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# Finding politically feasible conservation policies: the case of wildlife trafficking

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*Abstract.* Conservation management is of increasing importance in ecology as most ecosystems nowadays are essentially managed ecosystems. Conservation managers work within a political-ecological system when they develop and attempt to implement a conservation plan that is designed to meet particular conservation goals. In this article, we develop a decision support tool that can identify a conservation policy for a managed wildlife population that is both sustainable and politically feasible. Part of our tool consists of a simulation model composed of interacting influence diagrams. We build, fit, and use our tool on the case of rhino horn trafficking between South Africa and Asia. Using these diagrams, we show how a rhino poacher's belief system can be modified by such a policy and locate it in a perceived risks-benefits space before and after policy implementation. We statistically fit our model to observations on group actions and rhino abundance. We then use this fitted model to compute a politically feasible conservation policy.

*Key words: anti-poaching policies; biodiversity; conservation management; conservation politics; decision-making models; individual-based models; rhinoceros poaching; socio-ecological models; statistical fitting of ecological models; wildlife trafficking.*

## Introduction

Global environmental change is a key threat to ecological resilience of ecosystems from which humans benefit. Most drivers such as climate change, invasive species, pollution, emerging diseases, and habitat change are largely a consequence of inappropriate human activities (Janssen et al. 2006). Conservation management authorities have the task of finding conservation policies that can be implemented under political constraints. Such constraints can either result from the formal political process of environmental law creation and enforcement or from informal, non-state, political processes such as habitat destruction through economic development. Developing an ecosystem management plan or policy, therefore, is the problem of finding a policy that stands the best chance of reaching conservation goals, while at the same time having enough political support to allow its implementation.

Illegal resource use is a key driver of global environmental change. Most noticeable is the widespread explosion of global wildlife trafficking that threatens the persistence of biodiversity (Rosen and Smith 2010). A high profile case study is the poaching of rhinoceroses (rhinos) for horn. South Africa is home to 88.2% and 36.8% of the world's white (*Ceretotherium simum*) and black (*Diceros bicornis*) rhinos, respectively (Emslie 2013). Conservation managers are challenged by the uncontrolled harvesting of these animals by so-called poachers. Poachers, who do the actual shooting and hacking off of the horns, form the first link in a chain of criminals who together, run an illegal trading operation in rhino horn that stretches from South Africa to consumers of rhino horn in Asia. Such an illegal trading operation is referred to as wildlife trafficking (Warchol 2004). In this case, rhino poachers interact directly with the ecosystem that the rhinos are a part of. Identifying and implementing a combination of actions aimed at curbing rhino poaching, then, can be viewed as the management of a political-ecological system composed of rhino horn consumers in Asia; criminal groups running the illicit rhino horn supply chain; groups working to hold up the rule of law (anti-poaching enforcement personnel, the judicial system, port authority officials, and conservation managers within wildlife protected areas); and the rhino-hosting ecosystem itself. We acknowledge that any management policy implemented by authorities that does not target the elimination of Asia's demand for rhino horn, or at least create sustainable demand, is only treating the symptoms of the problem. We do not, however, discuss demand reduction policies in this article and therefore refer to the policies we develop herein as anti-poaching policies.

Traditional anti-poaching is focused at local scales and at poachers that enter protected areas (Arcese et al. 1995). A key requirement is thus understanding the decision making by people, often those living next to protected areas, to poach or not. This in turn will influence the decision making process of law enforcers. Our predictions are that poacher decisions to not poach will only materialize

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if disincentives created by anti-poaching outweigh incentives (Ferreira et al. 2014). Several drivers create incentives (Conrad 2012) including high profit potential, histories of trade, inelastic demand, unclear property rights, and human–wildlife conflict. We speculate that appropriate law enforcement may override a combination of these drivers. In addition, we predict that providing economic options alternative to poaching may also disrupt poaching incentive–disincentive interactions. This view that poaching behavior is driven by rational actor mechanisms directed toward either poverty alleviation or the pursuit of greater wealth is echoed by an exhaustive literature review of the motivations behind elephant ivory and rhino horn trafficking (Duffy and St John 2013).

## Rhino Poaching: Current Situation

Kruger National Park (KNP), South Africa is a stronghold of two sub-species of rhino, the southern white rhino (*Ceratotherium simum simum*) and the southeastern black rhino (*Diceros bicornis minor*). In KNP, both these species of rhinos are suffering a poaching onslaught for their horns since 2008 (Thomas 2010). Despite intensified anti-poaching activities, poachers continue to kill rhinos (Ferreira and Okita-Ouma 2012, Bale 2016). Rhinos are poached by small groups of individuals referred to here as poaching parties. A poaching party consists of a shooter, axeman, and water carrier. There were 174 poachers arrested in 2014, 36 of whom died either during the process of being arrested or while in incarceration. In this same year, there were 827 rhinos poached in the park. An estimated 4,329 poachers entered KNP (some of these are the same individuals entering more than once). There were 111 contacts with rangers and 80 sightings of poachers by rangers. That translates to 573 poachers interacted with or seen by rangers. That in-turn, translates to a 4% chance of being arrested (174/4329). There is a 0.8% chance of being killed (36/4329). By 2016, a total of 8,650 people, some multiple entrants, entered KNP to poach rhinos and had a 3.2% chance of being arrested (K. Maggs, *personal communication*).

There is some evidence that, as KNP tightens its security, poachers move to other parks in South Africa. For instance, although only 682 rhinos were poached in KNP during the 2016 calender year, a substantial reduction in KNP from the 826 killed during 2016, 372 were killed elsewhere across South Africa in the same period, up from 349 during 2015 (DEA 2017). The outcome of such a poaching threat was not detectable at the population level in KNP for both black and white rhino by 2013 (Ferreira et al. 2015) because population reductions due to poaching are within the confidence intervals of abundance estimates. Continued trends in poaching predicted detectable declines by 2016 (Ferreira et al. 2012), which materialized (DEA 2017). In addition, two conservation values are already compromised: the opportunity to contribute to rhino range expansion programs (Emslie and Brooks 1999) as well as generating revenue from rhino sales (Ferreira et al. 2012).

The difference between demand and supply determines volume or availability of a commodity. In classical macroeconomics theory, price is negatively related to the volume or availability of a commodity. The higher the price, the more attractive is a commodity for exploitation. Incentives for poaching are offset by disincentives with some critical thresholds. For instance, if jobs are available, then the minimum wage of such jobs in part determines the threshold when fines and jail sentences are large enough disincentives to override price incentives for poaching (Messer 2010). Poachers, then, balance their perceptions of the outcome of a poaching raid based on the perceived strength of incentives relative to disincentives. Here, we develop a model that quantitatively captures this trade-off and use it to assess what conservation management policies might lead to a sustainable rhino population in the face of this decision making process on the part of poachers.

Following Milliken (2014, p. 18), a first-tier middleman (also called a receiver, courier, or transporter) commissions a poaching party and buys whatever horn the party is able to poach. Second-tier middlemen (also called buyers) buy horn from first-tier middlemen and then turn around and sell it to third-tier middlemen (also called port exporters or simply exporters). These exporters sell their horn to Asian retailers. The network composed of poaching parties, middlemen, and Asian retailers is called hereafter the wildlife trafficking criminal network.

The amount of money offered by middlemen to poachers for rhino horn have been estimated through interviews with arrested middlemen and poachers. These interviews suggest that, between 2013 and 2015, middlemen paid about US$2,000 for 1 kg of rhino horn to a poaching party and then sold it to a trader for about US$12,000 (Haas and Ferreira 2016*b*). Over time, the price that a trader pays a middleman for 1 kg of rhino horn affects the bid price middlemen communicate to poachers. Poachers in turn decide whether this price is high enough to outweigh the risks of being either shot or sent to jail for poaching. Poacher sensitivity to current horn price, then, is implicitly represented through the behavior poachers choose to engage in (poaching or poaching avoidance) based on different amounts offered for rhino horn by middlemen. In effect, poachers are hearing through middlemen what the most recent street price of rhino horn is in China or Vietnam.

Hsu (2017) gives an overview of the Asian market for rhino horn. For at least 800 years, the Chinese and other east Asians have valued rhino horn as a health restorative. Typically, the ground horn is mixed with warm water. Many Asians believe that this drink will reduce a fever, treat rheumatism, treat arthritis, and most recently, cure a variety of cancers (PBS 2011, Hsu 2017). Medical studies have failed to find such properties of rhino horn (Nowell 2012).

The Chinese have an emerging upper-middle class who can afford what the West would call "designer medicines," (Conca 2014) in this case, rhino horn. Medicinal use of rhino horn appears to be a tradition in these societies. Hence, these rhino horn consumers may not be interested in studies that examine the effects on human health from rhino horn consumption. The Vietnamese use this concoction to ostensibly relieve hangovers (Vaughan 2012), but actually do so to display their wealth (Milliken and Shaw 2012). Sas-Rolfes (2011) sees the demand for rhino horn to be little affected by increases in its price, i.e., Asian demand for rhino horn is price inelastic.

## A Decision Support Tool for Developing Conservation Policies

One way to find a politically feasible, sustainable conservation policy is to cast the problem as a nonlinear program. This program's objective function quantifies conservation goals and the program's constraints quantify political realities. Here, we implement such an approach by building an ecosystem management tool (EMT) proposed by Haas (2011).

Optimization of an ecologically motivated objective function is central to the adaptive management approach to environmental management. As Walters and Hilborn (1978) state in their landmark article, "Objectives are the goals of management, the criteria used to compare the outcomes of management alternatives. Simple objectives are the maximization of harvest, maximization of economic value, or preservation of minimum population densities."

For the case of rhino horn trafficking, an EMT consists of the following activities. (1) Development of an operational, computational, and dynamic model of poacher decision making, consequent rhino poaching events, poacher arrest and prosecution, rhino horn consumption, anti-poaching patrols, funding decisions for these patrols, and rhino abundance response to ecosystem processes and poaching pressure. We call this resulting model a political-ecological simulator. (2) Statistical estimation of the parameters of this model using a data set consisting of observations on poaching events, poacher prosecution events, horn price and consumption, decisions about funding levels for anti-poaching patrols, and rhino abundance. (3) Identification of the factors and their thresholds at which a poacher's cost–benefit perceptions changes regimes by finding those career advancement perceptions that always outweigh the perceived costs of any combination of disincentives. (4) Discovery of how effective anti-poaching activities and conviction sentences are at discouraging poaching behavior. (5) Identification of those anti-poaching policies that, if implemented by conservation managers and law enforcement officials, are predicted to result in desirable ecosystem state outcomes.

### *Political-ecological simulator parameter estimation*

We fit our simulator to data gathered in activity 2, above with a statistical estimation method called consistency analysis (Haas 2011: chapter 4). Consistency analysis balances parameter values that are based on cognitive/ecological theory with values supported by observations on group actions and rhino abundance.

Software to automatically acquire rhino-poaching-related articles from online newspapers was also developed. This system, commonly referred to as a news aggregator, uses Google News (Google 2013) to select news stories that are relevant to rhino horn trafficking. The system then downloads these articles, parses them, and adds their parsed content to a rhino poaching events database.

