

# An evolutionary game theory model for devaluing rhinos

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## Abstract

Rhino populations are at a critical level due to the demand for rhino horn and the subsequent poaching. Wild life managers attempt to secure rhinos with approaches such as devaluing the horn. The most common strategy of devaluing horns is dehorning. Game theory has been used before to examine the interaction of poachers and wild life managers. A manager can either 'dehorn' their rhinos or leave the horn attached. Poachers may chose to to behave 'selectively' or 'indiscriminately'. The approach described in this paper builds on this previous work and investigates the interactions between the poachers. Using evolutionary game theory, we determine which strategy is preferred by a poacher in various different populations of poachers. The purpose of this work is to discover whether conditions which encourage the poachers to behave selectively exist, that is, they only kill those rhinos with full horns. Notwithstanding, the analytical results prove that poachers will never adopt a selective strategy as long as there is gain from a partial horn. Additionally, poachers behaving indiscriminately is stable and robust. However, the model is adapted further to include a disincentive factor, which may represent factors such as harsher punishment, or lower demand for horn. With a disincentive, poachers can be encouraged to behave selectively, but only when there are few devalued rhinos. This paper aims to contribute to the necessary research needed for informed discussion about the lively debate on legalising rhino horn trade.

## Introduction

The demand for rhino horn continues to pose a serious threat to rhinoceros populations world-  
21 wide Amin et al. (2006). The illegal trade in rhino horn supports aggressive poaching syndicates  
and a black market Nowell et al. (1992); Warchol et al. (2003). This lucrative market entices peo-  
ple to invest their time and energy to gain a ‘windfall’ in the form of a rhino horn, through the  
24 poaching of rhinos. In recent years poaching has escalated to an unprecedented level resulting in  
concerns over their future existence Biggs et al. (2013); Smith et al. (2013). In response, rhino con-  
servation has seen increased militarisation with ‘boots on the ground’ and ‘eyes in the sky’ Duffy  
27 et al. (2015). An alternative method is to devalue the horn itself, one of the main methods being  
the removal so that only a stub is left. The first attempt at large-scale rhino dehorning as an anti-  
poaching measure was in Damaraland, Namibia, in 1989 Milner-Gulland and Leader-Williams  
30 (1992). Other methods of devaluing the horn that have been suggested include the insertion of  
poisons, dyes or GPS trackers Gill (2010); Smith et al. (2013). However, like dehorning, they  
cannot remove all the potential gain from an intact horn (poison and dyes fade or GPS trackers  
33 can be removed and have been found to affect only a small proportion of the horn). Moreover,  
several methods include addressing the problem by reducing the demand in the market. In Biggs  
et al. (2013) the authors suggest meeting the demand for rhino horn through a legal market by  
36 farming the rhino horn from live rhinos. This controversial proposal is an active conversation,  
with the actual quantity of horn that could be farmed being estimated recently by Taylor et al.  
(2017). Moreover, the debate is not limited to rhinos - Harvey et al. (2017) considered ivory and  
39 stated that by enforcing a domestic ivory trade ban we can reduce the market’s demand. This pa-  
per builds on the work of Lee and Roberts (2016) and considers the general strategy of devaluing  
horns, which includes dehorning.

42 Rhino populations now persist largely in protected areas or on private land, and require in-  
tensive protection Ferreira et al. (2014). For wildlife managers law enforcement is often one of  
the main methods of deterring poaching, however rhino managers can remove the poaching in-

centive by devaluing their rhinos Milner-Gulland and Leader-Williams (1992). In Milner-Gulland and Leader-Williams (1992) they found the optimum proportion to dehorn using mean horn length as a measure of the proportion of rhinos dehorned. They showed, with realistic parameter values, that the optimal strategy is to dehorn as many rhinos as possible. A manager does not need to choose between law enforcement or devaluing, but perhaps adopt a combination of the two; especially given that devaluing rhinos comes at a cost to the manager, and the process comes with a risk to the rhinos.

A recent paper modelled the interaction between a rhino manager and poachers using game theory Lee and Roberts (2016). The authors consider a working year of a single rhino manager. A manager is assumed to have standard yearly resources which can be allocated on devaluing a proportion of their rhinos or spent on security. It is assumed that all rhinos initially have intact horns. Poachers may either only kill rhinos with full horns, ‘selective poachers’, or kill all rhinos they encounter, ‘indiscriminate poachers’. This strategy may be preferred to avoid tracking a devalued rhino again, and/or to gain the value from the partial horn. If all rhinos are left by the rhino manager with their intact horns, it does not pay poachers to be selective so they will chose to be indiscriminate since being selective incurs an additional cost to discern the status of the rhino. Conversely, if all poachers are selective, it pays rhino managers to invest in devaluing their rhinos. This dynamic is represented in Fig. 1. Assuming poachers and managers will always behave so as to maximise their payoff, there are two equilibriums: either all rhinos are devalued and all poachers are selective; or all horns are intact and all poachers are indiscriminate. Essentially, either the managers win, the top left quadrant of Fig. 1, or the poachers win, the bottom right quadrant of Fig. 1. The paper Lee and Roberts (2016) concludes that poachers will always choose to behave indiscriminately, and thus the game settles to the bottom right quadrant, i.e., the poachers win.

