Contributed Paper

Identification of policies for a sustainable legal trade in rhinoceros horn based on population projection and socioeconomic models

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Abstract: *Between 1990 and 2007, 15 southern white (*Ceratotherium simum simum*) and black (*Diceros bicornis*) rhinoceroses on average were killed illegally every year in South Africa. Since 2007 illegal killing of southern white rhinoceros for their horn has escalated to >950 individuals/year in 2013. We conducted an ecological–economic analysis to determine whether a legal trade in southern white rhinoceros horn could facilitate rhinoceros protection. Generalized linear models were used to examine the socioeconomic drivers of poaching, based on data collected from 1990 to 2013, and to project the total number of rhinoceroses likely to be illegally killed from 2014 to 2023. Rhinoceros population dynamics were then modeled under 8 different policy scenarios that could be implemented to control poaching. We also estimated the economic costs and benefits of each scenario under enhanced enforcement only and a legal trade in rhinoceros horn and used a decision support framework to rank the scenarios with the objective of maintaining the rhinoceros population above its current size while generating profit for local stakeholders. The southern white rhinoceros population was predicted to go extinct in the wild <20 years under present management. The optimal scenario to maintain the rhinoceros population above its current size was to provide a medium increase in antipoaching effort and to increase the monetary fine on conviction. Without legalizing the trade, implementing such a scenario would require covering costs equal to approximately $147,000,000/year. With a legal trade in rhinoceros horn, the conservation enterprise could potentially make a profit of $717,000,000/year. We believe the 35-year-old ban on rhinoceros horn products should not be lifted unless the money generated from trade is reinvested in improved protection of the rhinoceros population. Because current protection efforts seem to be failing, it is time to evaluate, discuss, and test alternatives to the present policy.*

Keywords: African rhinos, CITES, conservation policy, economics, poaching, population model

El Grano de los Datos de Costo Económico con Referencia Espacial y de Beneficio a la Biodiversidad y la Efectividad de una Estrategia de Determinación de Costos

Resumen: *Entre 1990 y 2007, en promedio fueron cazados ilegalmente cada año 15 rinocerontes sureños blancos (*Ceratotherium simum simum*) y negros (*Diceros bicornis*) en Sudáfrica. Desde 2007 la caza ilegal de rinocerontes sureños blancos por su cuerno ha escalado a más de 950 individuos al año en 2013. Llevamos a cabo un análisis ecológico-económico para determinar si el comercio legal de cuerno de rinoceronte sureño*

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Paper submitted March 22, 2014; revised manuscript accepted August 8, 2014.

Conservation Biology, Volume 29, No. 2, 545–555

DOI: 10.1111/cobi.12412

blanco podría facilitar la protección del rinoceronte. Se usaron modelos lineales generalizados para examinar a los conductores socio-económicos de la caza furtiva, con base en datos colectados desde 1990 hasta 2013, y también para proyectar el número total de rinocerontes con probabilidad de ser cazados ilegalmente desde 2014 hasta 2023. Las dinámicas poblacionales de los rinocerontes fueron entonces modeladas bajo ocho escenarios políticos diferentes que podrían implementarse para controlar la caza furtiva. También estimamos los costos económicos y los beneficios de cada escenario solamente bajo la ejecución aumentada del plan de manejo y el comercio legal de cuerno de rinoceronte y usamos un marco de trabajo de apoyo a decisiones para ordenar los escenarios con el objetivo de mantener la población de rinocerontes por encima de su tamaño actual mientras se generan ganancias para los accionistas locales. Se predijo que la población de rinocerontes sureños blancos se extinguiría en menos de 20 años bajo el manejo actual. El escenario óptimo para mantener la población de rinocerontes por encima de su tamaño actual fue el de proporcionar un incremento mediano en el esfuerzo contra la caza furtiva e incrementar la multa monetaria de la condena. Sin legalizar el mercado, implementar tal escenario requeriría cubrir costos de aproximadamente $147, 000, 000 al año. Con un comercio legal de cuerno de rinoceronte, la iniciativa de conservación podría ganar potencialmente $717, 000, 000 al año. Creemos que la prohibición de 35 años de los productos de cuerno de rinoceronte no debería ser levantada a menos que el dinero generado de este comercio sea reinvertido en la protección mejorada de la población de rinocerontes. Ya que los esfuerzos de protección actuales parecen estar fallando, es momento de evaluar, discutir y probar alternativas a la política actual.