## Finding Politically Feasible Management Plans

To identify decision-switching thresholds, we identify critical points where the optimal decision between do not poach vs. poach switches and associate these critical points with combinations of perceived risk and perceived potential career advancement. Using these critical points, we run the fitted model forward in time under different combinations of direct disincentives, and indirect disincentives as short- to medium-term management policies as given in Ferreira et al. (2012). Doing so allows us to report on whether short- to medium-term management policies advocated by range states (Ferreira and Okita-Ouma 2012) may lead to a reduction in rhino poaching.

Next, we search for new values of our model's parameters that result in the simulator predicting the ecosystem reaching a desired set of conservation goals, which, in our case, is a target value of rhino abundance at a particular future time. Haas (2011: chapter 4) calls the sequence of actions that result from these new parameter values the most practical ecosystem management plan (MPEMP).

### *Additional examples*

The applicability of the EMT proposed herein to the conservation of other species can be judged by examining the introductory EMT for blue whale management given in Haas (2011: chapter 3), and the extensive EMT for cheetah management in East Africa (Haas 2011: chapter 7) that includes a MPEMP computation.

## Modeling Rhino Poaching Dynamics

To build our decision support tool, we model the decision making of poaching parties, middlemen, rhino horn retailers in Asia, rhino horn consumers in Asia, and anti-poaching units. We do this by constructing separate decision-making submodels for each of these groups using the family of probabilistic decision-making models commonly referred to as influence diagrams. We call these influence diagram-based models of decision making decision-making diagrams (Haas 2011: chapter 2).

### *A simplified example of a group decision making diagram*

Consider the decision problem that a poacher faces: should he poach rhinos for career advancement and

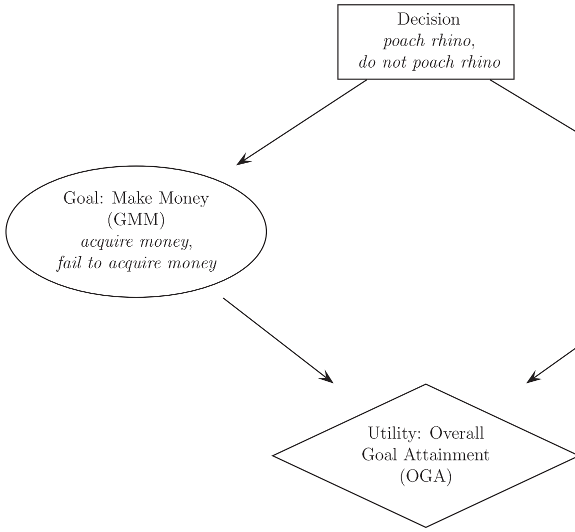


FIG. 1. Simplified example of a group decision-making diagram.

TABLE 1. Conditional probability table (CPT) for the nodes Goal: Make Money, and Goal: Avoid Prosecution.

| | Goal: Make Money | | Goal: Avoid Prosecution | |
|---|---|---|---|---|
| Parent value | Acquire money | Fail to acquire money | Arrested for poaching | Not arrested for poaching |
| Poach rhino | 0.9 | 0.1 | 0.7 | 0.3 |
| Do not poach rhino | 0.001 | 0.999 | 0.001 | 0.999 |

run the risk of being prosecuted for poaching? Fig. 1 gives a simplified group decision-making diagram that represents this decision problem. The diagram's path directions quantify the ideas that (1) executing a decision option causes impacts on pursued goals, and (2) patterns of goal attainment perceptions across a collection of goals collectively causes a single sense of utility.

Table 1 gives the conditional probability tables (CPTs) for the two goal nodes, and Table 2 gives the utility node's importance weights. The entries in these tables are the parameter values for this group decision-making diagram. Because chance nodes correspond to random variables, their labels are capitalized. Decision node labels are also capitalized. Values that a node may take on are italicized. The probability values in these three tables represent a decision maker who believes that there is a high chance of being caught but also believes the prospect of career advancement is more important than the possibility of being arrested for poaching.

TABLE 2. Relative importance weights for the node Utility: Overall Goal Attainment.

| | Value of Goal: Avoid Prosecution | |
|---|---|---|
| Value of Goal: Make Money | Arrested for poaching | Not arrested for poaching |
| Acquire money | 0.8 | 1.0 |
| Do not acquire money | 0.0 | 0.5 |

The Overall Goal Attainment (OGA) node in a group decision-making diagram represents the group's perceived utility of a proposed decision option. The combination of an action and a target that maximizes the expected value of this node is the out-combination (decision option) that the group implements. Because the two goal nodes are independent given a decision, the expected utility of poaching rhino is

$$
\begin{aligned}
E[\mathrm{OGA}|poach] = \\
& 0.8P(\mathrm{GMM} = \textit{acquire money}|poach) \\
& \times P(\mathrm{GAP} = \textit{arrested for poaching}|poach) \\
& + 0P(\mathrm{GMM} = \textit{do not acquire money}|poach) \\
& \times P(\mathrm{GAP} = \textit{arrested for poaching}|poach) \\
& + 1P(\mathrm{GMM} = \textit{acquire money}|poach) \\
& \times P(\mathrm{GAP} = \textit{not arrested}|poach) \\
& + 0.5P(\mathrm{GMM} = \textit{do not acquire money}|poach) \\
& \times P(\mathrm{GAP} = \textit{not arrested}|poach) \\
& = 0.8 \times 0.9 \times 0.7 + 0.0 \times 0.1 \times 0.7 + 1.0 \times 0.9 \\
& \times 0.3 + 0.5 \times 0.1 \times 0.3 \\
& = 0.789
\end{aligned}
\tag{1}
$$

and for not poaching rhino,

$$E[\mathrm{OGA}|do\,not\,poach] = 0.8 \times 0.001 \times 0.001 + 0.0 \times 0.999 \times 0.001 + 1.0 \times 0.001 \times 0.999 + 0.5 \times 0.999 \times 0.999 = 0.500 \quad (2)$$

making the decision to poach rhino the optimal one.

As this example shows, expected utility is a deterministic function of both the perceived probabilities and the perceiver's utility weights. Changing the pattern of these values (Tables 1, 2) can change what option the decision maker sees as the optimal one. For instance, if the utility of making money along with being arrested is changed from 0.8 as in the example, to 0.2, the optimal option would be to avoid poaching.

Selecting the decision option that maximizes the decision maker's expected utility is similar to selecting an option that maximizes an expected net present value (NPV). For example, Boettiger et al. (2016) give procedures for selecting a fisheries management policy that is predicted to maximize the "expected net present value of the fishery." These authors bring the cost of policy adjustment into their NPV function so that these costs can affect the selection of a policy. This idea of including costs in a decision option selection procedure is similar to our inclusion of the risk of being arrested or shot for poaching, as these events can be viewed as potential costs to the poacher if they engage in poaching.

### *Modeling group-level decision making*

In decision-making diagrams, the decision-making process of players belonging to a group is aggregated up to produce a group-level submodel of how a group responds to inputs. Each of these decision-making diagrams produces output actions and receives input actions from the other decision-making diagrams, and the rhino population dynamics influence diagram. The model that emerges from these interacting decision-making diagrams and rhino population influence diagram is called an Interacting Influence Diagrams (IntIDs) model (Haas 2011: chapter 2).

A theory of consciousness and the architecture of the cognitive activity of reaching a decision due to Baars (1988) is expressed as an influence diagram. Essentially, the theory states that a decision maker maintains two models of their world: the current situation, and the world if a particular decision option were implemented by the decision maker. In particular, goals are represented as contexts that contain desired images of perceived future reality (Baars 1988: 230). See Haas (2011: chapter 2) for a detailed description of the theory and how it is expressed as an influence diagram.

*Goal sets of would-be poachers.*—Decisions faced by some residents living close to protected areas motivate the need for a decision-making simulator that can model conflicting goals. For example, Raoul du Toit, director of the Lowveld Rhino Trust in Zimbabwe describes poachers as mostly young black men with cellphones who are economically frustrated (Russo 2010). These individuals work in tight gangs and carefully research a target area before they strike. SANParks staff have interviewed arrested poaching suspects and have visited the extremely poor Mozambique villages where many of the poachers are recruited. These officials are of the opinion that the Mozambican rhino poachers are prized as economic providers by everyone in the village they hail from, not just their immediate family (News24 2013). Indeed, poachers and particularly the middlemen who sponsor poaching raids have high social status in Mozambican villages that border KNP (Grill 2015, Hübschle 2016: 305–311).

Most South African residents of towns that are adjacent to KNP are on social grants or remittances (Ngomane 2012:6–7). This is at present how South Africa is handling the high unemployment in these towns that descend from apartheid-era homelands (Gwanya 2010, Pienaar and Von Fintel 2013). Hence, survival is not a challenge as up to 95% of the residents of these towns report supermarkets as being their main source of food (Ngomane 2012: 7). Due to high unemployment and few economic initiatives, the young men in these towns lack career opportunities and the income (Swemmer and Mmethi 2016), social status, and hope for the future that such careers bring. The high priority that residents in these towns place on having a career is echoed in the frequent mention of a lack thereof along with a desire for such as recorded in a survey administered to residents of towns bordering Golden Gate National Park, South Africa by Pelser et al. (2013). These authors also reinforce the importance of a career rather than a dead-end job in their *Lesson 2: To maximize impact, the lasting and multiplier effects of a poverty relief programme should extend beyond mere job creation and immediate financial relief* (Pelser et al. 2013). Finally, these authors caution that as the population of towns bordering a protected area grows, the impact of poverty alleviation initiatives sponsored by the protected area will progressively decrease.

### *IntIDs model and its operation*

We construct decision-making diagrams of four groups: poachers, anti-poaching units operating within and around KNP, rhino horn consumers in Asia interacting with rhino horn traders in Asia, and an aggregated submodel of first- and second-tier middlemen. In addition, an influence diagram is constructed of the South African rhino population. This ecosystem submodel interacts with the poachers group decision-making diagram. These four decision-making diagrams along with the rhino population dynamics influence diagram form our IntIDs model of rhino horn trafficking. See Appendix S1 for descriptions of the middlemen and anti-poaching units decision-making diagrams.

A somewhat related model is the "dynamical socioecological simulation framework" of Pirotta and Lusseau (2015). These authors simulate the profit that wildlife tourism operators can achieve over time under different policies for running animal-viewing trips. Profit is a function of repeat ticket sales (from repeat business with satisfied customers) and the cost of fuel expended during animal-viewing trips. The animal population is modeled as a spatiotemporal process and reacts to over-exploitation due to excessive contact with tour vehicles. As the authors state, a simple microeconomic model is assumed for the operators that includes ticket revenues and fuel costs.