The work of Lee and Roberts (2016) did not take in to account the population dynamic effect of these strategies. In a population full of indiscriminate poachers would there be a benefit to a single poacher becoming selective or vice versa? This notion is explored here using evolutionary





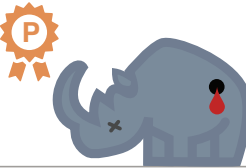
		Manager strategies	
		Horn devalued	Horn intact
Poacher strategies	Selective	 	
	Indiscriminate		

Figure 1: The game between rhino manager and rhino poachers. The system settles to one of two equilibriums, either devaluing is effective or not.

game theory Smith and Price (1973). The game is not that of two players anymore (manager and poacher) but now the players are an infinite population of poachers. This allows for the interaction between poachers over multiple plays of the game to be explored with the rhino manager being the one that creates the conditions of the population.

In evolutionary game theory, we assume infinite populations and in our model this will be represented by  $\chi = (x_1, x_2)$  with  $x_1$  proportion of the population using a strategy of the first type and  $x_2$  of the second. We assume there is a utility function  $u_1$  and  $u_2$  that maps the population to a fitness for each strategy,

$$u_1(\chi) \quad u_2(\chi).$$

In evolutionary game theory these utilities are used to dictate the evolution of the population over time, according to the following differential equations,

$$\begin{cases} \frac{dx_1}{dt} = x_1(u_1(\chi) - \phi), \\ \frac{dx_2}{dt} = x_2(u_2(\chi) - \phi), \end{cases} \quad (1)$$

where  $\phi$  is the average fitness of the whole population. Here, the overall population is assumed to remain stable thus,  $x_1 + x_2 = 1$  and

$$\frac{dx_1}{dt} + \frac{dx_2}{dt} = 0 \Rightarrow x_1(u_1(\chi) - \phi) + x_2(u_2(\chi) - \phi) = 0. \quad (2)$$

84 Thus the average fitness can be written as,

$$\phi = x_1 u_1(\chi) + x_2 u_2(\chi). \quad (3)$$

By substituting (3) and  $x_2 = 1 - x_1$  in (1),

$$\frac{dx_1}{dt} = x_1(1 - x_1)(u_1(\chi) - u_2(\chi)). \quad (4)$$

The equilibria of the differential equation (4) are given by,  $x_1 = 0$ ,  $x_1 = 1$ , and  $0 < x_1 <$   
 87  $1$  for  $u_1(\chi) = u_2(\chi)$ . These equilibria correspond to stability of the population: the differential equation (4) no longer changes.

The notion of evolutionary stability can be checked only for these stable strategies. For a  
 90 stable strategy to be an Evolutionary Stable Strategy (ESS) it must remain the best response even in a mutated population  $\chi_\epsilon$ . A mutated population is the post entry population where a small proportion  $\epsilon$  starts deviating and adopts a different strategy. Fig. 2 illustrates two potential  
 93 strategies: without outside stimulation neither marble would move. In Fig. 2b however the

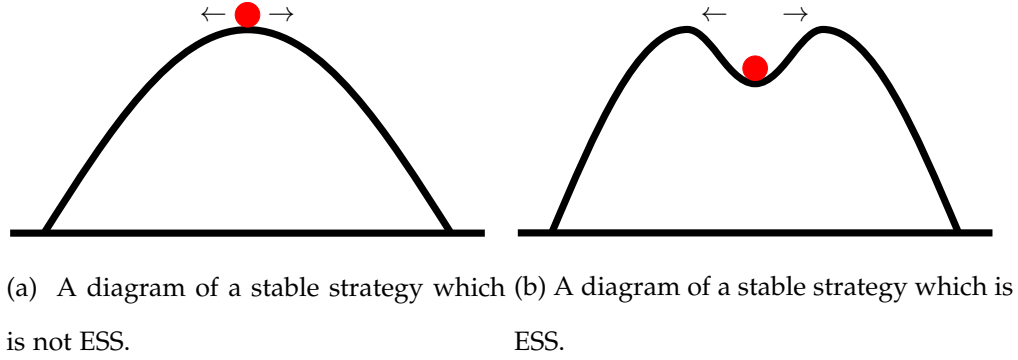


Figure 2: Diagrams of stable strategies.

stability can be described as “stronger”: with a small nudge the marble would return to its stable position. In Fig. 2a any non zero nudge would move the marble out of its equilibria.