Palabras Clave: caza furtiva, CITES, economía, modelo poblacional, política de conservación, rinocerontes Africanos

Introduction

Africa supports 2 species of rhinoceros, and South Africa is internationally recognized for its success in conserving both species (Linklater 2003). Fewer than 50 southern white rhinoceros (*Ceratotherium simum simum*) probably remained in the former province of Natal by 1895, after white settlers had overhunted them throughout most of their historical range (Emslie et al. 2009). In situ recovery strategies were then developed to bring this iconic species back from the brink of extinction, including the establishment of protected areas on state and private land and translocation of rhinoceros back to their historic range (Emslie et al. 2009). South Africa now has approximately 19,000 southern white rhinoceroses, some 95% of Africa's total population in 2010 (Emslie et al. 2013). As a result of ongoing demand for rhinoceros horn in East Asia and the Middle East, numbers of the more wide-ranging black rhinoceros (*Diceros bicornis*) plummeted from an estimated 100,000 across Africa in 1960 to <2500 in 1995 (Leader-Williams 2003). Contrastingly, South Africa bucked this trend through sound protection and management, and numbers of its black rhinoceros increased from 630 in 1980 to 1915 by 2010, some 40% of Africa's black rhinoceros population (Emslie et al. 2013). Between 1990 and 2007, only 15 rhinoceroses on average were poached every year in South Africa. However, illegal killing of black and, mostly, southern white rhinoceros has escalated since 2007; the rate of poaching increased exponentially from 0.03 rhinoceroses/day prior to 2007 to 2.75/day in 2013 (Department of Environmental Affairs 2014).

Rhinoceros horn has historically been in demand for traditional Chinese medicine and ornamental use in East Asia and the Middle East (Graham-Rowe 2011). In 1977, an international ban on all trade in rhinoceros products was agreed under the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) (Leader-Williams 2003). The Appendix I listing of all species of African and Asian rhinoceroses sought to reduce demand in consuming countries and to halt poaching (Leader-Williams 2003). However, the ban has not achieved its purpose, as demonstrated by ongoing poaching of rhinoceroses in both Africa and Asia (Milliken & Shaw 2012). Recently, 2 subspecies of rhinoceroses, the Vietnamese subspecies of Javan rhinoceros (*Rhinoceros sondaicus annamiticus*) and the west African subspecies of black rhinoceros (*D. bicornis longipes*), have become extinct in the wild, whereas the northern white rhinoceros (*C. simum cottoni*) teeters on the edge of extinction (Emslie et al. 2013). Cultural, historical, and more recent beliefs render rhinoceros horn a luxury good and a must-have status symbol, and it is used in medicines in countries such as China and Vietnam (Graham-Rowe 2011; Milliken & Shaw 2012). Thus, the illegal market for rhinoceros horn has become more profitable for poaching syndicates, which, by controlling the market, can stockpile in anticipation of future price rises (Mason et al. 2012).

Conservationists in South Africa have been considering alternative approaches to curbing poaching for some years. Rather than placing an even greater focus on improved law enforcement and demand reduction in the Far East (Lawson & Vines 2014), some of those who bear the costs of rhinoceros conservation in South Africa advocate the introduction of a legal trade in southern white rhinoceros horn (Biggs et al. 2013). Because the market in rhinoceros horn has been illegal since 1977, there is a

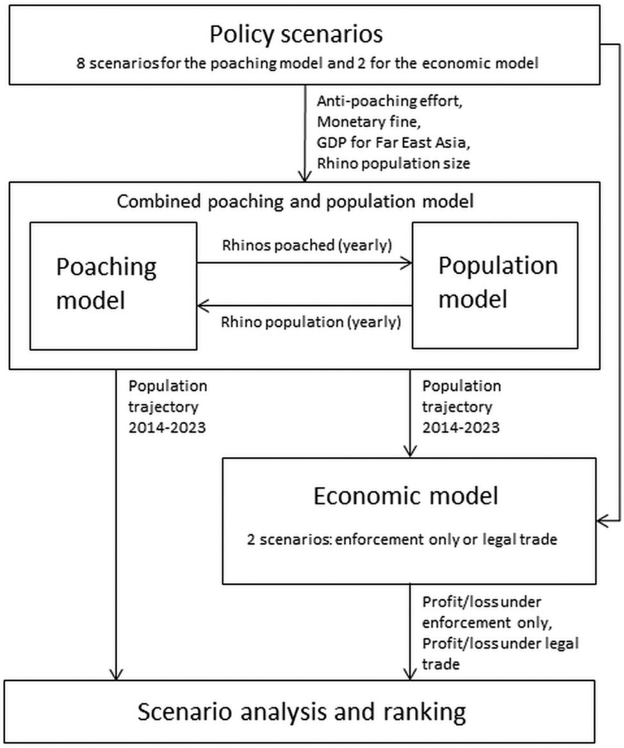

Figure 1. Flowchart of the main parts of the simulation framework (boxes, different parts of the framework; arrows, variables transferred from one part to another). Poaching and population models are updated each from 2014 to 2023.

lack of data on price increases and quantity demanded by consumers over time, which prevent the estimation of a full-price quantity model for rhinoceros horn. (See, e.g., Van Kooten [2008] for a dynamic bioeconomic model of ivory trade.) However, unprecedented poaching rates are also expected to cause declines in the biggest white rhinoceros population in Kruger National Park, which is now heavily targeted by poachers (Ferreira et al. 2012). Because it is the intention of the South African government to submit a proposal to legalize the trade in rhinoceros horn at the next Conference of the Parties of CITES in 2016, it is timely to develop quantitative studies that can provide improved information to decision makers (Leader-Williams 2013). Hence, we modeled the dynamics of the rhinoceros population and poaching. We investigated whether the funding generated by introducing a quota system under a central selling organization could be used to enhance rhinoceros protection while providing economic incentives to local stakeholders.