We use this IntIDs model for our EMT's political-ecological simulator (as outlined in *Introduction*). Each group's repertoire of actions is given in Table 3. Note that a particular group's list of recognized input actions are those output actions of other groups that list the group in question as the target. A time interval to be studied is divided into weeks. Each week, each group decision-making diagram reads actions that were posted to a bulletin board the previous week by other decision-making diagrams and the ecosystem influence diagram. If a decision-making diagram recognizes an action, it computes a single output action (decision) and posts it back to the bulletin board. A decision-making diagram reads bulletin board actions in a random order so as to not introduce an artifact effect due to the order in which actions are posted to the bulletin board. Additionally, the order in which decision-making diagrams access the bulletin board is randomized anew each week. The ecosystem influence diagram computes probability distributions on its output variables from the end of the previous week to the end of the current week and posts the mean of each of these distributions to the bulletin board.

Table 3. Repertoire of output actions and associated targets of decision making diagrams.

| Action | Target |
|---|---|
| Poachers | |
| Do nothing | rhinoeco |
| Take legal employment | rhinoeco |
| Sell a few rhino horns | rhinoeco |
| Sell several rhino horns | rhinoeco |
| Sell many rhino horns | rhinoeco |
| Shoot an anti-poaching officer | anti-poaching units |
| Middlemen | |
| No action | |
| Sponsor poaching raid | poachers |
| Asian retailers | |
| No action | |
| Bid for rhino horn | middlemen |
| Anti-poaching forces | |
| No action | |
| Seize rhino horn | middlemen, poachers |
| Arrest middleman | middlemen |
| Arrest poaching suspects | poachers |
| Shoot poaching suspects | poachers |
| Increase anti-poaching enforcement | poachers |

*Notes:* Selling rhino horn is identified as an ecosystem-damaging action (Appendix S5). The target rhinoeco is the rhinoceros-supporting ecosystem.

### *Poachers group submodel*

For the purpose of evaluating different scenarios, we define a decision option of take legal employment in our poachers group decision-making diagram but represent the current lack of such jobs by setting hypothesis values for the chance of achieving career goals from such employment to very low values. To represent the decision to not poach when there are no other alternatives such as taking legal employment, we add the decision option do nothing.

Note that poaching is not limited to poor people living next to protected areas: veterinarians and park rangers have been known to engage in rhino poaching (Macleod 2012, GlobalPost 2012). We do not focus on the decision making of these types of poachers.

A poacher's sole audience is his immediate and extended family (Fig. 2). Poachers are pursuing the four goals of making a living, supporting their immediate and extended family, raising their social standing in their community, and avoiding prosecution. The goals of making a living, supporting family, and raising their social status are very similar and interlinked. Hence, for simplicity, we aggregate these goals into one goal: the pursuit of a career. Therefore, the poacher decision-making diagram contains only two goals. Poachers perceive their chances of running into an antipoaching patrol during a future poaching raid with the node Scenario: Imminent Interaction With Police (SIIWP) that takes on the values will be arrested for poaching, and no interaction. Poachers imagine the effects on their career goals that different decision options might have with the node Scenario: Pursue Career Goal (SPCG). This node takes on the values unattained, middling, and attained.

Path directions in Fig. 2 quantify the ideas that (1) the current situation impacts possible, future scenarios, (2) perceived family reactions influence career goals, (3) interactions with police influence the goal of staying out of jail, and (4) the perceived riskiness of poaching influence how much a poacher asks to be paid for any rhino horn they may be able to poach.

Poachers sell their rhino horn by physically trading the rhino horn for cash during an interaction with a transporter (see *IntIDs model and its operation*). Middlemen are a diverse group of businessmen, former poachers, and diplomats (Montesh 2012, Smillie 2013). Subsistence is not a goal for these upper-middle class individuals. Rather, the profit motive is their sole personal goal for engaging in this illegal activity.

*Feedback from the rhino-hosting ecosystem.*—The poachers group decision-making diagram has a rhino prevalence node. This node represents the poachers' perception

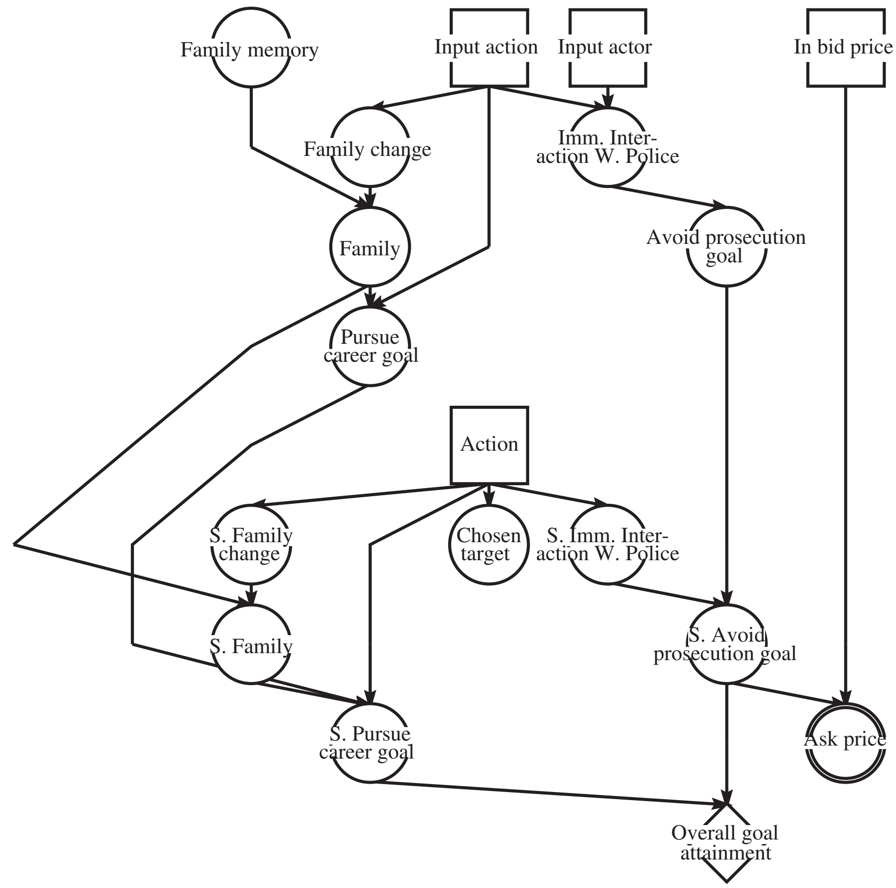


FIG. 2. Poachers group decision-making diagram. Abbreviations are S., scenario; Imm., Immediate; W., With.

of rhino abundance in the reserve they are targeting. This node allows a feedback mechanism from the ecosystem back into the political system to develop. When rhino spatial density becomes low enough, rhinos are difficult to find in the reserve, thus reducing the chance of a successful raid.

### *Interacting traders and consumers submodel*

The decision-making diagram of retail traders interacting with rhino horn consumers models the bid-ask spread that traders contend with (Fig. 3). This diagram also contains nodes for representing traders' pricing decisions and resupply requests that are both functions of rhino horn consumer decision making. In effect then, this decision-making diagram is an agent-based submodel of rhino horn consumers in Asia interacting with a number of competing rhino horn traders in Asia.

This submodel is derived from a model developed by Catullo (2013). In general, an agent-based economic model represents individual firms as agents and individual consumers as agents. One cycle consists of each trader making decisions about product resupply and product pricing that maximizes their expected profit. Also during this cycle, each consumer makes decisions about entering a market, and once entered, purchasing decisions that minimize their costs. Time is incremented, and another cycle is executed (Tesfatsion 2006, Geanakoplos et al. 2012, Ng and Kang 2013). See Haas and Ferreira (2016*a*) for details of this submodel.

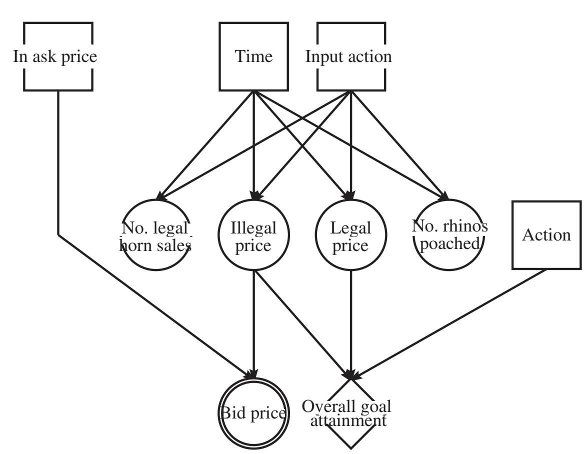


FIG. 3. Decision-making diagram of rhino horn traders interacting with rhino horn consumers.

Table 4. Two entries from the actions history data set used to find the consistent values of the political-ecological simulator's parameters.

| DAN | Source | Date | Location | Action | Actor | Target |
|---|---|---|---|---|---|---|
| 9 | news24 | 12 July 2010 | KNP | arrest some poaching suspects | anti-poach | poachers |
| 10 | news24 | 12 July 2010 | KNP | kill some rhinos | poachers | rhinoeco |

*Notes:* DAN is the document archive number. The target rhinoeco is the rhinoceros-supporting ecosystem.

Path directions in Fig. 3 quantify the idea that input actions concerning the legality of rhino horn trade and the numbers of rhino horns sold previously, influence how traders price their rhino horn product. Path directions also encapsulate the idea that price levels along with poaching and/or legal harvesting cause a trader's perceived level of utility.

### *Rhino population dynamics submodel*

The Rhino Abundance node of the rhino population influence diagram represents a stochastic submodel of rhino abundance in the form of an Individual Based Model (IBM; Grimm and Railsback 2005) of a wildlife population modified from a model developed by Kostova et al. (2004). This IBM tracks the South African rhino population as member individuals are impacted through time by their birth process, natural death process, food in-take, and poaching off-takes generated by the poachers group decision-making diagram (see *Poachers group submodel*).

The submodel responds to a poaching decision made by the poachers group by (1) reading from the bulletin board the number of rhinos that are to be poached, (2) randomly selecting this number of rhinos from the adult population, and then (3) setting the life-status variable for each of those selected to dead. See Haas and Ferreira (2016*a*) for a detailed description of this submodel.

### *Formal documentation of this political-ecological simulator*

Our model is formally documented using the Dahlem ABM documentation protocol (Wolf et al. 2013). We have placed this documentation on the rhino EMT's website (*available online*).[4] This website also includes a step-by-step guide for running the simulator. The Dahlem protocol is related to a documentation protocol used in ecological modeling referred to as ODD (overview, design concepts, and details; see Grimm et al. 2010) but is better suited to large, multi-agent economics models such as ours. Specifically, the Dahlem protocol allows large, complex models to be documented through a mix of description and actual code rather than a duplication of the model's code in a natural language form as employed in ODD. This style allows very complex models to be described in less than about 20 pages. Also, the Dahlem protocol, unlike the ODD protocol, allows the model to be described for general use rather than for the simulation of only one set of circumstances. This capability is more appropriate for our application as we are proposing a general-purpose tool that can be applied to any political-ecological system. Finally, the Dahlem protocol has specific requirements for describing the interactions between agents. This requirement is particularly important in our case as our model uses a unique bulletin board interface to both the group submodels and the ecosystem submodel.

