abide by the rules of society, and in particular the quality of contract enforcement, property rights, the police and the courts, as well as the likelihood of crime and violence'. These indices measure completely different aspects of institutional quality.

Independent variables are chosen in accordance with the hypotheses derived from the economic model of collusion. The possibility of collusion in horn supply between South Africa and India should yield $\beta_1 > 0$. Better corruption control and conservation policy should reduce poaching in India. These can be adjudged by the signs and magnitudes of the coefficients β_2, β_3, and β_5. We also hypothesise that rhino poaching in India is positively related to income in East Asia, that is $\beta_4 > 0$ for China and Vietnam. We will estimate regression Equations (2)–(5) using ordinary least squares in Section 4.1. In Figure 1b, we note that rhino poaching increases in both the range states from 2005 to 2016. We accordingly add a binary indicator variable for these years and interact it with income variables to ascertain the effect of horn demand from China and Vietnam in this period. One can derive income elasticities of horn demand from China and Vietnam by taking natural logarithms of the dependent and income variables and use the regression coefficients from Equations (4) and (5).

We then account for poaching events being correlated over time by examining regression models with all variables in first-difference format, that is $(X_t - X_{t-1})$. This accounts for autocorrelation in error terms (Nau 2016). It also controls for any effects of the previous year's dependent and independent variables on the current year's dependent variable. Endogeneity in regression may arise if there is omitted variable bias – wherein the dependent and independent variables are correlated with an extraneous variable for which there are no data (Angrist and Pischke 2009). For an unbiased estimate of the relationship between the principal independent variable of interest (i.e. Poaching in South Africa) and the dependent variable, a regression model must account for any determinants of the dependent variable that are possibly correlated with the independent variable. This identification issue is resolved by using an instrumental variable. We use the Index in Table 1 on 'Political Stability in South Africa' as an instrument. This Index 'measures perceptions of the likelihood of political instability and/ or politically-motivated violence, including terrorism'. It is hypothesised that this instrument is correlated with the independent variable and could have an indirect impact on the dependent variable – a necessary condition for a valid instrument (Angrist and Pischke 2009).

3.4 Retracing black-market prices

Black-market prices are largely unavailable post-CITES ban. In this subsection, we use the oligopolistic collusion framework to retrace black-market prices. We develop a novel model that utilises the regression coefficients to predict these prices and also forecast them. Forecast prices have the potential to be immensely useful to policy practitioners since it would provide signals on demand and supply characteristics. Lopes (2014) develops a price index for rhino horns sourced from Assam, by assuming South African rhino poaching to be an indicator for poaching in the Kaziranga National Park. However, that index is developed in the context of sociopolitical unrest in Assam that had subsided by the mid-1990s. In this paper, the study period is postunrest and poaching is considered in all of Assam's national parks. Expanding upon Lopes' index, we propose an inventory model of a criminal syndicate that controls the supply chain of rhino horns from South Africa and India to East Asian black-markets.

$H_t =$	South African rhino poaching in year t.
$D_t\ (Y_t, I_t) =$	Demand for Indian rhino horns. Y_t: GDP per capita in China or Vietnam. $I_t = I_t\ (H_t)$: estimable horn prices; H_t: indicator for black-market prices; $I'(\cdot) > 0$.
$D_t\ (Y_t, I_t\ (H_t)) =$	$\alpha_t Y_t^{\beta_t} H_t^{-\gamma_t}$. Demand function; $\alpha_t > 0$, $\beta_t > 0$, $\gamma_t > 0$; $D_Y > 0$, $D_I < 0$
$S_t = S_t\ (H_t)$	Reduced-form of Indian rhino horn supply (poaching) derived using regression coefficients
$S_t(\cdot) - D_t(\cdot) =$	Inventory of Indian rhino horns held by syndicate at time t

Inventory management entails that the syndicate maintains a regular supply of rhino horns to match the demand as closely as possible at time t. Maintaining unsold stocks of horns would increase storage costs and also increase the risk of detection by authorities. The syndicate may wish to manage inventories that minimise the difference between supply and demand at each t. One can accordingly calibrate parameters α_t, β_t, γ_t as per Equation (6). The adjustment of supplied stocks to meet demand as closely as possible mimics the market equilibrium process, which is subsumed in our reduced-form regressions.