Methods

We developed a simulation framework that integrates poaching and population models with an economic model to investigate how 8 different policy scenarios, which would be implemented to control illegal killing, could improve the protection of the southern white rhinoceros population in South Africa (Fig. 1). The poaching model was first used to examine the socioeconomic drivers of poaching based on data collected from 1990 to 2013 and then to predict in combination with the population model the total number of rhinoceroses illegally killed from 2014 to 2023 under 8 policy scenarios. We also estimated the economic costs and benefits of each scenario under enhanced enforcement only and a legal trade and used a decision support framework to rank the scenarios with the objective of maintaining the rhinoceros population above its current size while generating profit for local stakeholders. A legal trade in rhinoceros horn does not imply any killing of rhinoceroses. Rhinoceros horn could be harvested from individuals that die of natural causes; it can also be harvested from live animals with minimum risk to the rhinoceroses (Lindsey & Taylor 2011).

Poaching Model

The number of rhinoceroses poached per year was used as an indicator of poaching. We chose the candidate explanatory variables based on prior expectation of their relevance to illegal killing of rhinoceroses (Leader-Williams et al. 1990; Leader-Williams & Milner-Gulland 1993; Milner-Gulland 1993; Jachmann & Billiouw 1997; Lemieux & Clarke 2009; Poudyal et al. 2009). The variables used in the poaching model and data sources are summarized in Supporting Information. The maximum fine upon conviction (corrected for inflation) and the number of years in prison were included in the poaching model to delineate the relative importance of penalties when illegal traders and poachers get caught. The total number of field rangers deployed for antipoaching activities was used to evaluate the antipoaching effort. We included the total number of southern white rhinoceroses for each year of simulation to examine the effect the increasing rhinoceros population has had on poaching.

To understand the impact on poaching of an increase in rhinoceros horn price, we used the gross domestic product (GDP) per capita for Far East Asia as a proxy for illegal price. We used GDP for Far East Asia because it is strongly correlated with GDP in both Vietnam and China, which are currently considered the largest markets for rhinoceros horn (Milliken & Shaw 2012). The GDP per capita for Mozambique, which is the country from which most arrested poachers originate (Milliken & Shaw 2012), was used as an indicator for the lack of alternative economic opportunities. Governance was based on 6 indicators (voice or accountability, political stability, government effectiveness, regulatory quality, rule of law, and control of corruption). Principal components analyses showed that 89% of variation between these indicators was captured by a single component (hereafter called governance). We also included potential effects that stricter regulations to prevent Far Eastern nationals from acquiring rhinoceros horn through so-called pseudo-hunts and through a ban on domestic trade on rhinoceros horn, which were implemented in South Africa after 2008, have had on poaching of rhinoceroses (Milliken & Shaw 2012).

We used an information theoretic approach (Burnham & Anderson 2002) and Akaike's information criterion corrected for finite sample sizes (AICc) to calculate statistical models. We used generalized linear models with a negative-binomial error distribution and a log-link function to examine the socioeconomic drivers of poaching. We determined the magnitude and direction of the coefficients for the independent variables with multimodel averaging implemented in the *R* (version 3.1.0) (R Core Development Team 2014) package glmulti (Calcagno 2010). The relative importance of each predictor variable was measured as the sum of the Akaike weights over the 10 top-ranked models containing the parameter of interest (Conroy & Brook 2003). Finally, we validated the top-ranked model by using leave-one-out cross validation, which is used to estimate the mean model-predictor error by successively omitting 1 observation from the training data set and using it for validation.

Population Model

We developed a population model for southern white rhinoceros in RAMAS GIS (version 6) (Akçakaya & Root 2013). Overall, the population dynamics of both black and white rhinoceros are well known because their populations have been extensively monitored in the wild (Conway & Goodman 1989; Owen-Smith 2007; Di Minin et al. 2013*b*). We modeled southern white rhinoceros population dynamics with a stochastic age-structured demographic model based on 11 age classes for both males and females. Fecundity in the model was based on the product of the probability of breeding, sex ratio at birth, average number of calves, and first year survival (Supporting Information for more details). Survival rates for each age class were calculated independently from this study based on long-term censuses (Owen-Smith 1988, 2007). More details are provided in Supporting Information. The most important parameters included in the population model are summarized in Table 1.

We used the total number of the southern white rhinoceros in South Africa in 2010 (18,780) as the initial population size (Emslie et al. 2013). We calculated the ecological carrying capacity (*K*), which depends on the amount of forage produced based on rainfall (Martin 2011). Details on how *K* was calculated are provided in Supporting Information. A ceiling model of density dependence was used to approximate the intraspecific competition for resources as the population approaches carrying capacity (Owen-Smith 2007). In each simulation, which was run 10,000 times, we accounted for environmental and demographic stochasticity (Akçakaya & Root 2013).