[4] https://doi.org/10.5061/dryad.t8952, www4.uwm.edu/people/haas/rhino_emt

## Estimation of the Simulator's Parameters

### *Overview*

Prior to statistically fitting the IntIDs model to data, parameter values that are based solely on what is expected from theoretical considerations (hypothesis values) are assigned to each parameter. Then, these hypothesis values are used with consistency analysis (Haas 2011: chapters 4 and 11) to statistically fit a subset of the political-ecological simulator's parameters to an actions history data set. A portion of this data set is shown in Table 4. The complete data set is available from Dryad and at the rhino EMT's website (see footnote 4).

Let $\mathbf{U}$ be the vector that contains all of the chance nodes that make up the influence diagram (a decision-making diagram or an ecosystem model). Let the vector $\boldsymbol{\beta}$ contain all of the influence diagram's parameters. Let $g_S(\boldsymbol{\beta})$ be a goodness-of-fit statistic scaled to the unit interval that measures the agreement of the influence diagram's probability distribution (referred to here as the $\mathbf{U}|\boldsymbol{\beta}$ distribution) and a data set, S. Larger values of $g_S(\boldsymbol{\beta})$ indicate better agreement.

Each parameter in the influence diagram is assigned a value a priori that is derived from either expert opinion, subject matter theory, or the results of a previous consistency analysis. Let $\boldsymbol{\beta}_H$ be such a value assigned to a particular parameter of the influence diagram. Collect all of these hypothesis parameter values into the hypothesis parameter vector, $\boldsymbol{\beta}_H$. Let $g_H(\boldsymbol{\beta})$ be a measure of agreement between the distribution identified by the values of $\boldsymbol{\beta}_H$ (the $\mathbf{U}|\boldsymbol{\beta}_H$ distribution) and the $\mathbf{U}|\boldsymbol{\beta}$ distribution with larger values indicating better agreement. As with $g_S(\boldsymbol{\beta})$, also assume that $g_H(\boldsymbol{\beta})$ is scaled to the unit interval. Note that $g_S(\boldsymbol{\beta})$ is the agreement between a sample and a stochastic model, the $\mathbf{U}|\boldsymbol{\beta}$ distribution, while $g_H(\boldsymbol{\beta})$ is the agreement between two stochastic models: the $\mathbf{U}|\boldsymbol{\beta}_H$ distribution and the $\mathbf{U}|\boldsymbol{\beta}$ distribution.

The consistency analysis parameter estimator maximizes the function

$$g_{CA}(\boldsymbol{\beta}) \equiv (1 - c_H) g_S(\boldsymbol{\beta}) + c_H g_H(\boldsymbol{\beta}) \tag{3}$$

where $c_H \in (0, 1)$ is the ecosystem manager's priority of having the estimated distribution agree with the hypothesis distribution as opposed to agreeing with the empirical (data-derived) distribution. Haas (2001: Appendix) gives suggestions for assigning $c_H$. Let $\boldsymbol{\beta}_C \equiv \arg\max_{\boldsymbol{\beta}}\{g_{CA}(\boldsymbol{\beta})\}$ be the consistency analysis estimate of $\boldsymbol{\beta}$. We refer to $\boldsymbol{\beta}_C$ as the influence diagram's consistent parameter values.

Consistency analysis consists of the following four steps: (1) specify the values for $\beta_{\mathbf{H}}$, (2) initialize the values in $\beta$, (3) maximize the agreement function, $g_{CA}(\boldsymbol{\beta})$, (4) analyze the differences between hypothesis and consistent parameter values.

The method's name comes from this final step: analyze the model's parameters by scrutinizing areas of the subject matter theory that had suggested hypothesis parameter values that are very different from their consistent values. We summarize how we met the computational challenge of Step 3 in our Appendix S2. Appendix S3 contains the definitions of our hypothesis, actions history data, and ecosystem data agreement functions.

### *Actions history data collection protocol and data set*

Actions are automatically acquired from news articles that have been posted to the web by various online newspapers. This is accomplished with a software system that searches the web for these articles once a week. This system, part of the id software package (see footnote 4), uses a Visual Basic® script to (1) give Google News a search string such as "Kruger rhino poaching", (2) download the links returned by this search, (3) download the article text of each of these links.

Then the id package automatically parses each text to find who did what to whom, where it was done, and when it was done. This information is used to find the corresponding action in the Ecosystem Management Actions Taxonomy (EMAT; Haas 2011: chapter 9) and enter an instance of it into the actions history database. The parsing algorithm is similar to the memory-based shallow parser of Daelemans et al. (1999). The main difference is that the word part-of-speech lexicon has been embedded in the file of recognized $m$-word verbs, direct-object phrases, and prepositional phrases. See Aarts (2011) for definitions of these phrase types.

Executing this automated data collection procedure resulted in 2,688 online stories over the years 2011–2015. Of these, 205 were parsed (Fig. 4). This low yield stems from two causes. First, several reported actions are not in any submodel's repertoire. Second, particular actions tend to be retold by many different online news outlets for several days after the action but the parsing system does not enter multiple stories of the same event into its database.

Table 5 contains the numerical values of the KNP white rhino abundance estimates plotted in Fig. 4 along with associated confidence intervals.

### *Assessing the uncertainty in behavior predictions*

Ecosystem managers need a sense of poacher behavior variability under different combinations of incentives (e.g., high rhino horn price, low risk of arrest) and disincentives (e.g., low rhino horn price, high risk of arrest). Any model-based measure of variability will require probability values for each decision option. Decision-making diagrams, however, are deterministic functions of their inputs. Hence, the poachers group decision-making diagram does not produce a probability value for the poaching option. Such a probability may be defined for the poachers group interacting with the other groups and the ecosystem through time. In this approach, the probability of deciding to poach is defined to be the ratio of the number of decisions to poach when the IntIDs model is run over some time interval divided by the total number of decisions made by the poachers group over this same time interval. This definition can be extended to the probability of any particular action in any group's repertoire.

Under this definition of decision-making diagram action probabilities, the uncertainty in poacher behaviors can be expressed with an entropy-based measure of variability, $V_{\text{behavior}}$ due to Wilcox (1973). This measure reaches its maximum when all outcomes are equally likely. Here, these outcomes are do not poach, sell a few rhino horns, sell several rhino horns, and sell many rhino horns. Let poach be the union of the events sell a few rhino horns, sell several rhino horns, and sell many rhino horns. Let $K$ be the number of possible behaviors, e.g., for the behaviors of do not poach and poach, $K = 2$. The variability measure is

$$V_{\text{behavior}} \equiv -\frac{\sum_{j=1}^{K} p_j \ln p_j}{\ln K}. \tag{4}$$

This measure is the standardized entropy of the distribution of a group's out-combinations that occur across a run of the political-ecological simulator. Wilcox (1973) uses this function as an index of variation of a nominally valued discrete random variable. Standardization allows comparisons to be made across groups that have different numbers of possible out-combinations. This standardization is accomplished by the denominator term which is the maximum entropy of a $K$-valued discrete distribution. Values close to 0 indicate low variance and hence a low amount of uncertainty about the group's predicted behavior.

### *Parameter estimate results*

*Estimation problem setup.*—Using the above actions history data set, estimates are found for the parameters that

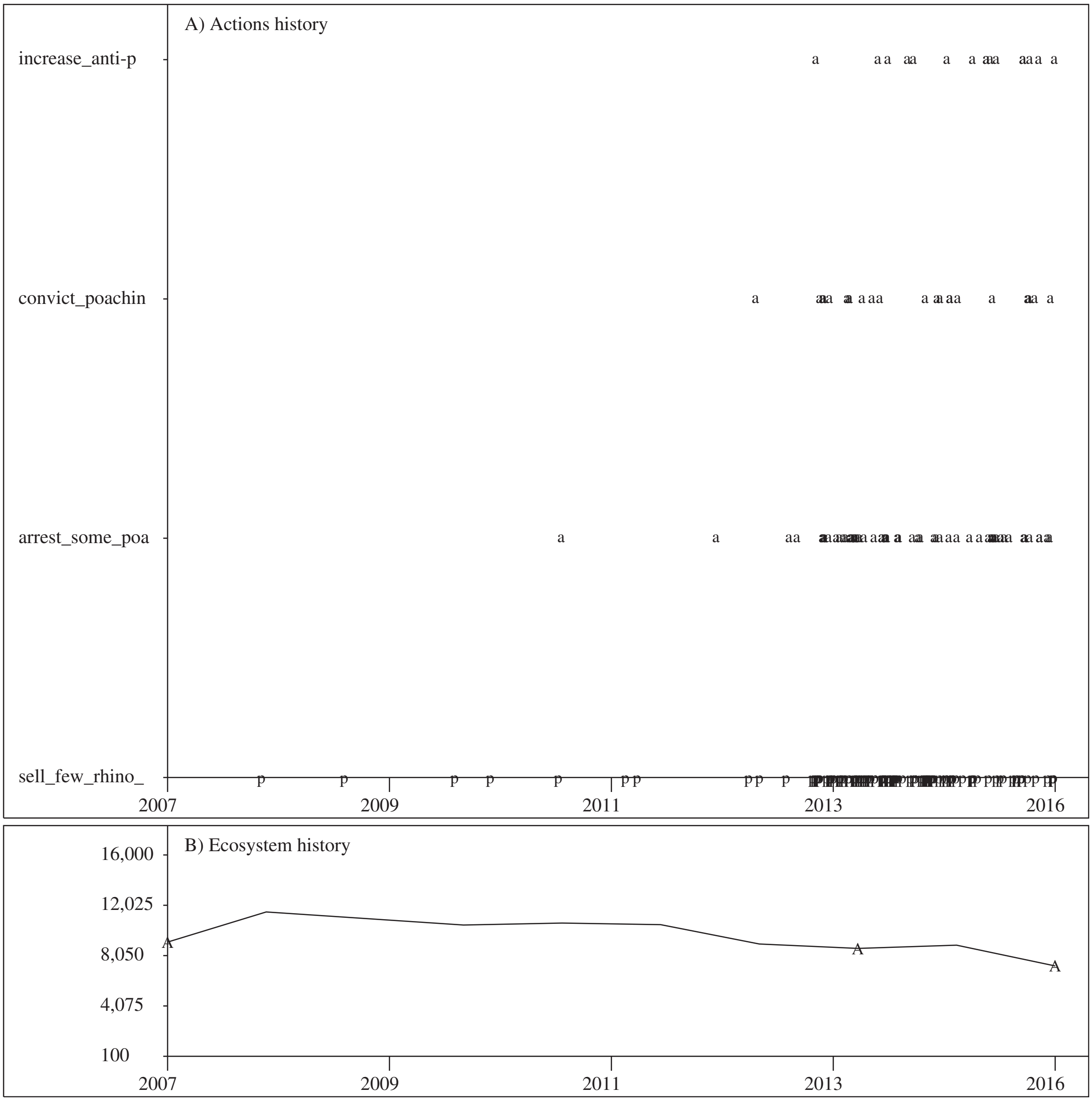


FIG. 4. (A) Observed actions history from 2007 through 2016. A plot symbol is the first letter of the group executing the output action: (p)oachers, (m)iddlemen, (a)nti-poaching forces. Actions are increase_anti-poaching; convict_poaching_suspects; arrest_some_poachers; and sell_few_rhino_horns. (B) Survey estimates of rhino abundance in Kruger National Park.

define the nodes of the poachers group submodel SIIWP and SPCG mentioned in *Poachers group submodel*. To reduce computational expense, the ecosystem submodel was not updated each time the objective function was evaluated during execution of the optimization algorithm. Doing so does not affect our results as no ecosystem submodel parameters are being estimated.