96 In Section “”, we determine expressions for  $u_1, u_2$  that correspond to a population of wild rhino poachers and we explore the stability of the equilibria identified in Lee and Roberts (2016). The results contained in this paper are proven analytically, and more specifically it is shown that:

- 99
- all poachers behaving selectively is trivially unstable,
  - a mixed population where selective and indiscriminate poachers learn to co exist can not hold,
- 102
- all poachers adopting an indiscriminate strategy is an evolutionary stable strategy.

This implies that under almost all conditions, no matter what current proportion of of poachers are acting selectively, the population will eventually turn in to a population of only indiscriminate poachers.

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## The Utility Model

As discussed briefly in Section “Introduction”, a rhino poacher can adopt two strategies, to either behave selectively or indiscriminately. To calculate the utility for each strategy, the gain and cost

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that poachers are exposed to must be taken into account. The poacher incurs a loss from seeking a rhino, and the risk involved. The gain depends upon the value of horn, the proportion of horn remaining after the manager has devalued the rhino horn and the number of rhinos (devalued and not).

Let us first consider the gain to the poacher, where  $\theta$  is the amount of horn taken. We assume rhino horn value is determined by weight only, a reasonable assumption as rhino horn is sold in a grounded form Sav (2017). Referring to Fig. 1, clearly if the horn is intact, the amount of horn gained is  $\theta = 1$  for both the selective and the indiscriminate poacher. If the rhino horn has been devalued, and the poacher is selective, the amount of horn gained is  $\theta = 0$  as the poacher does not kill. However, if the poacher is behaving indiscriminately, the amount of horn gained is  $\theta = \theta_r$  (for some  $0 < \theta_r < 1$ ). Therefore, the amount of horn gained in the general case is

$$\theta(r, x) = x(1 - r) + (1 - x)((\theta_r - 1)r + 1), \quad (5)$$

where  $r$  is the proportion of rhinos that have been devalued, and  $x$  is the proportion of selective poachers and  $1 - x$  is the proportion of indiscriminate poachers. Note that since  $\theta_r, r, x \in [0, 1]$ , then  $\theta(r, x) > 0$ , that is, some horn will be taken. Standard supply and demand arguments imply that the value of rhino horn decreases as the quantity of horn available increases Mankiw (2010). Thus at any given time the expected gain is

$$H\theta(r, x)^{-\alpha}, \quad (6)$$

where  $H$  is a scaling factor associated with the value of a full horn, and  $\alpha \geq 0$  is a constant that determines the precise relationship between the quantity and value of the horn. Fig. 3, verifies that the gain curve corresponds to a demand curve.

An individual interacts with the population, denoted as  $\chi = (x, 1 - x)$ . For simplicity, from herein the population  $\chi$  is referred to in terms of the proportion of selective poachers only,  $x$ .



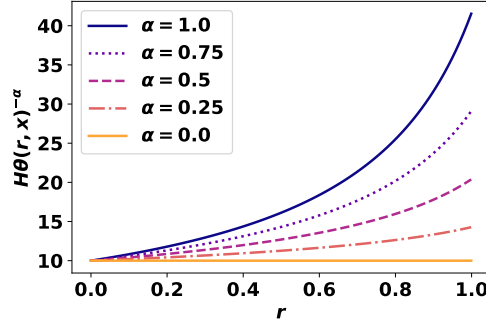


Figure 3:  $H\theta(r, x)^{-\alpha}$  for values  $H = 10, \theta_r = 0.3$  and  $x = 0.2$ .

Therefore, the gain for a poacher in the population  $x$  is either

$$\begin{cases} \theta(r, 1)H\theta(r, x)^{-\alpha} & \text{selective poacher} \\ \theta(r, 0)H\theta(r, x)^{-\alpha} & \text{indiscriminate poacher} \end{cases} \quad (7)$$

depending on the chosen strategy of the individual, see Fig. 1.

132 Secondly we consider the costs incurred by the poacher. Let us denote the number of rhinos  
that will be considered at risk given  $r$  and  $x$  as  $\psi(r, x)$ . The rhinos **not** at risk are the devalued  
ones that cross the paths of selective poachers. Thus the cost to seek a rhino depends on  $r$  and  $x$   
135 by,