$$\text{minimize} \sum_t (S_t(\cdot) - D_t(\cdot))^2 \rightarrow \underset{\{\alpha_t,\beta_t,\gamma_t\}_{t=1994}^{t=2016}}{\text{minimize}} \sum_t (S_t(H_t) - \alpha_t Y_t^{\beta_t} H_t^{-\gamma_t})^2. \quad (6)$$

We utilise Excel's Solver to minimise the sum of squared differences between S_t $(\cdot)$ and D_t $(\cdot)$ with initial values of α_t, β_t, and γ_t. To calculate S_t (H_t), we choose any regression model's coefficients from Equations (2)–(5) and multiply them by their corresponding independent variables to estimate the number of rhino horns sourced from India. The calibrated values of γ_t are used to derive a price index for rhino horns, $I_t(H_t) = H_t^{\gamma_t}$. This index stems from demand: $D_t(Y_t,\ I_t(H_t)) = \alpha_t Y_t^{\beta_t} H_t^{-\gamma_t}$. The negative sign of γ_t drops out because the partial differential of demand with respect to price is negative, that is $D_I < 0$ and $\gamma_t > 0$. This step yields a time-series of price indices, which are normalised as per Equation (7):

$$[\text{Normalised price Index}]_t = \frac{[\text{Price Index}]_t}{\text{minimum}\left\{[\text{Price Index}]_{t=1994}, \ldots, [\text{Price Index}]_{t=2016}\right\}} \times 100. \quad (7)$$

Horn prices at each t are derived by using a reference point for which there is a given price – notably US\$ 65, 000/kg at t = 2012(Sas-Rolfes 2012). Horn prices at $t \neq 2012$ can be calculated using Equation (8):

$$[\text{Rhino horn price(US\$)}]_{t\neq2012} = \frac{[\text{Normalised price Index}]_{t\neq2012}}{[\text{Normalised price Index}]_{t=2012}} \times \text{US\$65,000}. \quad (8)$$

In order for this methodology to be useful for policy, we can use the regression coefficients to forecast black-market prices as and when data on rhino poaching, GDP, conservation policy and institutional quality are updated over time. Estimated black-market prices can be used independently by other rhino poaching studies to shed more light on market demand and supply characteristics, such as elasticity of supply and/or demand.

4. Results and discussion

4.1 Collusion amongst horn suppliers

We first test for the basic association between South African and Indian rhino poaching. The correlation between poaching in South Africa and India from the mid-90s to 2016 is 0.53, which increases to 0.802 from the 2000s onwards. Using Equation (2), we note that this parsimonious regression with Indian rhino poaching as the dependent variable and South African rhino poaching as the only independent variable indicates a significant degree of association. This result is under Model (0a) in Table 2. Equation (3) is used to estimate Model (0b) and the result suggests that the previous year's poaching in South Africa is significantly associated with the current year's poaching in India. We also test the causal relationship between South African and Indian poaching by using the nonparametric causality test – Fisher's Exact Probability. Fisher's test of causality between South African poaching in the previous year and Indian poaching in the current year yields a significant P-value of 0.054, thereby corroborating Model (0b). However, given the complexities of illegal poaching and confounding effects of other independent variables, a deeper investigation into the relationship between South African and Indian poaching is warranted.