The computation of consistency analysis parameter estimates involves the search of a space defined by 145 parameters and required 6,425 function evaluations on the Triton Shared Computing Cluster (TSCC; SDSC 2015) running the MDAS algorithm (Appendix S2).

*Solution.*—The consistency analysis optimization step results in the value of $g_{CA}$ increasing from 0.168 to 0.640 (Table 6). This indicates a fitted model whose agreement with observations has been much-improved through the smallest possible deviation from a model derived from cognitive theory.

Fig. 5 contains the actions history generated by this fitted political-ecological simulator. This figure is a causality graph. Vigueras and Botia (2008) argue that such a graph is an effective visualization tool for understanding global and local chains of causality contained in the output of a multi-agent model.

Table 5. White rhinoceros abundance estimates with 95% confidence intervals for KNP over the years 2007–2016.

| Year | Estimated abundance | Confidence interval |
|---|---|---|
| 2007 | 9,119 | 7,665–12,438 |
| 2008 | 11,498 | 9,734–15,619 |
| 2009 | no survey | |
| 2010 | 10,466 | 9,320–11,360 |
| 2011 | 10,621 | 8,767–12,682 |
| 2012 | 10,495 | 8,500–12,900 |
| 2013 | 8,968 | 8,394–9,564 |
| 2014 | 8,619 | 8,001–9,290 |
| 2015 | 8,875 | 8,365–9,337 |
| 2016 | 7,235 | 6,649–7,830 |

*Note:* Taken from Haas and Ferreira (2016*b*) and Ferreira (2017) SANParks (*unpublished data*).

Under consistent parameter values, the poachers group always decides to poach and hence, their $V_{\text{behavior}}$ value is 0.0. In other words, there is no uncertainty surrounding the question of how poachers will behave: they will always choose to poach.

*Interpretation of consistent parameter values.*—Recall that a hypothesis parameter value is simply a rough guess of what the value should be given current understanding of how humans reach decisions and assumptions of how would-be poachers view the current rhino poaching situation. Hypothesized and consistent parameter values of the SIIWP and SPCG nodes appear in Table 7 and Fig. 6, respectively. Recall that the parameters of the SIIWP node represent a poacher's perception of his chance of being arrested if he engages in poaching. For instance, the mathematical definition of this node's third parameter is

$$\boldsymbol{\beta}_3 \equiv P(\textit{arrested} \mid \textit{sell a few rhino horns}). \quad (5)$$

The consistent parameter values are similar to the hypothesis values wherein there is no perceived risk to taking legal employment and the risk of arrest increases as the planned amount of poaching increases.

Table 6. Hypothesis evaluation parameters.

| Measure | Hypothesis value | Initial value | Consistent value |
|---|---|---|---|
| $g_S$ | 0.210 | 0.824 (28/34) | 0.824 |
| $g_H$ | 1.000 | −0.210 | −0.104 |
| $g_{CA}$ | 0.168 | 0.617 | 0.640 |

*Notes:* The quantity $g_H$ is the agreement between the hypothesis distribution and another distribution. The quantity $g_S$ is the agreement of simulator output with observations (number of matched actions/number of observed actions). For both of these measures, larger values indicate better agreement. The hypothesis value for $g_{CA}$ is $0.2 \times 1.0 + 0.8 \times 0.21 = 0.168$. Differences between initial and consistent values show how much the optimization procedure has improved the solution.

As indicated in Fig. 6, consistent parameter values have poachers perceiving less chance of attaining their career goals from poaching (decision options sell a few rhino horns, sell several rhino horns, and sell many rhino horns) than hypothesized (most blue bars under these options are positively valued). The figure also shows that under the consistent distribution, poachers perceive little hope of gaining legal employment except for the case of currently unattained career goals coupled to the perception that family members are dissatisfied. This latter characteristic of the fitted model is a result of it being fitted to match the many instances in the actions history data set of poachers selling a few rhino horns and no instances of them taking legal employment.

### *The threshold between poaching and not poaching*

We define a threshold to be a combination of values on one or more parameters of a decision-making diagram at which the group switches from one decision option to another. We use our fitted cognitive model of the poachers' decision-making process to find the threshold between choosing to poach vs. choosing to not poach. First, we define a proxy for the poachers' perception of the risks from poaching

$$\rho = \bar{P}(\textit{arrested} \mid \textit{decide to poach}) \quad (6)$$

where the conditioning event, decide to poach takes on the values in turn, of sell a few rhino horns, sell several rhino horns, and sell many rhino horns. The value of ρ then, is the average of the three perceived chances of being arrested for poaching. The hypothesized values of these three parameters represent the theory that poachers perceive a 40–70% chance that they will be arrested should they attempt to poach rhinos. This range is based on interviews with poachers, interviews with rangers who have had many contacts with poachers, observed behaviors of poachers, and observed behaviors of antipoaching units. Appendix S4 contains these interview excerpts, behavior observations, the sources of these evidence items, and how such evidence is used to arrive at our hypothesis values.

Next, we define a proxy for the perceived chance of attaining career goals by poaching. Recall that the nodes Pursue Career Goal (PCG), and SPCG in the poachers group decision making diagram each take on the values unattained, middling, and attained. Let goal value be any one of these values. Then

$$\begin{aligned} \phi = \bar{P}(\texttt{SPCG} = \textit{attained} \mid \\ \texttt{PCG} = \textit{goal value},\ \textit{decide to poach}) \end{aligned} \quad (7)$$

where the average is taken over all combinations of goal value and decide to poach.

The poachers decision-making diagram is run at each point in a 50 × 50 grid of ϕ and ρ combinations. For each run, the poachers' decision is recorded. Using this

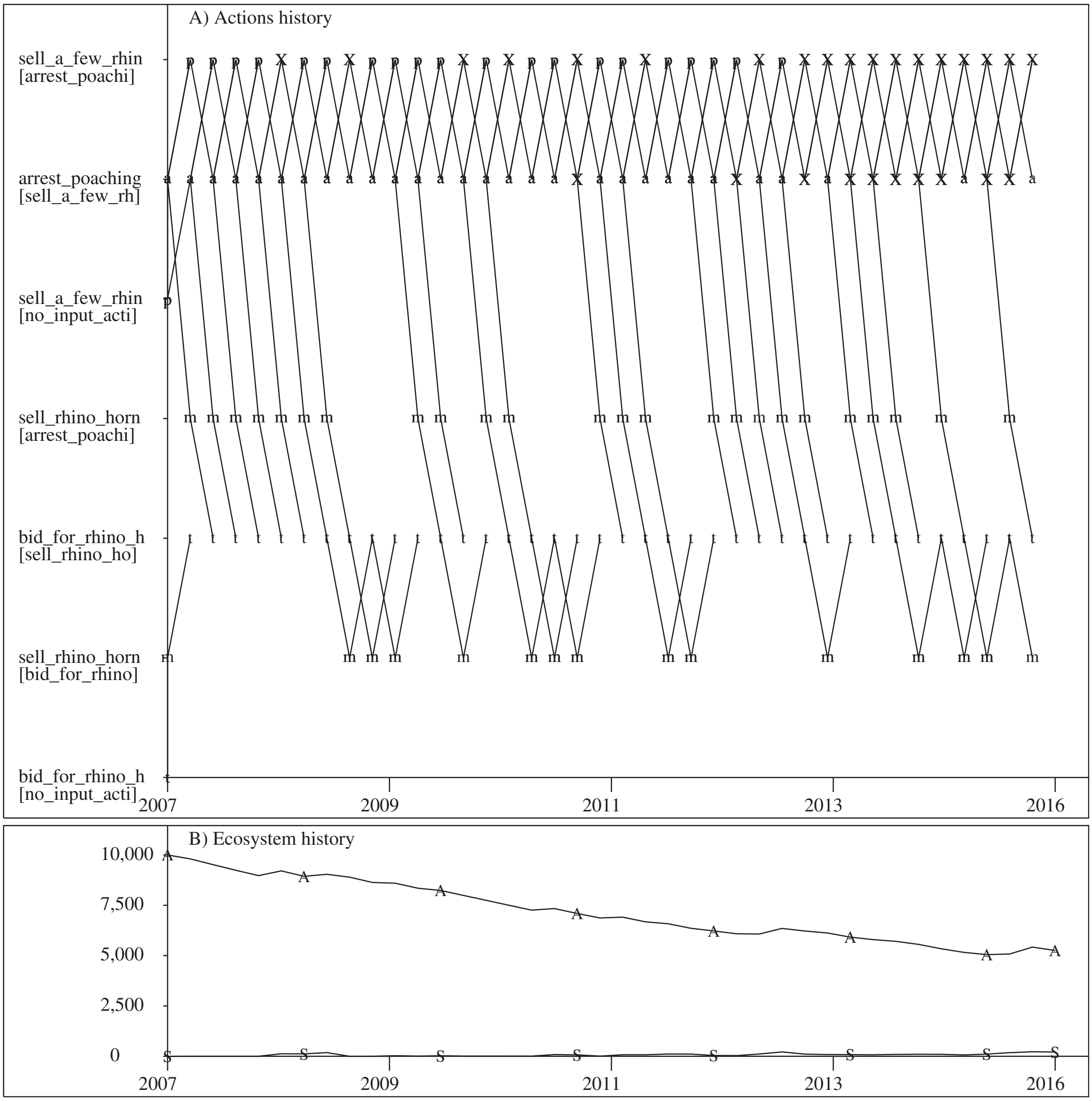


FIG. 5. (A) The political-ecological simulator's actions history output under consistent (statistically estimated) parameter values run over the time span 2007 through 2016. Input actions are placed inside square brackets under the output action. Lines connect action–reaction sequences. An "X" indicates that an action generated by the political-ecological simulator matches an observed action. (B) Simulator-computed rhino abundance in Kruger National Park ("A" symbol) along with the simulation's standard deviation ("S" symbol).

TABLE 7. Hypothesis and consistent values of the Scenario: Imminent Interaction with Police (SIIWP) node's parameter that represents the probability of being arrested for poaching.

| Conditioning value of parent node action | Value | | |
|---|---|---|---|
| | Hypothesis | Initial | Consistent |
| Do nothing | 0.01 | 0.01 | 0.01 |
| Take legal employment | 0.01 | 0.07 | 0.01 |
| Sell a few rhino horns | 0.40 | 0.10 | 0.09 |
| Sell several rhino horns | 0.50 | 0.20 | 0.22 |
| Sell many rhino horns | 0.70 | 0.30 | 0.29 |

gridded output, the threshold between deciding to poach and deciding to not poach may be plotted in the two-dimensional space of $\phi \times \rho$ (Fig. 7). The vertical axis of this plot is a proxy for the poachers' perceived potential for career advancement while the horizontal axis is a proxy for poachers' perception of risk. As the perceived risks of poaching increase, poaching is the action of choice only if the perceived chance for payoffs is high. From an ecosystem management perspective, the amount of change in these two meta-parameters needed to cause would-be poachers to decide that poaching is not worth the risk can be read off of this figure.