We developed a global sensitivity analysis to examine the impact of varying the values of key model parameters (carrying capacity, survival for each age class, and fecundity for breeding age classes) on the southern white rhinoceros mean final population size (Iman et al. 1981). Specifically, we used Latin hypercube sampling with 100 sampling dimensions to simultaneously vary the values of each parameter randomly from within 100 evenly sized partitions across $\pm 10\%$ ranges. The Latin hypercube sampling was performed with the R package lhs (Carnell 2009). For each iteration of randomly selected parameter values, we projected the southern white rhinoceros population for 10 years and recorded the mean final population size. We then fit a generalized linear model with the mean final population size as the response and the varied parameters as fixed effects. To assess the sensitivity of the model to the input parameters, we measured the relative importance of each predictor variable as the sum of the Akaike weights over the 10 top-ranked models containing the parameter of interest (McCarthy et al. 1995; Conroy & Brook 2003).

Economic Model

The population model was used as an input to an economic model that we used to calculate the net present value of southern white rhinoceros conservation in South Africa. First, we calculated the net present value under a legal trade whereby the trading of a yearly quota was promoted, as an alternative to a trade ban, to finance additional enforcement, and disrupt illegal activities to safeguard the rhinoceros population. Promoting strict quantities through a quota system is more beneficial than a supply-side approach to rhinoceros conservation (e.g., Bulte & Damania 2005). When policy that restricts the trading quota is in place, in fact, the competition between legal suppliers and illegal traders is restricted, potentially decreasing poaching pressure (Bulte & Damania 2005). The net present value was calculated as

$$\mathrm{NPV} = \sum_{t=0}^{10} \frac{(V_t + H_t - C_t)}{(1+\delta)^t}, \tag{1}$$

where V_t is the profit derived from selling an effective quota of rhinoceros horn; H_t is the total profit derived from trophy hunting and live sales; C_t is the total cost to protect the rhinoceros population; and δ is a discount factor (5.5%) on the basis of cost of borrowing money in South Africa in 2012 (International Monetary Fund 2012). The V_t was calculated as

$$V_t = p_t w y_t, \tag{2}$$

Table 1. Parameter ranges used in the southern white rhinoceros population model.

Parameter	Description	Value	SD	References
S_1	calf survival	0.950	0.0095	Owen-Smith (1988, 2007)
S_2	survival 1–2 years	0.965	0.0096	Owen-Smith (1988, 2007)
S_3	survival 2–3 years	0.965	0.0096	Owen-Smith (1988, 2007)
S_4	survival 3–4 years	0.975	0.0097	Owen-Smith (1988, 2007)
S_5	survival 4–5 years	0.975	0.0097	Owen-Smith (1988, 2007)
S_6	survival 5–6 years	0.975	0.0097	Owen-Smith (1988, 2007)
S_7	survival 6–7 years	0.985	0.0098	Owen-Smith (1988, 2007)
S_8	survival 7–8 years	0.985	0.0098	Owen-Smith (1988, 2007)
S_9	survival 8–9 years	0.985	0.0098	Owen-Smith (1988, 2007)
S_{10}	survival 9–10 years	0.985	0.0098	Owen-Smith (1988, 2007)
S_{11}	adult survival	0.977	0.0075	Owen-Smith (1988, 2007)
F_8	fecundity 7- to 8-year-olds	0.225	0.0045	Owen-Smith (1988, 2007)
F_9	fecundity 8- to 9-year-olds	0.225	0.0045	Owen-Smith (1988, 2007)
F_{10}	fecundity 9- to 10-year-olds	0.225	0.0045	Owen-Smith (1988, 2007)
F_{11}	fecundity adults	0.200	0.0038	Owen-Smith (1988, 2007)
N	initial population size	18,780	-	Emslie et al. (2013)
K	carrying capacity	42,500	2,125	based on Martin (2011)

where w is the average weight (4 kg) of a horn (Milliken & Shaw 2012), p_l is the whole-horn market price, and Y_t is the legal stock of rhinoceros horn. We set p_l to 20,000, 40,000, and 60,000 U.S. dollar/kg to show the potential revenue generated under a low, medium, and high selling price. At any time, the legal stock of rhinoceros horn Y_t was by

$$Y_t = s_t + n_t + d_t, \tag{3}$$

where s_t is the proportion of the previously accumulated stock on sale for that year, n_t is the addition to the stock due to natural mortalities for that year, and d_t is the addition to the stock by dehorning the proportion of the rhinoceros population found on private conservation land (approximately 24%). In 2013, the stock size (s_t) was approximately 16,600 horns.

We calculated the total profit derived from trophy hunting and live sales (H_t) at year ***t*** was

$$H_t = G_t + Z_t, \tag{4}$$

where G_t is the profit generated from trophy hunting and Z_t is the profit generated from live sales. We accounted for trophy hunting in the population model by removing a fixed proportion of the adult population every year of simulation:

$$N_{11,t+1} = S_{11}\,(1 - v_{11})\,N_{11}, \tag{5}$$

Where S_{11} is the adult survival rate and v_{11} is the harvesting rate for adults calculated based on the 1% proportion of the total rhinoceros population hunted per year for trophies from 2000 to 2010 (Milliken & Shaw 2012). We then calculated the gross profit generated from trophy hunting as

$$G_t = p_b v_{11} N_{11}, \tag{6}$$

where p_b is the average trophy hunting price of \$31,629/rhinoceros from 2000 to 2010 (Milliken & Shaw 2012). We calculated the gross profit from live sales as

$$Z_t = p_s l_t N_t, \tag{7}$$

where p_s is the average live sale price of \$18,950/rhinoceros auctioned from 2000 to 2010 (Milliken & Shaw 2012) and l_t is the 4% proportion of the total population sold per year from 2000 to 2010 (Milliken & Shaw 2012). We hypothetically started legal trade in 2016, after the next CITES meeting will take place. Therefore, from 2014 to 2016 gross profit was generated only from trophy hunting and live sales.