$$\psi(r, x) = 1 - rx. \quad (8)$$

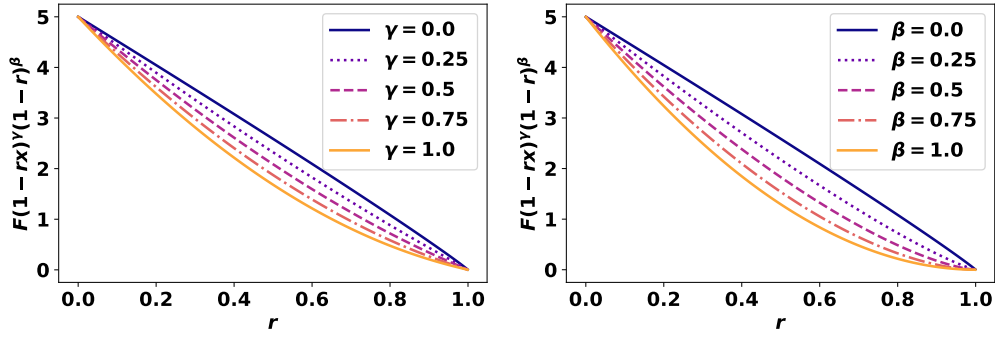
Additionally, the poachers are also exposed to a risk. The risk to the poacher is directly  
related to the proportion of rhinos not devalued,  $1 - r$ , since the rhino manager can spend more  
138 on security if the cost of devaluing is low. In real life this is not always the case. The cost of  
security can be extremely high thus it can not be guaranteed that much security will be added  
from the saved money. However, our model assumes that there is a proportional and negative  
141 relationship between the measures.

$$(1-r)^\beta, \quad (9)$$

where  $\beta \geq 0$  is a constant that determines the precise relationship between the proportion of rhinos not devalued and the security on the grounds. Therefore, at any given time the expected cost for a poacher is,

$$F\psi(r, x)^\gamma(1-r)^\beta = F(1-rx)^\gamma(1-r)^\beta \quad (10)$$

where  $F$  and  $\gamma \geq 0$  are constants that determine the precise relationship between the proportion of vulnerable rhinos and the probability of finding a rhino, such that  $\gamma$  close to zero indicates very sparse rhinos. Fig. 4, verifies the decreasing relationship between  $r$  and the cost.



(a) For values,  $x = 0.7, F = 5$  and  $\beta = 0.95$ . (b) For values,  $x = 1, F = 5$  and  $\gamma = 0.95$ .

Figure 4:  $F(1-rx)^\gamma(1-r)^\beta$ .

Note that a selective poacher needs more time to secure an 'available' rhino, if they exist at all. Hence, there is an additional cost that tends to infinity as  $r \rightarrow 1$ ,

$$\begin{cases} \frac{1}{\psi(r,1)} = \frac{1}{1-r} & \text{selective poacher} \\ \frac{1}{\psi(r,0)} = 1 & \text{indiscriminate poacher} \end{cases} \quad (11)$$

150 To summarise, the cost incurred by a given individual poacher when interacting with the population  $x$  is given by

$$\begin{cases} \frac{1}{1-r} F\psi(r, x)^\gamma (1-r)^\beta & \text{selective poacher} \\ F\psi(r, x)^\gamma (1-r)^\beta & \text{indiscriminate poacher} \end{cases} \quad (12)$$

Combining (7) and (12) gives the utility functions for selective poachers,  $u_1(x)$ , and indis-  
 153 criminate poachers,  $u_2(x)$ ,

$$u_1(x) = \theta(r, 1) H\theta(r, x)^{-\alpha} - \frac{1}{1-r} F\psi(r, x)^\gamma (1-r)^\beta, \quad (13)$$

$$u_2(x) = \theta(r, 0) H\theta(r, x)^{-\alpha} - F\psi(r, x)^\gamma (1-r)^\beta. \quad (14)$$

Let  $\sigma = (s, 1-s)$  denote an individual where  $\sigma = (1, 0)$  represents a selective poacher, and  $\sigma = (0, 1)$  represents an indiscriminate poacher. For simplicity, from herein the individual  $\sigma$  is  
 156 referred to in terms of the probability of behaving selectively,  $\sigma = s$ . Thus the general utility function for an individual poacher in the population with a proportion of  $0 \leq x \leq 1$  selective poachers is

$$u(s, x) = su_1(x) + (1-s)u_2(x). \quad (15)$$

159 Substituting (13) and (14) into (15) gives,

$$u(s, x) = H(\theta, r(1-s) - r + 1) \theta(r, x)^{-\alpha} - F \left( 1 - s + \frac{s}{1-r} \right) (1-rx)^\gamma (1-r)^\beta. \quad (16)$$

In Section “Evolutionary Stability”, the notions of stability and evolutionary stability of these two strategies as well as a potential mixed strategy will be investigated.

## 162 Evolutionary Stability

By definition, for a strategy to be an ESS it must first be a best response to an environment where the entire population is playing the same strategy. In our model there are three possible stable  
165 distributions based on the equilibria of equation (4):

- all poachers are selective;
- all poachers are indiscriminate;
- 168 • mixed population of selective and indiscriminate poachers.

Each of the equilibria will be examined in the following subsections.