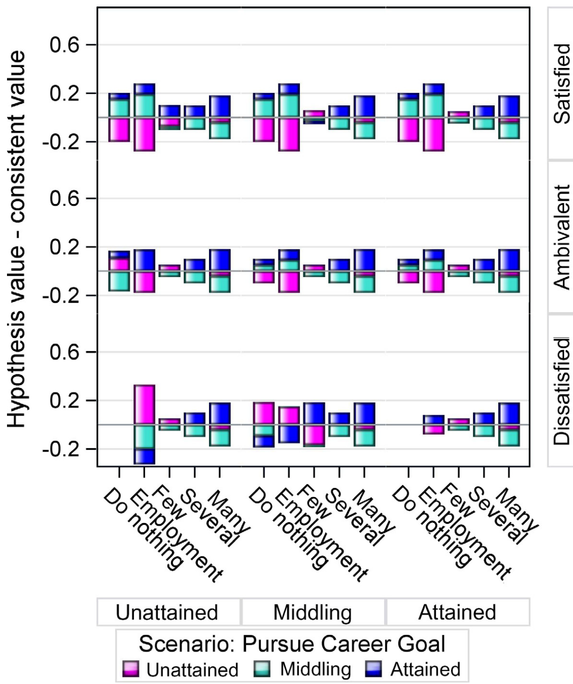


Fig. 6. Hypothesis value minus consistent value of each parameter of the Scenario Pursue Career Goal node under all combinations of conditioning node values. Horizontal axis: Situation Pursue Career Goal values; vertical axis: Scenario Family Satisfaction values. For example, the hypothesis value for believing that career goals will be unattained (magenta bars) by taking legal employment (the proposed decision) is about 0.33 higher than the corresponding consistent value when this goal is viewed as being unattained at present and the family is dissatisfied after this action is taken. See *Interpretation of consistent parameter values* for other relationships that can be drawn from this plot.

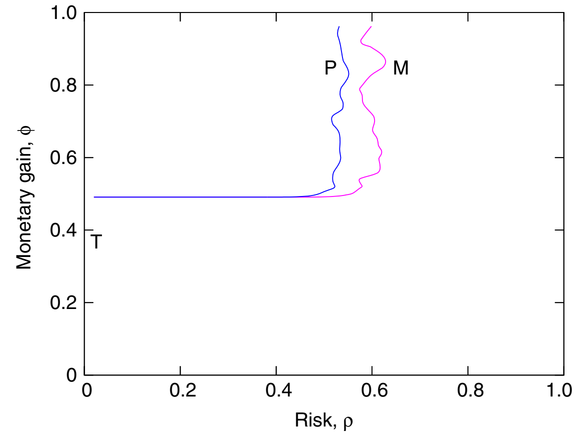


Fig. 7. Thresholds between the decision to poach and the decision to not poach. Thresholds are plotted as curves in the two-dimensional risk (ρ) by career advancement (ϕ) space. Magenta curve, no legal employment option available; blue curve, legal employment option is available. Poachers decide to poach for parameter value combinations that are to the left and above a curve and to refrain from poaching for combinations to the right and below a curve. Consistent values are used for all other parameters and arrest poaching suspects is the input action. Point P is the poachers' risk-advancement point under these consistent values. Point M is the closest point to point P but in the do not poach region. Point T is the risk-advancement point under the scenario that a viable take legal employment option is available.

Introduction of a viable legal employment alternative that carries low risk of arrest causes the poachers group to find poaching attractive only under lower levels of risk as now, a lower-risk alternative that has some potential for making money is available to them. As this derivation illustrates, a threshold (a curve in Fig. 7) may have to be defined by a collection of parameters because the simultaneous change in several parameters may be required for a decision-making diagram's optimal decision computation to switch from one option to another.

The price a poacher can sell a rhino horn for (the middleman's bid price) is a poor proxy for the poacher's perceived likelihood of career advancement because the poacher's internal assessment of such a price is dependent on other factors. Human decision making to a first approximation follows the rule of selecting the decision option that maximizes perceived expected utility rather than the option with high utility under a single future state, e.g., the state of not being arrested for poaching. For example, a legal employment option that offers only moderate remuneration compared to a rhino horn's bid price may actually have a higher expected utility to the poacher if the perceived chance of being arrested for poaching is high enough. This rationale leads us to abandon the idea of a threshold bid price.

An examination of Fig. 7 suggests that an anti-poaching policy could be developed that, by addressing both incentives and disincentives to poaching, poacher perceptions of risks vs. benefits could be brought into a region where they decide to not poach. One such policy would be to provide legal economic alternatives to the poachers group. Having such options would result in poachers having a lower tolerance for the risks involved in participating in a rhino poaching raid. This lower tolerance is graphically shown in Fig. 7 with the threshold under the presence of a legal employment option being to the left (lower risks) of the threshold when such an option is not available. Specifically, if would-be poachers perceive at least a 40% chance of achieving career goals through taking legal employment, they will choose that option over poaching.

## Developing Management Policies

### *Definitions*

The command-and-control method of developing management policies (Knight and Meffe 1997) consists of identifying a set of actions that ecosystem managers can implement by decree. A more general method of developing management policies is the most practical ecosystem management plan (MPEMP) of Haas (2011: chapter 4). The MPEMP emerges from the pattern of group behaviors that results from modifying one or more group belief systems. These modifications are such that the agreement between group belief systems that are estimated from data and the belief systems that produce group actions that cause a desired ecosystem state is maximized. In other words, the MPEMP is the sequence of group behaviors that occur from the least change in existing group beliefs systems that still achieves ecosystem state goals.

Changing a belief system here means either making changes to the values of parameters that define the decision-making diagram's CPTs and/or by modifying the diagram's node values and/or connectivity. A desired ecosystem state might be defined as a desired expected value of a monitored ecological variable at a specified point in time. The MPEMP incorporates a sequence of actions by ecosystem managers by finding parameter values that cause their decision-making diagrams to choose the needed sequence of actions.

The advantage of a MPEMP is that it is a new unfolding of future reality wherein modified behaviors of one or more groups result in ecosystem responses desired by the ecosystem manager, even when some of these groups are outside the ecosystem manager's control. By representing ecosystem management in perceptual space rather than actions space, the resultant MPEMP can be a synthesis of a grassroots, decentralized plan and a plan composed of a sequence of command-and-control actions. One way to achieve a MPEMP is to change a group's belief system by shifting the group's threshold-defining parameters from their estimated values to the closest set of values that lie on a threshold. See Appendix S5 for the algorithm used to compute the MPEMP.

### *General procedure for finding a management policy*

Policy identification is accomplished with the following procedure: (1) Use consistency analysis to fit the political-ecological simulator's parameters to a political-ecological data set. (2) For those groups that are under managerial control, e.g., anti-poaching units, specify a set of actions and associated time points that are both intended to result in desired ecosystem responses and are within budgetary constraints. (3) Implement this command-and-control management policy in the political-ecological simulator by forcing these controllable actions to occur at their specified time points during a political-ecological simulator run. Record the resulting mean values of the ecosystem's state variables at the specified future time point. (4) If the desired ecosystem state variable means are achieved by the actions of Step 2, stop: the optimal management policy is to implement in the real world the actions of Step 1 that are under managerial control. (5) Otherwise, compute the MPEMP to find a set of parameter values that results in groups outside managerial control changing their behaviors enough for the desired ecosystem state variable means to be achieved.

The idea behind this procedure is to first entertain a command-and-control policy. If this policy is either politically impractical or fails to produce the desired mean values of ecosystem state variables in a run of the simulator, then compute a MPEMP and make efforts to effect the perceptual changes of targeted groups as specified by the MPEMP.

### *Application of the general procedure to rhino conservation*

*A command-and-control policy.*—The South African government has set a target of 20,400 southern white rhinos (DEA 2015), 2,800 south-central black rhinos, and 260 southwestern black rhinos (*Diceros bicornis occidentalis*; Knight et al. 2013) across South Africa in the year 2020. This target (or desired ecosystem state in MPEMP parlance) is a consequence of the government's desired growth in rhino numbers that assumes poaching will continue at approximately current levels. By the end of 2014, SANParks contributed 22% and 65% of the individuals to the south-central and southwestern black rhinos, respectively, as well as 49% of the southern white rhinos (Ferreira et al. 2017) to rhinos in South Africa. Most of the south-central black rhinos and southern white rhinos live in KNP. The above representation predicts that KNP should have 538–676 south-central black rhinos and 9,854–10,232 white rhinos by 2020 given the contributions made during 2014. For ease of analyses we assume that it is desired by SANParks management to have 11,000 rhinos irrespective of species in KNP in the year 2020. By the end of 2015, 313–453 south-central black rhinos and 8,365–9,337 southern white rhinos lived in KNP (Ferreira et al. 2017).

Because rangers only make contact with about 4% of the poaching parties that enter KNP (see *Introduction*) the only real effect of these anti-poaching patrols and pursuits (other than the immediate effect on the terminated poachers) is to send a signal to other would-be poachers that their risks have increased. This observation suggests a command-and-control policy that is composed of the following two policies. First, anti-poaching patrols and pursuits are authorized to shoot on sight anyone they suspect of participating in a poaching raid. See Messer (2010) for a rationale that justifies this policy. Second, graphic images of gunned-down poachers are shown on a regular basis to the residents of communities that border KNP.

Our political-ecological simulator models the effects and implementation of these two policies by first setting parameter values on the Avoid Prosecution Goal (APG) node to represent a strong belief that the goal of avoiding prosecution will not be attained if the input action is shoot some poachers and second by making the option shoot some poachers the most preferred action of the anti-poaching group.

Using this command-and-control policy, execution of the above procedure's Step 2 produces the actions history plot shown in Fig. 8. Again, $V_{\text{behavior}} = 0.0$ for the poachers group. From 2016 to 2020, mean rhino abundance drops to a value that is significantly less than the target value.

The above command-and-control management policy may be politically infeasible and is not predicted to produce the 2020 rhino abundance targets. Therefore, Step 5 of the policy-finding procedure needs to be executed. Here, this means finding politically feasible ways to change would-be poacher decision making. As discussed above, there are two perceptions held by would-be poachers that, if changed, would cause them to avoid poaching: the likelihood of career advancement from poaching, and the riskiness of poaching.

*MPEMP.*—An MPEMP is computed under the assumption that opportunities for legal employment have been made available to would-be poachers living around KNP. This assumption is modeled with parameter values for which would-be poachers see at least a 40% chance of achieving career goals by taking legal employment. The MPEMP calculation is initialized with these values.