We calculated the total cost to protect the rhinoceros population (C_t)

$$C_t = Z_t c, \tag{8}$$

where Z_t is the number of field rangers deployed to protect the rhinoceros population and c is the protection cost per ranger deployed. We used cheap (\$29,500/ranger), average (\$31,000/ranger), and expensive (\$37,621/ranger) values for c according to field budgets from protected areas that have had different levels of poaching. Although c is here considered as cost per ranger deployed, it also accounts for other important protection costs (e.g., ranger salaries, vehicles running costs, communication costs, consumption, rewards to informers, etc.).

Second, we compared the economic model for a legal trade to an alternative scenario, which maintains the status quo and generates profit for rhinoceros conservation via trophy hunting and live sales only (Di Minin et al. 2013*c*). We calculated the net present value under this scenario as

$$\mathrm{NPV} = \sum_{t=0}^{10} \frac{(H_t - C_t)}{(1+\delta)^t}, \tag{9}$$

where H_t is the total profit derived from trophy hunting and live sales and δ is a discount factor (5.5%) on the basis of cost of borrowing money in South Africa in 2012 (International Monetary Fund 2012).

Our estimates of the net present value of southern white rhinoceros conservation can be considered conservative because we did not include economic returns from ecotourism (Di Minin et al. 2013*a*).

Policy Scenarios

We modeled near-future southern white rhinoceros dynamics for 13 years, 2010–2023. We used the predict function in *R* (R Core Development Team 2014) to predict the total number of rhinoceroses illegally killed between 2014 and 2023 by projecting the values of the variables with the highest relative importance (≥0.8) in the poaching model into the future. As an input, the population model provided the poaching model with the total number of rhinoceroses for each year of simulation. In the population model, we considered the immature, subadult, and adult age classes to be targeted by poachers (Ferreira et al. 2012). Particularly, we tested the effects of doubling the monetary fine and increasing the antipoaching effort (small, medium, and large increase in the number of field rangers) on poaching of rhinoceroses under increasing wealth in Far East Asia (Supporting Information). We used the projected GDP for Far East Asia from 2014 (International Monetary Fund 2012) to predict the average number of rhinoceroses illegally killed in each year. To take uncertainty about projected GDPs into account, we developed pessimistic and optimistic economic scenarios (Supporting Information), where the GDP for Far East Asia increased at the maximum and the minimum rate recorded from 2003 to 2013 (International Monetary Fund 2012). This allowed us to derive upper and lower envelopes of uncertainty for the population trajectory from the 95% confidence intervals.

Scenario Ranking

A form of uncertainty analysis was used to rank alternative policy scenarios in a robust manner. We ran a large number (10,000) of simulation replicates for the stochastic demographic model, accounting for environmental and demographic stochasticity. From these simulations, we derived upper and lower envelopes of outcome from the 95% confidence intervals of the output of the rhinoceros population model and the economic model. Performance in terms of the rhinoceros population was defined as the population size at the end of the planning horizon (2023). Equations (1) or (9) were used in the calculation of total profit, depending on whether the trade was legalized or not. Quasihyperbolic time discounting was used with a 5.5% discount rate, and $\beta = 1$ (Green & Myerson 2002) was used to summarize the economic performance of the scenarios across time. When comparing scenarios, we considered the lower 95% performance of a scenario as its robust performance. The best scenarios were identified as the most profitable (or least expensive) ones that 95% guaranteed that the rhinoceros population would not decline by 2023. Scenario ranking was implemented in RobOff software (Pouzols et al. 2012; Pouzols & Moilanen 2013). See Supporting Information for details.

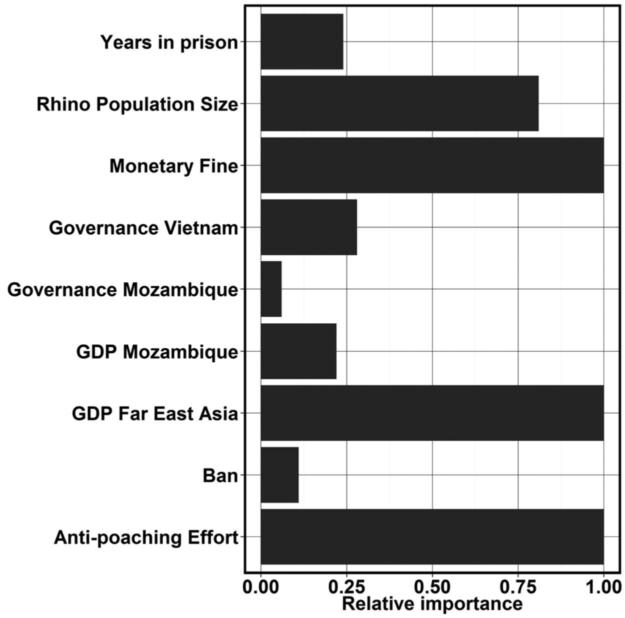

Figure 2. Relative importance of the most important variables affecting rhinoceros poaching. The response variable is the number of rhinoceroses illegally killed in South Africa from 1990 to 2013.