Regression coefficients under Models (1) and (2) in Table 2 are derived using Equations (4) and (5). Poaching in India is positively and significantly related to South African poaching while controlling for extraneous factors. The income coefficients are positive for Chinese and Vietnamese demand separately. The interactive term of the income variables with the binary indicator for year 2005 onwards are highly significant in Models (3) and (4). This suggests that the demand for rhino horns increased substantially from 2005 onwards in China and Vietnam, and this corresponds to the spike in rhino poaching in Figure 1b. Milner-Gulland (1993) and Crookes and Blignaut (2015) find positive and significant income effects for rhino horn demand; the former estimates income elasticity at 1.06 while the latter study estimates it at 3.445 – both values greater than unity suggest that rhino horns are luxury goods. In Models (5) and (6) of Table 2, we use natural logarithms of the dependent variable and income variables, which yield positive and significant income elasticities of 1.284 and 2.10 for China and Vietnam. Our results also suggest that rhino horns are luxuries with values greater than unity but lie between the others' estimates. A point of departure of this study is the use of data on illegal poaching as opposed to Milner-Gulland who uses preban data and Crookes and Blignaut who use legal trophy hunting data; the latter study's larger income elasticity is attributable to trophy hunters being high-income individuals who are more likely to treat rhino horns as luxuries.

In Table 2, we control for institutional quality across all models using World Bank's India indices on Corruption Control and Rule of Law. The indices measure separate aspects of governance quality as described in Section 3.3. Including these indices in our regressions accounts for separate aspects of institutional quality. Corruption control has always been weak in India's administration – an aspect of institutional quality reflected in all its Index's negative values in Table 1. The significantly negative coefficient points to its inverse association with poaching – thus corroborating claims

Table 2 Regression estimates of the effect of poaching in South Africa on poaching in India

	Dependent variable: Poaching in India (t)							
	Model (0a)	Model (0b)	Model (1)	Model (2)	Model (3)	Model (4)	Model (5)†	Model (6)†
Poaching in South Africa (t)	0.0109 (0.004)***	–	0.0271 (0.005)***	0.0314 (0.005)***	0.0315 (0.004)***	0.0349 (0.003)***	0.0015 (0.0003)***	0.0016 (0.0003)***
Poaching in South Africa (t − 1)	–	0.0105 (0.005)**	–	–	–	–	–	–
Corruption Control Index in India	–	–	−91.50 (32.72)**	−90.96 (35.46)**	−90.34 (30.71)***	−90.42 (30.66)***	−4.622 (1.690)**	−4.849 (1.877)**
Rule of Law Index in India	–	–	115.2 (40.99)**	112.17 (46.02)**	107.49 (34.95)***	106.26 (34.23)***	7.864 (2.078)***	7.851 (2.474)***
China GDP per capita	–	–	0.0057 (0.002)*	–	–	–	1.284 (0.536)**	–
Vietnam GDP per capita	–	–	–	0.0228 (0.017)	–	–	–	2.100 (1.153)*
China pcGDP (bin yr_2005)	–	–	–	–	0.0031 (0.001)***	–	–	–
Vietnam pcGDP (bin yr_2005)	–	–	–	–	–	0.009 (0.003)***	–	–
Poaching penalty in India	–	–	−0.0002 (0.0001)**	−0.0002 (0.0001)**	−0.0002 (0.0001)**	−0.0002 (0.0001)**	−9.27e–06 (8.63e–06)	−8.73e–06 (8.54e–06)
Intercept	16.45 (2.78)***	17.05 (2.63)***	−50.89 (23.19)**	−57.68 (33.59)*	−39.18 (18.21)**	−39.13 (18.01)**	−10.41 (4.623)**	−14.89 (8.547)*
R-squared	0.175	0.138	0.706	0.686	0.752	0.748	0.695	0.673
F-statistic	5.76	4.24	35.86	36.25	29.78	30.48	19.24	16.43
D-W statistic	0.610	0.606	0.951	0.892	1.116	1.128	1.371	1.258

Note: Robust standard errors in parentheses; statistical significance at 1% (***), 5% (**) and 10% (*) error levels. †Models (5) and (6) take natural logarithms of income and dependent variables to calculate income elasticity.