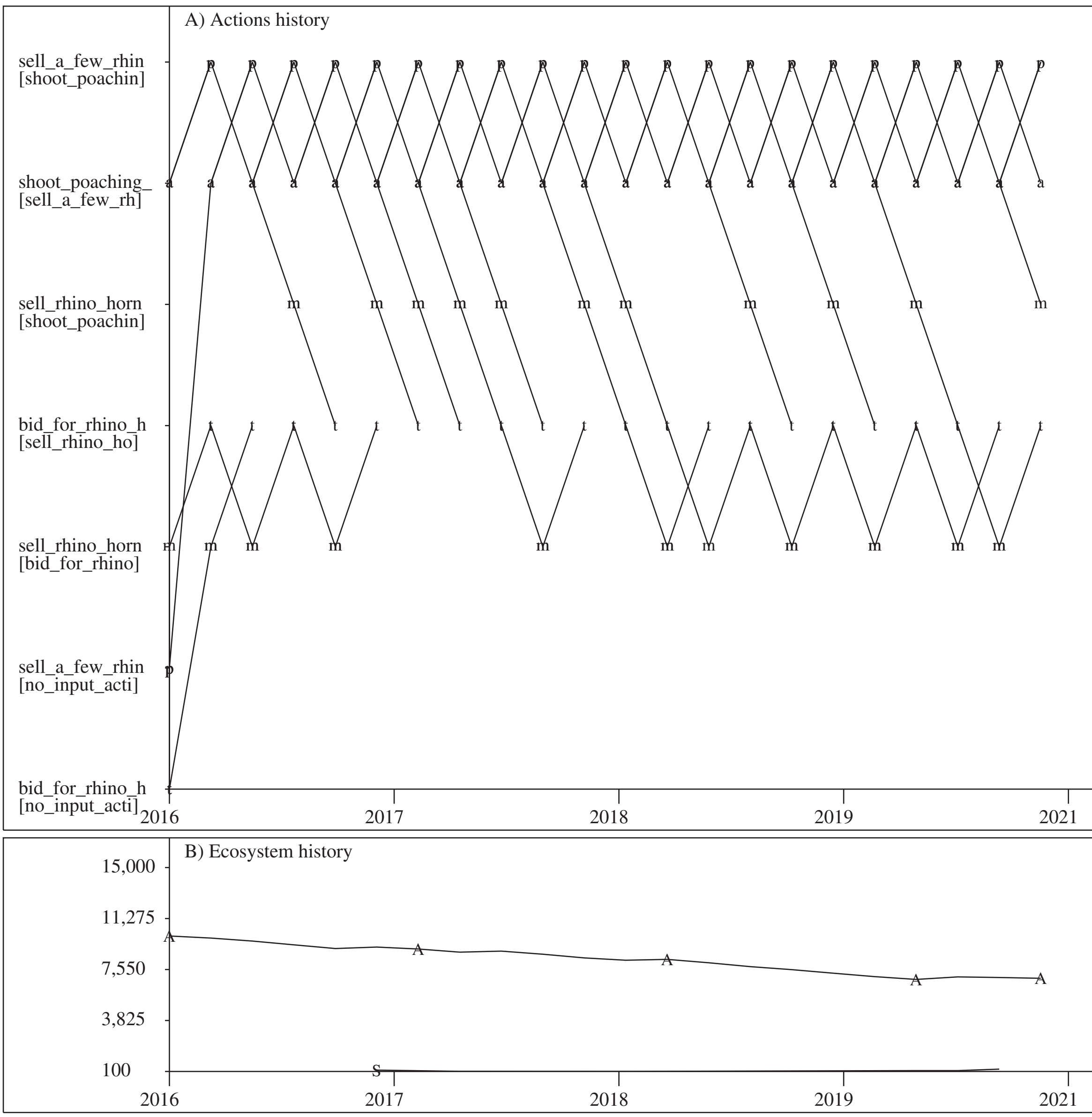


Fig. 8. (A) The political-ecological simulator's actions history output under the command and control policy. See Fig. 5 for an explanation of the plot's symbols. (B) Simulator-computed rhino abundance in Kruger National Park ("A" symbol) along with the simulation's standard deviation ("S" symbol).

Parameters defining the poachers group nodes, SIIWP and SPCG (145 parameters) are adjusted by the MPEMP algorithm until the rhino abundance submodel produces target values in the year 2020. This computation required 33,877 objective function evaluations on the TSCC and produced a final value of $g_{\mathrm{H}}^{(\mathrm{Grp})}$ of −0.3903. Rather than the desired abundance of 11,000 animals in the year 2020, there would be an average of 10,768 animals if the MPEMP were to be enacted, meaning that essentially, the target value would be reached under this policy.

A run of the political-ecological simulator under these MPEMP parameter values shows poachers rarely deciding to poach (Fig. 9). Under MPEMP parameter values, $V_{\mathrm{behavior}} = 0.0$ for the poachers group. Hence, there is no uncertainty surrounding the question of how poachers will behave: they will always choose to not poach should the MPEMP be implemented.

Table 8 and Fig. 10 give the consistent and MPEMP values for the nodes SIIWP and SPCG nodes, respectively. The MPEMP values constitute the perceptual shifts needed to achieve the desired future state of the

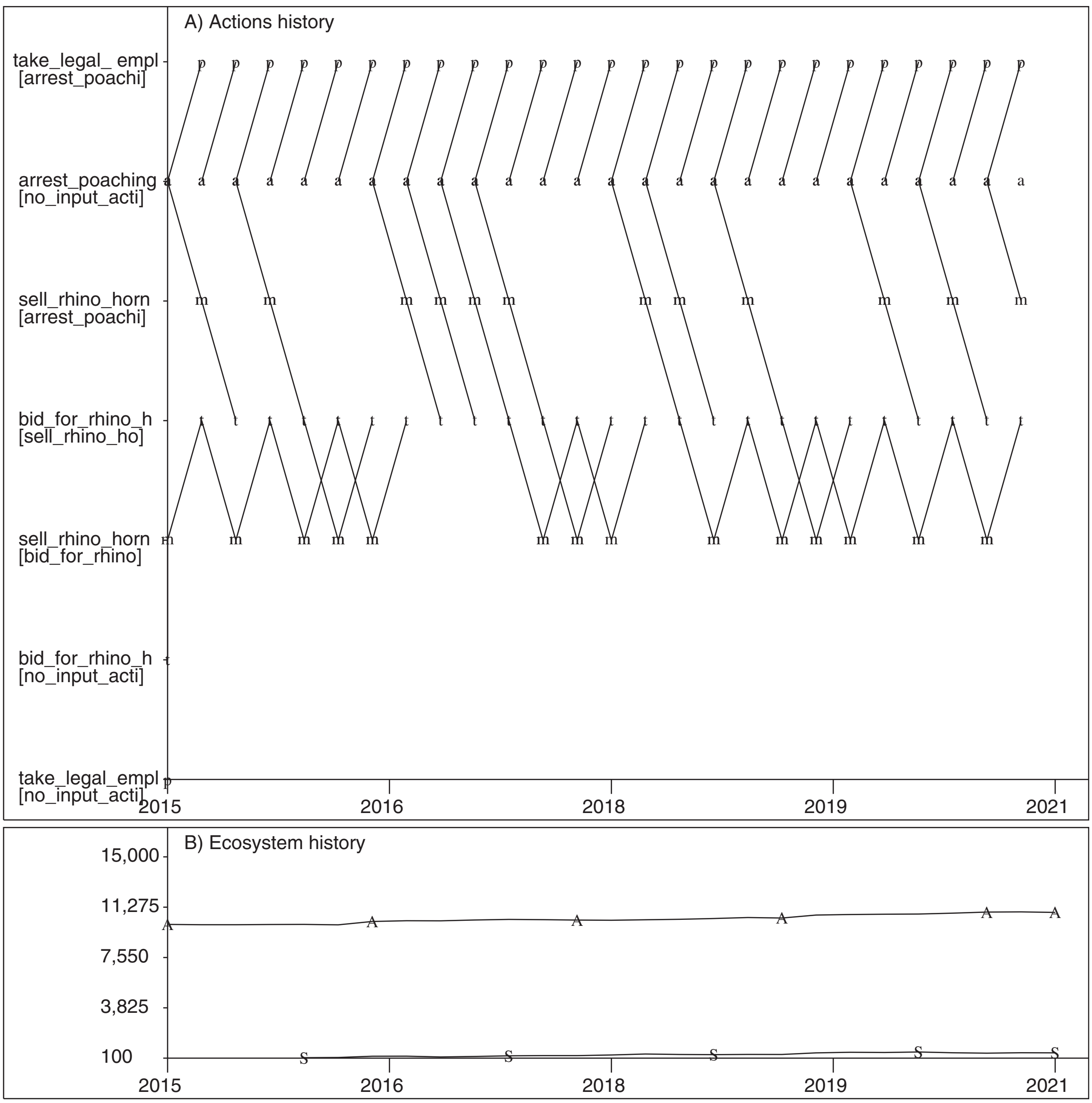


Fig. 9. (A) The political-ecological simulator's actions history output under the most practical ecosystem management plan (MPEMP). This policy assumes that opportunities for legal employment exist for would-be poachers living next to Kruger National Park (KNP), South Africa. (B) Simulator-computed rhino abundance in Kruger National Park ("A" symbol) along with the simulation's standard deviation ("S" symbol).

TABLE 8. Consistent and most practical ecosystem management plan (MPEMP) values of the SIIWP node's parameter that represents the perceived probability of being arrested for poaching.

| Conditioning value of parent node action | Consistent value | MPEMP value |
|---|---|---|
| Do nothing | 0.01 | 0.01 |
| Take legal employment | 0.01 | 0.01 |
| Sell a few rhino horns | 0.35 | 0.15 |
| Sell several rhino horns | 0.50 | 0.27 |
| Sell many rhino horns | 0.76 | 0.36 |

ecosystem. Under the MPEMP, SIIWP parameter values have poachers seeing poaching as increasingly risky.

As Fig. 10 indicates, consistent values have poachers seeing a potential career in poaching (decision options sell a few rhino horns, sell several rhino horns, and sell many rhino horns) whereas, under the MPEMP, poachers do not view poaching as a potential career (all blue bars are positive, and all magenta bars are negative under poaching options).