Results

According to the generalized linear models (Table 2), the best overall predictors of rhinoceros poaching in South Africa were the GDP per capita in Far East Asia, the antipoaching effort, and fine upon conviction (Fig. 2). The rhinoceros population size also had a large effect on rhinoceros poaching (Fig. 2). The top-ranked model, which included these variables, had an AICc weight of 0.47. The coefficients for fine upon conviction and antipoaching effort had—as expected—a negative sign, indicating that an increase is expected to result in a decrease in poaching. Governance in Vietnam, GDP per capita in Mozambique, years in prison, the restrictions preventing Far Eastern nationals from acquiring rhinoceros horn through so-called pseudo-hunts and a domestic trade in South Africa, as well as governance in Mozambique, had much smaller effects on rhinoceros poaching (Fig. 2). The coefficients for governance in Vietnam, GDP per capita in Mozambique, years in prison, and governance in Mozambique had—as expected—a

Table 2. Top-ranked predictors of rhinoceros poaching in South Africa.

		AICc[b]		
Model[a]	*No. of variables*	*Change relative to the top-ranked model*	*Weight*	*Percentage of deviance explained*
WRhPopSize + MonFine + APEff + GDP_FEA	4	0.00	0.47	88.79
∼ WRhPopSize + MonFine + APEff + GDP_Moz + GDP_FEA	5	2.46	0.19	88.18
∼ WRhPopSize + MonFine + APEff + GDP_Moz + GDP_FEA + Gov_Viet	6	2.56	0.11	90.29
∼ WRhPopSize + MonFine + APEff + GDP_FEA + Gov_Viet	5	2.71	0.09	90.67
∼ WRhPopSize + MonFine + APEff + GDP_FEA + Gov_Moz	5	2.90	0.07	89.13
∼ WRhPopSize + MonFine + APEff + GDP_FEA + YearsPris	5	6.17	0.02	88.69
∼ WRhPopSize + Ban + MonFine + APEff + GDP_FEA	5	6.51	0.02	90.60
∼ MonFine + APEff + GDP_FEA + YearsPris	4	6.55	0.02	87.96
∼ WRhPopSize + MonFine + APEff + GDP_Moz + GDP_FEA + YearsPris	6	7.44	0.01	88.41
∼ MonFine + APEff + GDP_Moz + GDP_FEA + Gov_Viet	5	12.10	0.00	90.44

[a] *Relationships between the predictors and the response variables (number of rhinoceroses killed illegally) are correlative. Plus signs imply additive terms in the model. WRhPopSize, rhinoceros population size; MonFine, maximum monetary fine for rhinoceros poaching corrected for inflation; APEff, conservation effort measured as the number of field rangers deployed for antipoaching activities; GDP_FEA, gross domestic product per capita Far East Asia; GDP_Moz, gross domestic product per capita for Mozambique; YearsPris, years in prison upon conviction; Gov_Viet, governance index for Vietnam; Gov_Moz, governance for Mozambique; Ban, restrictions on Far Eastern nationals to acquire rhinoceros born from domestic stocks and legal trophy hunts.*
[b] *Akaike's information criterion corrected for finite sample sizes.*