that corruption facilitates poaching. Rule of Law Index has almost all positive or near-zero values unlike Corruption Control. Perceptions of lawfulness are more positive compared to corruption control. In Table 1, the Rule of Law has a minimum index of −0.09 that is higher than the maximum of −0.25 on Corruption Control. With Rule of Law Indices being positive or opposite in sign to those of Corruption Control, this translates into a positive and significant regression coefficient. These results point to India's endemic institutional weaknesses. The fact that both the indices are significant determinants of poaching, but have opposite signs in their data and coefficients, highlights not just the importance of accounting for all aspects of governance but also for their relative strengths. As the results suggest, it is the extent to which one index is stronger (or weaker) than the other that determines whether their combined effect on poaching is positive or negative. The corruption effect appears to outweigh the perception of lawfulness about Indian institutions and the relative strengths of both indices facilitates an increase in poaching. We further control for conservation policy in India and find that poaching penalty significantly reduces poaching. Poaching penalties have become more stringent over time, thus reflecting the increasing attention paid by India's government towards rhino conservation. However, poor institutional quality remains an obstacle.

In Table 3, we report regressions with all the variables in first-difference format to account for autocorrelation. The signs, magnitudes and significance of coefficients in Models (7a) through (8b) are similar to those of Table 2, and larger Durbin–Watson statistics indicates insignificant autocorrelation. Testing for the presence of a unit root in the dependent variable, that is (Poaching in India (t) − Poaching in India (t − 1)), we find that the Dickey–Fuller test yields a statistic of −8.005 and a P-value of 0.000, thereby rejecting the null hypothesis.

Instrumental variables account for endogeneity in regression models. Political Stability Index in South Africa is used to identify the oligopolistic relationship between South African and Indian rhino poaching in Models (9a) through (10b) in Table 4. We derive similar signs, magnitudes and statistical significance of the coefficients as those in Tables 2 and 3. This identification strategy indicates no significant issue of endogeneity or model specification.

4.2 Retracing and predicting black-market prices

In order to retrace the unknown prices of illicitly traded rhino horns, we choose regression coefficients of Models (9a) and (10a) and substitute them into Equation (6). α_t, β_t, and γ_t are calibrated to provide black-market price estimates using Chinese demand from Model (9a) and Vietnamese demand from Model (10a). The parameter values (averages) are listed in Table 5. After normalising the price indices as per Equation (7) and plugging them

Table 3 Regression estimates using first-differences

	Dependent variable: (Poaching in India (t) − Poaching in India (t − 1))			
	Model (7a)	Model (8a)	Model (7b)	Model (8b)
Poaching in South Africa$_{(t)-(t-1)}$	0.0275 (0.008)***	0.0339 (0.008)***	0.0362 (0.009)***	0.0375 (0.010)***
Corruption Control_India$_{(t)-(t-1)}$	−85.65 (28.52)***	−97.90 (29.69)***	−78.39 (32.21)**	−79.97 (33.18)**
Rule of Law_India$_{(t)-(t-1)}$	66.77 (28.39)**	73.37 (26.98)**	51.74 (33.49)	53.84 (32.53)
China pcGDP$_{(t)-(t-1)}$	0.0205 (0.0105)*	–	–	–
Vietnam pcGDP$_{(t)-(t-1)}$	–	0.1298 (0.0774)	–	–
China pcGDP$_{(t)-(t-1)}$(bin yr_2005)	–	–	0.0034 (0.0016)*	–
Vietnam pcGDP$_{(t)-(t-1)}$(bin yr_2005)	–	–	–	0.0079 (0.0036)**
Poaching penalty_India$_{(t)-(t-1)}$	−0.0002 (0.0001)**	−0.0002 (0.0001)**	−0.0002 (0.0001)**	−0.0002 (0.0001)**
Intercept	−5.917 (3.138)*	−7.614 (4.228)*	−2.168 (2.194)	−1.727 (2.090)
R-squared	0.706	0.694	0.680	0.668
F-statistic	13.74	15.48	10.62	11.31
D-W statistic	1.751	1.869	1.728	1.661

Note: Robust standard errors in parentheses; statistical significance at 1% (***), 5% (**) and 10% (*) error levels.

into Equation (8), we depict two series of black-market prices in Figure 3 – one indicative of China's black-markets and the other of Vietnam's.