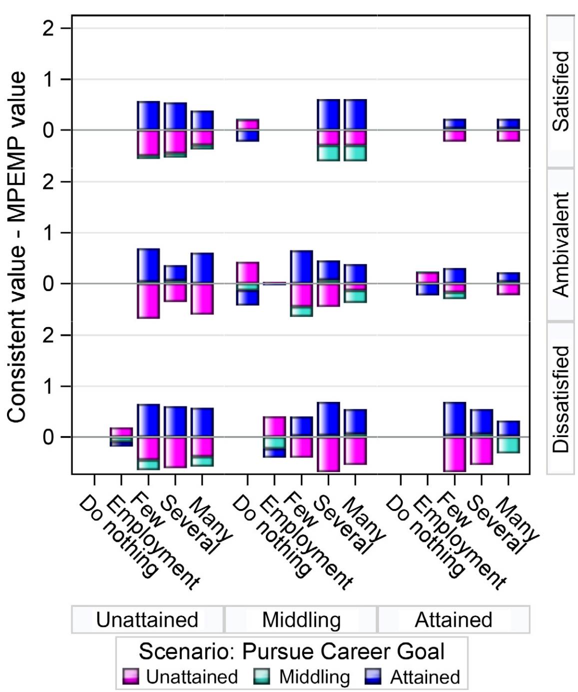


FIG. 10. Consistent value minus MPEMP value of each parameter of the Scenario Pursue Career Goal node under all combinations of conditioning node values. Horizontal axis: Situation Pursue Career Goal values; vertical axis: Scenario Family Satisfaction values. For example, the consistent value for believing that career goals will be attained (blue bars) by selling a few rhino horns is about 0.7 higher than the corresponding MPEMP value when this goal is viewed as being only middlingly attained at present and the family is perceived to be ambivalent after this action is taken. See *MPEMP* for other relationships that can be drawn from this plot.

A would-be poacher's perceptions of a raid's potential for making money is driven by verbal agreements made between them and their middlemen. Hence, specific actions that may cause these needed perceptual shifts are (1) shutting down the middlemen who buy rhino horns from poachers through the disruption of the rhino horn trafficking network (Haas and Ferreira 2016*b*) and (2) running far more frequent and more aggressive anti-poaching patrols in rhino-hosting reserves in order to convince poachers that poaching is becoming riskier.

## DISCUSSION

In response to the rhino poaching crisis, a rhino emergency summit comprising rhino range States representatives, the private sector, government officials, and non-governmental organizations proposed an integrated framework directed at reducing the demand and supply ratio associated with the use of rhino horn (Ferreira and Okita-Ouma 2012). The framework aimed to guide short- as well as medium- to long-term responses by range States directed at reducing the incentives for poaching (Ferreira et al. 2012) to ensure the persistence of rhinos. Expert-based risk-benefit analyses of various scenarios favored some form of supplying rhino horn to the market (Ferreira et al. 2012) followed by numerous proponents of implementing legal trade (Child 2012, Biggs et al. 2013, Di Minin et al. 2015).

Authorities, particularly in South Africa, implement an integrated response comprising compulsory anti-poaching in combination with innovative biological management interventions (Ferreira et al. 2017). South African authorities, however, combine these with a need for long-term sustainability at a local scale (e.g., financial costs of protecting rhinos) as well as potential future rhino horn trade mechanisms if governance conditions are satisfactory (Ferreira 2016). Protecting rhinos more intensely through anti-poaching, reducing demand for rhino horn or supplying horn to the market, however, only resulted in rhino population sustainability when done in concert with disrupting organized crime and providing economic alternatives for people living next to parks (Haas and Ferreira 2016*b*). A key additional game-changing element thus should focus on disrupting organized crime (Haas and Ferreira 2015) and addressing social injustices (Masse 2016).

We focused on addressing social injustices and in particular the assumption that the provision of economic alternatives in the form of career opportunities will impact the complex socio-ecological system in a way that causes rhinos to persist. Our models highlight that increased anti-poaching and protection does not result in the desired ecosystem outcome by 2020 (i.e., at least 11,000 rhinos in KNP). The increased protection scenario requires two politically non-feasible interventions. This includes establishing a shoot-to-kill policy accompanied by the regular exhibition through photographs of such victims.

Intensified and militarized anti-poaching (Lunstrum 2014, Duffy et al. 2015) may approximate and accentuate the perceptions of local people that authorities are again implementing historic shoot-to-kill policies in an attempt to curb poaching (Clifton 2014). Such policies may carry limited effectiveness when people have few other economic options for meeting their basic needs (Messer 2010). In addition, campaigns to discourage poaching behavior through, for instance, the showing of photographs of dead poachers may have considerable unintended consequences (Brehm 1966, 1989). For instance, several public demonstrations resulted following the inadvertent killing of village fisherman in KNP (SABC 2016). Increased protection that progressively uses more militarized techniques may result in overall alienation of people living next to parks who have few economic options (Lunstrum 2014, Duffy et al. 2015). Our modeling results confirm that such politically nonfeasible increases in anti-poaching are unlikely to change poaching incentives and disincentives in such a way that KNP rhino abundance targets will be met by 2020.

In contrast to the command and control plan, the MPEMP is both politically feasible (practical) and is predicted to result in rhino abundance targets being reached. In this case, it requires authorities to create opportunities of a career for young men, primarily because low income men often have provider role relationships (i.e., provision of resources to a partner for sex) and seldom have sex with a woman in prostitution. No-income men have limited opportunity to have a provider role relationship and often engage in sex with a woman in prostitution (Jewkes et al. 2012). Such no-income men operate extensively outside the law largely because women tend to favor men with money (Bhana and Pattman 2011). In the absence of career options, young men are likely to engage in any activity to meet the requirement of obtaining money. It predicts that men should dominate poaching activities. Indeed, few women are involved in poaching activities directly (Maggs 2017). It was thus not a surprise that the MPEMP focused on initiatives that changes young men's perception to 40% chance of having a career. This resulted in our model achieving the ecosystem target of more than 11,000 rhinos in KNP by 2020.

Our results highlight a key politically feasible and relatively low intensity intervention, but create a political conundrum for two reasons. First, authorities have already invested a substantial amount in protecting wildlife assets. For example, since 2008, the beginning of the rhino poaching crisis, a total of about R1.2 billion (about US$120 million) has been spent per year on anti-poaching patrols and poaching suspect litigation in an effort to protect rhinos living in South Africa's national reserves, state reserves, and private ranches (Naylor 2016). Second, many range states, and South Africa in particular, have embraced gender equality as a key principle in employment initiatives (Booysen and Nkomo 2014). Because of past practices, present policies provide guidelines to correct gender balance. The upshot is that obtaining employment as a young man is harder than for a young woman. Overcoming these political conundrums is the primary challenge if authorities seek to implement politically feasible policies of employment for young men that address standing social injustices, a key driver of poaching (Conrad 2012).

Even so, our analyses provide the first evaluation of the likelihood that providing alternative economic options for people is a key game-changing intervention. The disruption of organized crime is the second game changer highlighted by Haas and Ferreira (2016*b*) as a key element to achieve rhino population persistence. Disrupting organized crime has received key attention through the establishment and implementation of wildlife trafficking policies in several range states (SADC 2015). Disrupting organized crime and providing alternative economic opportunities, however, may be more effective at curbing poaching if protected areas and the areas abutting them are safe and secure from all kinds of crime. Such "broken-window" policies (Kelling and Bratton 2015) may thus be a key complement to the disruption of organized crime and provision of alternative economic options.

Our EMT could be improved in the following ways: (1) incorporating a learning mechanism into the group submodels so that a group can gradually change its perceptions in response to experiences with other groups and the ecosystem; (2) development of an automatic method for adding decision options to the various groups driven by observed new types of actions; and (3) incorporation of an explicitly geographical and spatial dimension into both the group decision-making diagrams and the ecosystem submodel.

Our work has focused on the supply side of rhino horn trafficking. Of course, reducing demand for rhino horn in the first place would essentially collapse the trade entirely. Advertising campaigns in countries that consume rhino horn attempt to do just that. Demand reduction campaigns to reduce the demand for wildlife products such as rhino horn need to be tuned to address the beliefs consumers hold towards these products (Hinsley et al. 2015, Liu et al. 2015). Developing ways to regularly gauge what these beliefs or themes are over many years is crucial to the success of such campaigns as it can take many years to change attitudes. For example, attitudes towards cigarette smoking changed slowly but significantly over the years 1947–1974 in the United States due to anti-smoking campaigns (Warner 1977). Because the consumption of many wildlife products is not physically addictive, it may be easier to reduce demand for them relative to products such as cigarettes or drugs that are.

Because behavior modification through suggestion is inherently a consumer behavior problem, the best professional advertising agencies who have expertise in target countries should be retained to develop and run such campaigns. These campaigns can cost about US$100,000 per year to run in just one country (Offord-Woolley

2017). Such financial support from conservation NGOs and cooperating governments will be needed over decades to have an impact on rhino population dynamics. Even with such campaigns, it is unlikely that demand will completely disappear. For example, cigarette consumption continues to be significant in the face of 70 years or so of cigarette smoking demand reduction campaigns.

Because demand reduction campaigns have not been operating very long, peer-reviewed, data-based evaluations of their effectiveness are difficult to find. The gray literature does offer several optimistic assessments. For example, a project funded by TRAFFIC claims a 25% reduction in demand for rhino horn in Vietnam but is silent on whether this is stated preference or an actual decline in black market sales (Offord-Woolley 2017). Another campaign jointly run by the International Humane Society and the Vietnamese government claims a reduction in survey respondents who admit to purchasing rhino horn from 4.2% in 2013 to 2.3% in 2016 (Humane Society International 2017). Data on black market purchases of rhino horn in both China and Vietnam would be very useful in assessing the effectiveness of rhino horn demand reduction advertising campaigns.

## Conclusions

We have demonstrated how an interpretable model of the socio-ecological dynamical system surrounding human–wildlife conflict can be constructed with agents (groups) modeled by decision-making diagrams and herbivore-hosting ecosystems modeled as a collection of interacting individuals (animals). We call such a model a political-ecological simulator. This model, although complex, can have subsets of its parameters statistically fitted to a political-ecological actions history data set via our estimation technique of consistency analysis. This fitted political-ecological model may then be used to find politically feasible management plans that stand the best chance of not only being implemented but also of achieving conservation goals. To this end, we give a computational scheme for finding these MPEMPs. We have also developed a web-based system for automatic acquisition of group actions data that makes possible the real-time updating of a political-ecological simulator's parameter values. We exhibit the use of our IntIDs model, parameter estimation method, and MPEMP algorithm on the management challenge of conserving the South African rhino population in the face of severe poaching pressure. Our model generates decisions (actions) that match 82.4% of those in a data set from the real world. It does so by deviating only a small amount from parameter values set by the cognitive theory of decision making. Our computed MPEMP couples small reductions in the attractiveness of poaching with small increases in anti-poaching efforts. We provide new graphical displays of the managed political-ecological process, a statistical measure of the amount of uncertainty surrounding a group's behavior, and graphical representations of the different group behavior models and their underlying mechanisms. Graphical display of such models makes them interpretable by a wide spectrum of stakeholders. In particular, we are able to quantify and display the perceptual threshold between a poacher's decision to poach or not.

Our data-validated modeling results lead us to two conclusions: (1) anti-poaching can increase disincentives against incentives, but it may require big investment that is not socially acceptable, and (2) providing employment can shift the trade off at a given level of incentives for a relatively low and politically feasible input.

Although not a focus of our work, advertising campaigns aimed at reducing the demand for rhino horn can play a role in curbing rhino poaching as long as they are contiguously run by professional advertising agencies over many years, and effectively adapt to the motives that drive consumers to purchase trafficked rhino horn.

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## Supporting Information

Additional supporting information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/eap.1662/full

## Data availability

Data available from the Dryad Digital Repository: https://doi.org/10.5061/dryad.t8952