### 0.1 All poachers are selective

171 **Theorem 1.** *Using the utility model described in Section “The Utility Model”, a population of selective poachers is unstable.*

*Proof.* For  $s = 1$  to be a best response to itself the utility of behaving selectively in a population  
174 of selective poachers must be greater than the utility of a poacher behaving indiscriminately in a population of selective poachers,

$$u(1, 1) > u(0, 1), \quad (17)$$

where

$$u(1, 1) = H(1 - r)^{1-\alpha} - F(1 - r)^{\beta+\gamma-1} \quad (18)$$

177 and

$$u(0, 1) = H(\theta_r r + 1 - r)(1 - r)^{-\alpha} - F(1 - r)^{\beta+\gamma}. \quad (19)$$

Setting (18) to be greater than (19) gives the condition,

$$H\theta_r < -F(1-r)^{\gamma+\beta+\alpha-1} \quad (20)$$

The right-hand side will always be negative for any  $r$ , on the other hand the left-hand side is  
 180 always positive. Thus, (20) can never hold.  $\square$

This implies that whilst Lee and Roberts (2016) identified the individual poachers acting  
 selectively as an equilibrium it is an extremely weak equilibrium from the point of view of  
 183 population stability: a slight change and the population will change.

## 0.2 All poachers are indiscriminate

**Theorem 2.** *Using the utility model described in Section “The Utility Model”, a population of indiscriminate poachers is evolutionarily stable.*  
 186

*Proof.* In order for  $s = 0$  to be an ESS it must remain the best response in a mutated population  
 $\chi_\epsilon$ , where  $\chi_\epsilon = (x_\epsilon, 1 - x_\epsilon)$ . Following the same notation, the mutated population will be denoted  
 189 as  $x_\epsilon$  from herein. Thus,

$$u(0, x_\epsilon) > u(x_\epsilon, x_\epsilon), \quad (21)$$

must hold. From (16),

$$(22)$$

$$u(0, x_\epsilon) = H(\theta_r r - r + 1)\theta(r, x_\epsilon)^{-\alpha} - F(1 - rx_\epsilon)^\gamma(1 - r)^\beta, \quad (23)$$

$$u(x_\epsilon, x_\epsilon) = H(\theta_r r(1 - x_\epsilon) - r + 1)\theta(r, x_\epsilon)^{-\alpha} - F(1 - rx_\epsilon)^\gamma(1 - r)^\beta \left(1 - x_\epsilon + \frac{x_\epsilon}{1 - r}\right). \quad (24)$$

Let the difference of (22) and (24) be denoted as,

$$\delta = u(0, x_\epsilon) - u(x_\epsilon, x_\epsilon), \quad (25)$$

$$= H\theta(r, x_\epsilon)^{-\alpha} \theta_r r x_\epsilon - F(1 - r x_\epsilon)^\gamma (1 - r)^\beta x_\epsilon \left( \frac{-r}{1 - r} \right) \quad (26)$$

all indiscriminate will be an ESS only if  $\delta > 0$  for any small value of  $\epsilon$ . Thus only if,

$$H\theta(r, x_\epsilon)^{-\alpha} \theta_r r x_\epsilon > F(1 - r x_\epsilon)^\gamma (1 - r)^\beta x_\epsilon \left( \frac{-r}{1 - r} \right) \quad (27)$$

The right-hand of inequality (27) is always negative since  $(\frac{-r}{1-r}) < 0$  for all  $r$ . On the contrary, the left-hand side is always positive for all  $r$ , thus the inequality always holds. Therefore, it is proven that all indiscriminate poachers is an evolutionary stable strategy.  $\square$

This shows that a population of indiscriminate poachers not only corresponds to the equilibrium of the individual based game identified in Lee and Roberts (2016) but also is a very robust and an attractive equilibrium at the population level.

### 0.3 Mixed population of selective and indiscriminate poachers

**Theorem 3.** *Using the utility model described in Section “The Utility Model”, a mixed stable strategy ( $s = s^*$ ) never exists for  $0 < r < 1$ .*

*Proof.* A mixed strategy  $s = s^*$  is said to be stable for a given  $s^*$  only if,

$$u(1, s^*) = u(0, s^*). \quad (28)$$

The left-hand side is,

$$u(1, s^*) = H(1 - r)\theta(r, s^*)^{-\alpha} - F\frac{1}{(1 - r)}(1 - r s^*)^\gamma (1 - r)^\beta$$

The right-hand side is

$$u(0, s^*) = H(\theta_r r + 1 - r)\theta(r, s^*)^{-\alpha} - F(1 - rs^*)^\gamma(1 - r)^\beta.$$

Substituting these into (28) gives

$$-(H\theta_r r\theta(r, s^*)^{-\alpha} + Fr(1 - rs^*)^\gamma(1 - r)^{\beta-1}) = 0. \quad (29)$$

Condition (29) can never hold for  $0 < r < 1$ . Thus a mixed stable equilibrium is never stable.  $\square$

207 In this section we have studied analytically the stability of all the possible equilibria. We have  
 proven the instability of any population with selective poachers and the evolutionary stability  
 of the indiscriminate behaviour. All of these theoretic results have been verified empirically, the  
 210 data for this has been archived at .