Our inventory management model can predict or forecast black-market prices. To do this, the data for our regression models need to be updated on rhino poaching in South Africa and India, World Bank indices on institutional quality, GDP per capita and poaching penalties. Let us consider a 3-year moving average to forecast the next five annual values of each of these variables. Forecast prices up to the year 2022 are depicted for China and Vietnam in Figure 3; these are estimated at \$69,454 to \$77,548/kg. Market prices provide signals about demand and supply characteristics. The estimated prices can be used in conjunction with black-market data to estimate price elasticities of supply or demand. Previous studies have estimated demand elasticities but paid little attention to the corresponding supply elasticities. For expository purposes, we calculate supply elasticity for the years 2013 and 2014 using corresponding rhino poaching data for South Africa (1,004 and 1,215 rhinos) as indicators of horn supply. The corresponding retraced black-market prices are US\$61,672 and US\$69,540. Supply elasticity is estimated at 1.585 with the midpoint formula. This highly elastic value suggests that suppliers in South Africa were responsive to an increase in black-market price by increasing poaching from 2013 to 2014. In future studies, elasticities can be estimated when black-market data on rhino horn supply and demand become available.

5. Summary

Within the last two decades, rhino poaching has increased substantially in the South African and Indian range states and the demand for rhino horns in East Asian black-markets has kept apace. Curiously, poaching trends have been quite similar in these range states. The possibility of 'coordination' in rhino horn supplies across range states has not been considered in the literature. This paper proposes a framework of oligopolistic collusion between South African and Indian rhino horn suppliers to ascertain the plausibility of such coordination. Our empirical findings provide compelling evidence of this claim. This provides a new lens on species conservation policy. Conservation policy has traditionally focused on demand reduction and improving antipoaching. However, given the increasing interconnectedness of trade and information flows across borders we propose that conservation policy also focus on the possibility that endangered species trade might be coordinated across borders – from source to final consumer.

In examining the evidence to support the coordination hypothesis, we control for a number of covariates in our reduced-form regressions. Our findings are broadly similar to other rhino poaching studies. However, there are important departures from other studies both in terms of methodology and inclusion of covariates not considered previously. Other studies (Milner-Gulland 1993; Crookes and Blignaut 2015) find that rhino horns are luxuries

Table 4 Instrumental variable regressions to identify the effect of Poaching in South Africa

	Instrumental variable: Political stability in South Africa			
	Model (9a)	Model (10a)	Model (9b)	Model (10b)
Poaching in South Africa	0.0233 (0.0136)*	0.0243 (0.0122)**	0.0381 (0.0155)**	0.0433 (0.0193)**
Corruption Control Index_India	−94.94 (33.45)***	−98.83 (37.16)***	−87.97 (26.96)***	−88.86 (27.06)***
Rule of Law Index_India	120.30 (43.53)***	122.99 (47.85)**	104.85 (31.08)**	104.90 (30.21)**
China GDP per capita	0.0064 (0.003)*	–	–	–
Vietnam GDP per capita	–	0.0293 (0.019)	–	–
China pcGDP (bin yr_2005)	–	–	0.0027 (0.0012)**	–
Vietnam pcGDP (bin yr_2005)	–	–	–	0.0083 (0.0033)**
Poaching penalty_India	−0.0002 (0.0001)	−0.0001 (0.0001)	−0.0003 (0.0002)	−0.0004 (0.0003)
Intercept	−55.14 (27.85)*	−69.47 (38.32)*	−36.38 (16.77)**	−36.53 (16.74)**
R-squared	0.705	0.678	0.743	0.733
F-statistic (first stage IV)	6.79	6.97	4.56	3.90

Note: Robust standard errors in parentheses; statistical significance at 1% (***), 5% (**) and 10% (*) error levels.