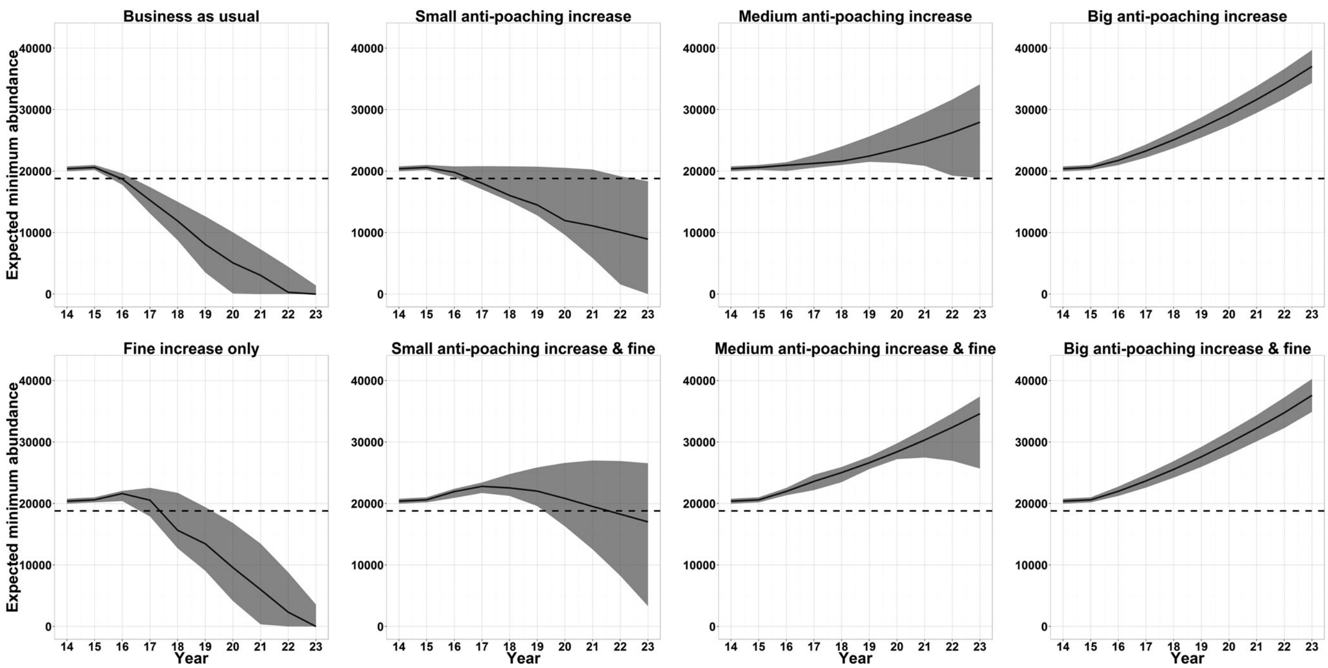

Figure 3. Predicted southern white rhinoceros abundance from 2014 to 2023 under 8 policy scenarios that could be implemented to reduce poaching in South Africa. The uncertainty envelopes correspond to the average abundance projected under a scenario of maximum (lower envelope) and minimum (upper) increase in the GDP in Far East Asia. The horizontal dotted line is the southern white rhinoceros population size in 2010.

negative sign, indicating that an increase is expected to result in a decrease in poaching. With the leave-one-out cross validation, the top-ranked model (Table 2) had a mean prediction error of approximately 10%.

The future predictions for rhinoceros poaching under the 8 policy scenarios suggested that increasing the antipoaching effort and the monetary fine upon conviction would be crucial to maintain the population at or above its current size under increasing wealth in Far East Asia (Fig. 3). Notably, the population (in the wild) was predicted to go extinct around 2023 under present management (business as usual). Increasing only the monetary fine did not effectively conserve the southern white rhinoceros population in South Africa (Fig. 3). Survival of adults, calves, 1- to 2-year-olds, 4- to 5-year-olds, and 6- to 7-year-olds was the most influential parameter in the sensitivity analysis for the population model (Supporting Information). The other important parameters of the population model were fecundity of adults and survival of 8- to 9-year-olds; all other parameters had smaller effects.

Under enhanced enforcement only, maintaining the population was extremely expensive (Supporting Information), whereas legalizing the trade increased the size of the population and generated profit under enhanced law enforcement (Supporting Information). According to the scenario ranking, the optimal scenario to maintain the rhinoceros population above its size in 2010, while maximizing profit, was to provide the medium increase in antipoaching effort and to increase the fine upon conviction (Table 3). Without legalizing the trade, maintaining the population above its current size required covering costs equal to approximately $147,000,000/year under the most cost-effective scenario (Table 3). With a legal trade in rhinoceros horn, under the same scenario, the conservation enterprise made a profit of $717,000,000/year (Table 3). By 2023, under the same policy scenario, the net profit generated through the legal trade was predicted to exceed $1,000,000,000 and the southern white rhinoceros population was predicted to increase to approximately 35,000 individuals (Supporting Information).

Discussion

Our results suggest that the funds generated by selling a quota under a central selling organization could be used to enhance law enforcement to levels that would undermine illegal poaching activities. Meanwhile, the profit generated from the legal trade in horn could be used for human and economic development of local stakeholders and to protect other biodiversity. Legalizing the trade without improving the protection of the rhinoceros population will not, according to our results, generate extra benefits for rhinoceros conservation.

Our results suggest that the rapid increase in poaching can be attributed to growing demand for rhinoceros horn from Far East Asia. The significance of the population size variable highlights how increasing the size of the rhinoceros population over time has made South Africa the main target for criminal syndicates seeking rhinoceros horn. At the same time, law enforcement levels (both fine upon conviction and anti-poaching effort) appear to be too low to disrupt illegal activities. In particular, the antipoaching effort, which we evaluated as the total number of field rangers deployed to protect rhinoceroses, was insufficient for counteracting the current spike in rhinoceros poaching—a finding in line with prior studies (Leader-Williams et al. 1990; Leader-Williams & Milner-Gulland 1993; Poudyal et al. 2009). In addition, the monetary fine upon conviction most likely represents a small tax for criminal syndicates compared with the revenue they generate illegally. As recent policy recommendations suggest, prosecutors in South Africa should consider increasing fines, as well as enforcing asset forfeitures, as an increased deterrent to criminals (Emslie et al. 2013).

Although other variables had less effect in the poaching model, they reinforced our main results. A large threat to the rhinoceros population is surely the reward that poachers from impoverished communities in Mozambique, bordering Kruger National Park, receive for rhinoceros horns. Considering how cheap it might be for criminal syndicates to recruit new poachers in the future, it is of crucial importance, as we highlight below, that more funding is generated to increase the antipoaching effort to deter rhinoceros poachers. This should happen in combination with increased penalties upon conviction both in terms of monetary fines and imprisonment, as suggested by the poaching model. Finally, results of the poaching model suggest that an improvement in governance in Vietnam would help decrease poaching. Although this is a challenging goal, it is key that the Vietnamese government implement measures that limit opportunities for corruption that can result in the successful prosecution and punishment of rhinoceros horn smugglers (Milliken & Shaw 2012).