Theorems 1, 2, 3 are illustrated in Fig. 5 which shows the numerical solutions to (4) using (13)  
 and (14) with  $x_1 = x$ . This is done using numerical integration implemented in Eric et al. (2001–).  
 213 As is evident from the scenarios considered, all populations converge to being all indiscriminate.

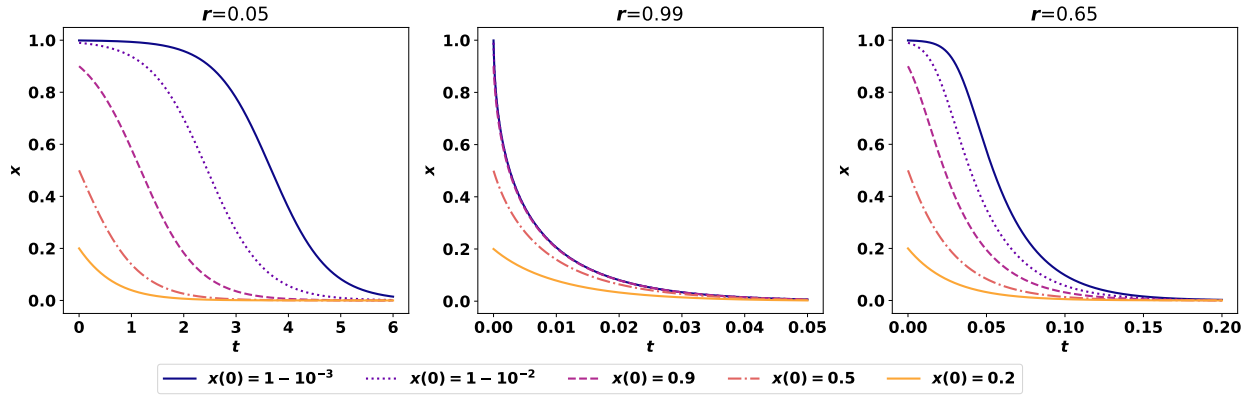


Figure 5: The change of the population over time with different starting populations. For  $F = 5, H = 50, \alpha = 2, \beta = 2, \gamma = 1, \theta_r = 0.6$ .

Note that these results essentially follow by comparing equations (13) and (14), which show that  $u_1(x) \leq u_2(x)$  for all  $x$ . Consider the reverse scenario,

$$u_1(x) > u_2(x) \quad (30)$$

$$F\psi(r, x)^\gamma(1-r)^{\beta-1} < -H\theta(r, x)^{-\alpha}\theta_r \quad (31)$$

216 which gives the required contradiction. This shows that the utility model used implies that given the choice of acting selectively or indiscriminately, in any given environment it will always be a rational deviation to act indiscriminately.

219 In the following section a disincentive to acting indiscriminately will be introduced. This can be interpreted in many ways:

- more severe punishment for indiscriminate killing of rhinos;
- 222 • educational interventions that highlight the negative aspects of indiscriminate killing;
- the possibility of a better alternative being on offered to selective poachers.

## 1 Disincentive for indiscriminate behaviour

225 Let us consider the following modification of the utility to an indiscriminate poacher:

$$\tilde{u}_2(x) = u_2(x) - \Gamma \quad (32)$$

where  $\Gamma > 0$  is some constant representing a disincentive only applied to indiscriminate poachers.

This leads to the following modified form of (15):

$$\tilde{u}(s, x) = u(s, x) - (1-s)\Gamma \quad (33)$$

228 This leads to the following theorem:

**Theorem 4.** *Using the modified utility model described a population of selective poachers is stable if and only if:*



$$\theta_r H - F(1-r)^{\gamma+\beta+\alpha-1} < \frac{\Gamma(1-r)^\alpha}{r} \quad (34)$$

231 *Proof.* Following a similar structure to that of Theorem 1,

$$\tilde{u}(1,1) > \tilde{u}(0,1), \quad (35)$$

where

$$\tilde{u}(1,1) = H(1-r)^{1-\alpha} - F(1-r)^{\beta+\gamma-1} \quad (36)$$

and

$$\tilde{u}(0,1) = H(\theta_r r + 1 - r)(1-r)^{-\alpha} - F(1-r)^{\beta+\gamma} - \Gamma. \quad (37)$$

234 Setting (36) to be greater than (37) gives the condition,

$$\theta_r H - F(1-r)^{\gamma+\beta+\alpha-1} < \frac{\Gamma(1-r)^\alpha}{r} \quad (38)$$

□

This immediately leads to the following important remark:

237 **Theorem 5.** *Using the modified utility model described, if all rhinos have been dehorned a population of selective poachers is not stable.*

*Proof.* All rhinos being dehorned implies that  $r = 1$ . Substituting this into (34) gives,

$$\theta_r H < 0 \quad (39)$$

240 which is not possible. □

Theorem 5 is due to the fact that given two options, if all rhinos have been dehorned then all poachers will need to act indiscriminately to have any source of utility. Theorem 4 states that a mixed population can be stable with a disincentive, as opposed to Theorem 3 which states that a mixed stable strategy does not exist for  $0 < r < 1$ . This is illustrated in Fig. 6 where the evolutionary dynamics are represented for a number of scenarios.