Table 5 Calibrated parameters of demand function ($D_t(\cdot)$)

Parameter	Initial values	Calibrated values using S_t (H_t) from Model (9)	Calibrated values using S_t (H_t) from Model (10)
α_t	1.0000	1.0295	1.1376
β_t	0.5000	0.5580	0.7413
γ_t	0.5000	0.4564	0.3516

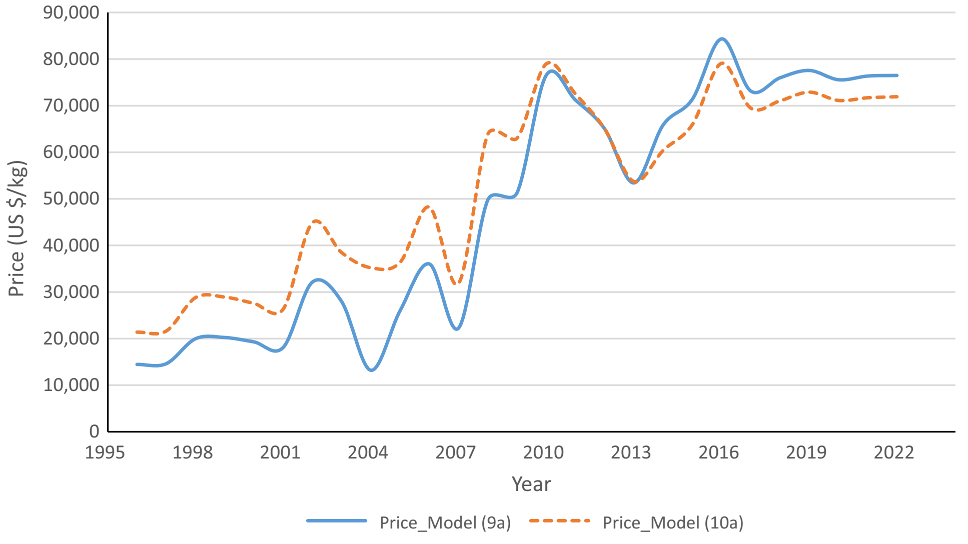

Figure 3 Retraced black-market prices for 1996–2016 from Model 9a (Chinese demand) and Model 10a (Vietnamese demand), and forecast prices up to 2022. [Colour figure can be viewed at wileyonlinelibrary.com]

and therefore demand is a principal driver of black-markets. In this study, we control for demand from China and Vietnam and similarly find income elasticities greater than unity – Vietnam's income elasticity is estimated at 2.10 and China's is 1.28; demand appears more responsive to income changes in Vietnam. The departure here is that these income elasticity estimates use data on illicit rhino poaching, whereas other studies use preban data and/or legal trophy hunting data.

An increasing amount of evidence points to how corruption facilitates poaching. Surprisingly, not much attention has been devoted to this in economics studies. We account for the effects of corruption, lawfulness and conservation policy as measures of institutional strength. We find that corruption significantly increases rhino poaching. With poaching becoming more organised via the involvement of criminal syndicates, it might be that some administrative officials are complicit in coordinating rhino horn supplies across range states. Policies have focused mostly on demand in black-markets and largely but ignored the supply side. Trade bans have been ineffective in curbing poaching. Corruption would need to be tackled head-on in order to successfully reduce poaching. Policy focus on consumer demand might be inadequate since there are two sides to any market, black or otherwise. A two-pronged approach – targeting both demand and supply reductions – might stand a better chance at rhino conservation.

Inadequate black-market price data inhibit economic analysis. It is important for policy practitioners to understand the evolution of black-market prices to ascertain market trends and unknown characteristics like supply or demand elasticities. Our study provides a novel methodology to estimate such prices under the premise of oligopolistic collusion. The inventory management model can retrace these prices and forecast them. A preliminary estimate of supply elasticity is derived at 1.585 for South Africa between 2013 and 2014. Further research on estimating supply elasticities of illicitly procured rhino horns has the potential to add an important facet to the rhino conservation debate.

Only recently, other sub-Saharan range states have begun gathering data on rhino poaching. With advancements in data availability, the models developed here can further ascertain if there are potentially undiscovered links in criminal syndicate supply chains beyond South Africa and India. Work in this direction can be taken forward by studying similar possibilities for other endangered megafauna species like tigers and elephants that have subspecies across borders and high black-market prices. The investigation of the role of transnational links in the supply of illegally harvested rhino horns is a first step in this direction. At a policy level, this will require coordination between conservation agencies, both public and private, in different countries to identify joint threats and collaborate on possible solutions.

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