Reducing demand for rhinoceros horn through consumer behavior modification and conservation education is unlikely in the short term because of long-established cultural beliefs; use of rhinoceros horn has continued since the trade ban was implemented in 1977 (Rivalan et al. 2007; Graham-Rowe 2011). Our model predicted that increasing poaching of subadults and adults will have a negative impact on the dynamics of the southern white rhinoceros population in the imminent future. Ensuring population viability under increased poaching levels will require using many tens of millions of dollars every year just for rhinoceros protection alone, which is problematic in areas where pressing issues of human development remain a societal priority (Adams et al. 2004). Private and communal landowners would find it

Table 3. Ranking of the most robust policy scenarios to reduce rhinoceros poaching and increase population size and profit in South Africa between 2014 and 2023.*

Rank	*Scenario*	*Total profit with legal trade (MM US$)*	*Rhinoceros population size*	*Total profit, no trade (MM US$)*
1	medium increase in no. of rangers & fine	717	25,690	−147
2	big increase in no. of rangers & fine	709	34,920	−189
3	big increase in no. of rangers	698	34,356	−190
4	medium increase in no. of rangers	629	18,886	−149
5	small increase in no. of rangers & fine	583	3,332	−132
6	small increase in no. of rangers	456	0	−136
7	no trade (business as usual)	353	0	−128
8	increase fine only	334	0	−123

**Only the 4 top scenarios maintain the rhinoceros population above its size in 2010, and a positive total profit is only possible for scenarios with legal trade. The values shown are robust. For more information see Supporting Information.*

almost impossible to cover such protection costs unless alternative sources of funding were found. Hence, an important contribution that the legal trade could make is to cover such costs, at least in the short term, until other measures over longer periods lead to a reduction in demand from users in the Far East. In addition, a legal supply of rhinoceros horn could potentially diminish the prestige value that has recently emerged in Vietnam (Milliken & Shaw 2012).

At the same time, the profit generated from the legal trade could also be used to financially empower communities in Mozambique, where many poachers originate, in accordance with some of the principles of the London Conference on Wildlife Crimes (Lawson & Vines 2014). Although increasing enforcement only might not keep criminals from committing a crime (Ariely 2012), economic incentives may be an important solution to promote participation of local communities in improved enforcement (but see Andrade & Rhodes 2012). Enhanced enforcement combined with effective engagement with local communities, for example, has enabled Nepal to not lose a single rhinoceros to poaching in 2011 and 2013 (Emslie et al. 2013). Finally, the funding generated from the legal trade could also be used for the protection of other biodiversity via the umbrella effect of rhinoceroses (Di Minin et al. 2013*c*; Di Minin & Moilanen 2014).

Because the market in rhinoceros horn has been illegal since 1977, there is a lack of data, which prevented us from explicitly modeling potentially important aspects driving rhinoceros poaching. As in Poudyal et al. (2009), we had to use a proxy (GDP) to capture demand for rhinoceros horn in consumers' countries. In our economic model, we assumed that the legal price of rhinoceros horn would remain constant over time. At this stage, it is not possible to estimate a full-price quantity model for rhinoceros horn. Yet, our results highlight that even at a lower selling price than the illegal price (currently > $50,000/kg) (Milliken & Shaw 2012) the profit generated could cover important protection costs required to maintain the rhinoceros population above its current size. Finally, we assumed that poaching pressure is evenly distributed in space because this information is currently not available for all conservation areas that have rhinoceroses.

International donors cannot be expected to raise many millions of dollars year after year to protect rhinoceroses from poaching, especially when endless other uses for conservation resources exist. Similarly, given long-established cultural beliefs, consumers are unlikely to reduce their near-future demand for rhinoceros horn. Under current management the southern white rhinoceros population could go extinct in <20 years. Instead, our results suggest that a legal trade in horn that does not require killing any rhinoceroses could cover higher protection costs, allowing the rhinoceros population to increase in size. A legal trade could also provide sustainable economic incentives to local stakeholders. At the same time, policy makers in South Africa should be careful in advocating for CITES to lift a 35-year-old ban on rhinoceros horn products unless the funding generated from the trade will be reinvested in improved protection of the rhinoceros population. The recent escalation in poaching in South Africa and the recent losses of 3 subspecies of rhinoceroses elsewhere in Asia and Africa (Milliken & Shaw 2012) make it timely to evaluate, discuss, and test alternatives to the present long-standing policy.

Acknowledgments

E.D.M. was supported by the Academy of Finland Centre of Excellence Programme 2012–2017, grant 250444. J.L., F.M.P., and A.M. were supported by the European Research Council grant, ERC-StG 260393 (project GEDA, Global Environmental Decision Analysis).

Supporting Information

Supplementary methods (Appendix S1) and results (Appendix S2) are available online. The authors are responsible for the content and functionality of these materials. Queries (other than missing material) should be directed to the corresponding author.

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