Note that now the manager has control over the point of convergence by controlling  $r$ , as shown in Fig. 7 where a difference in the value from  $r = 0.7$  to  $r = 0.5$  changes the point of convergence from a mixed to a selective one. Moreover, the manager can also manipulate how fast the population converges, as shown in the difference from  $r = 0.5$  to  $r = 0.2$ . Fig 8a shows the equilibrium for  $x$  for a number of different values of  $r$ , and indicates that having a large  $r$  pushes poachers to behave indiscriminately. However all selective poachers can save at most, the  $r$  proportion of dehorned rhinos, so a low  $r$  is not ideal. As demonstrated in Fig 8b, a higher value of  $H$  also has a non-ideal effect on the poachers, as one would expect. Thus, high values of  $H$  and  $r$  lead to more indiscriminate poachers.

The insights gained from the results are discussed in Section “Discussion and Conclusions”.

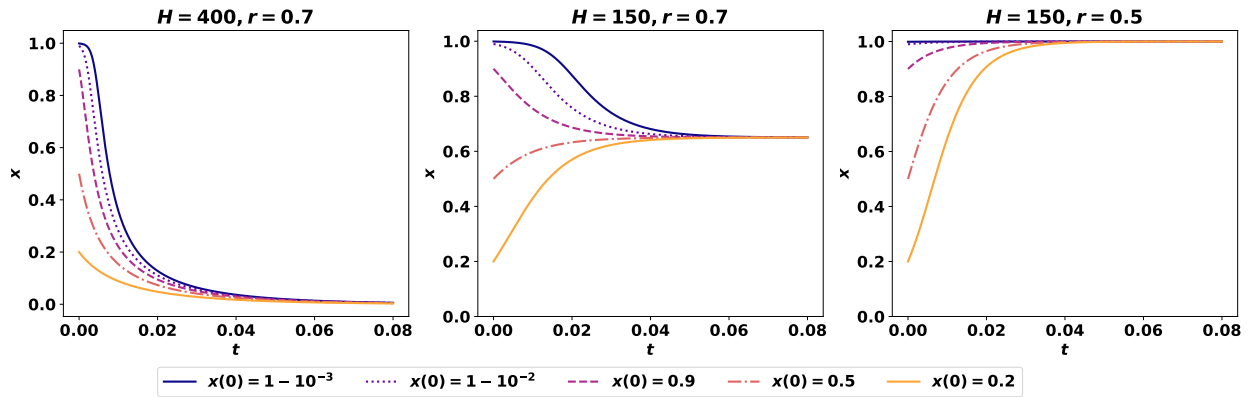


Figure 6: The change of the population over time with different starting populations with a disincentive. For  $F = 50, \alpha = 2, \beta = 2, \gamma = 1, \theta_r = 0.5, \Gamma = 300$ .

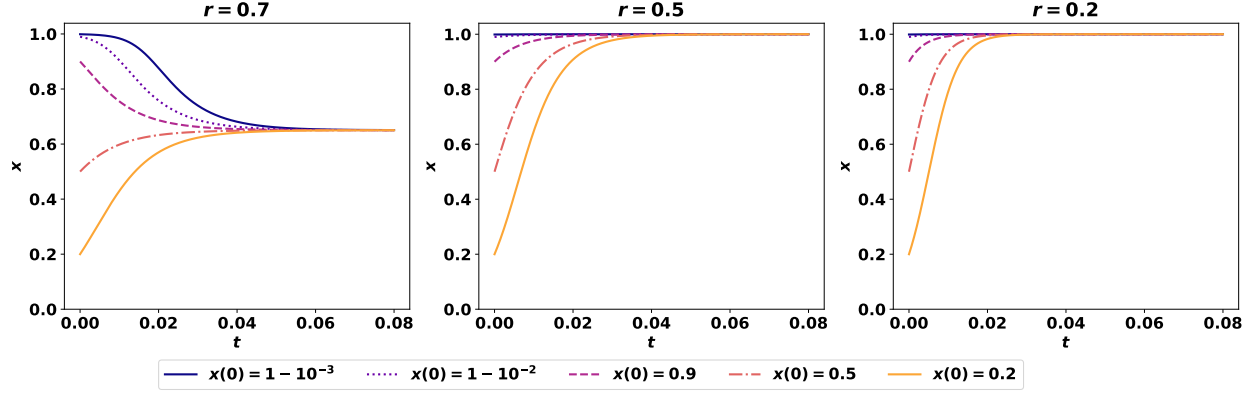
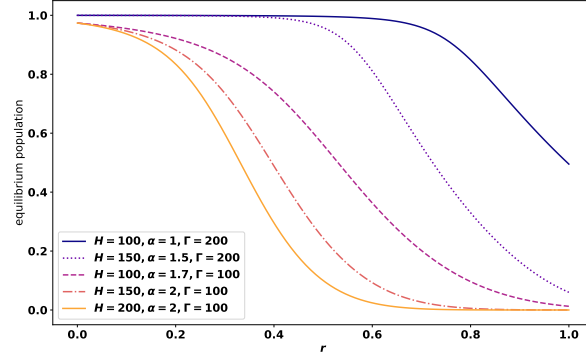
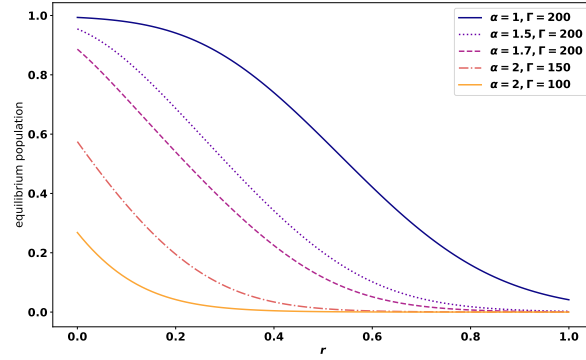


Figure 7: The change of the convergence point with different values of  $r$  with different starting populations with a disincentive. For  $F = 50, H = 150, \alpha = 2, \beta = 2, \gamma = 1, \theta_r = 0.5, \Gamma = 300$ .



(a) Effect of  $r$  for  $F = 50, \beta = 2, \gamma = 1, \theta_r = 0.6$ .



(b) Effect of  $H$  for  $F = 50, r = 0.6, \beta = 2, \gamma = 1, \theta_r = 0.6$ .

Figure 8: Equilibrium behaviour with a disincentive.

## Discussion and Conclusions

In this work the dynamics of a selective population were explored. It was proven that being selective is not a best response even in a population where everyone is behaving selectively. More specifically, even a mixed population with a small percentage of the population behaving selectively will not persist. Thus, a poacher would never adopt a selective strategy over an indiscriminate one.

Using a realistic and generic utility model it was found that the only strategy that was proven to be stable is the indiscriminate one. Moreover, it was proven to be evolutionary stable as well. Meaning, that for any given starting population, the poachers would evolve to adopt an indiscriminate behaviour.

Our results indicate however that it is possible for a population of selective poachers to exist, but for this to occur a disincentive must be applied to the utility of indiscriminate poachers. Numerical results indicate that even in this case, the more rhinos which are dehorned, the less probability that a poacher will be selective. Assuming basic supply and demand arguments, the demand of a partial horn will increase by removing horns thus the probability of being selective decreases. Therefore, even in the scenario with a disincentive, the proportion of rhinos which could be saved is limited. As such approaches which aim to reduce demand (as suggested in Biggs et al. (2013)) would have more potential.

The disincentive factor can have several interpretations. According to Biggs et al. (2017), engaging the rural communities that neighbour or live with wildlife is the key to fighting the illegal trade of wildlife. Strengthening disincentives for illegal behaviour can be interpreted as the disincentive factor. Likewise, increasing incentives for wildlife stewardship, decreasing the cost of living with wildlife and supporting livelihood that is not related to poaching can serve as incentives for selective behaviour.

Note that the proportion of dehorned rhinos  $r$  is continuous over  $[0, 1]$  in the model. However, standard practice of a given park manager in almost all cases is to either dehorn all the animals

in a defined enclosed area, or none at all. This is thought to be because partial dehorning tends to cause havoc in rhino social structures. The theoretic model presented here, whilst allowing for consideration at the park level with park managers playing a mixed strategy, also can be considered at the macroeconomic level. Where  $r$  represents the quantity of dehorned rhinos available across multiple parks.

Thus the insights gained, notably that a population of selective poachers is sustainable only if a large disincentive is in place (even if all rhinos have been dehorned) have implication at the long term national policy level.

Following discussions with environmental specialists it is clear that dehorning is empirically thought to be one of the best responses to poaching. This indicates that whilst of theoretic and macroeconomic interest the modelling approach investigated in this work has potential for further work. For example, a detailed study of two neighbouring parks with differing policies could be studied using a game theoretic model. Another interesting study would be to introduce a third strategy available to poachers: this would represent the possibility of not poaching (perhaps finding another source of income) and/or leaving the current environment to poach elsewhere.

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