An Evolutionary Game Theoretic Model of Rhino Horn Devaluation

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Abstract

Rhino populations are at a critical level due to the demand for rhino horn and the subsequent poaching. Wildlife managers attempt to secure rhinos with approaches to devalue the horn, the most common of which is dehorning. Game theory has been used to examine the interaction of poachers and wildlife managers where a manager can either 'dehorn' their rhinos or leave the horn attached and poachers may behave 'selectively' or 'indiscriminately'. The approach described in this paper builds on this previous work and investigates the interactions between the poachers. We build an evolutionary game theoretic model and 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 required for informed discussion about the lively debate on legalising rhino horn trade.

1   Introduction

Rhino populations now persist largely in protected areas or on private land, and require intensive protection [7] because the demand for rhino horn continues to pose a serious threat [2]. The illegal trade in rhino horn supports aggressive poaching syndicates and a black market [16, 21]. This lucrative market entices people to invest their time and energy to gain a 'windfall' in the form of a rhino horn, through the poaching of rhinos. In recent years poaching has escalated to an unprecedented level resulting in concerns over their future existence [4, 18]. Several methods include addressing the problem by reducing the demand in the market. In [4] the authors suggest meeting the demand for rhino horn through a legal market by 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 [19]. Moreover, the debate is not limited to rhinos - [10] considered ivory and stated that by enforcing a domestic ivory trade ban we can reduce the market's demand.

Nonetheless, for wildlife managers law enforcement is often one of the main methods to deter poachers. In response, rhino conservation has seen increased militarisation with 'boots on the ground' and 'eyes in the sky' [5]. 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 [15]. Other methods of devaluing the horn that have been suggested include the insertion of poisons, dyes or GPS trackers [8, 18]. However, like dehorning, they cannot remove all the potential gain from an intact horn (poison and dyes fade or GPS trackers can be removed and have been found to affect only a small proportion of the horn). In [15] 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 [12]. 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. 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 and rhinos survive or the poachers win and rhinos are killed. The paper [12] concludes that poachers will always choose to behave indiscriminately, and thus the game settles to the bottom right quadrant, i.e., the poachers win.

In this manuscript, we explore the population dynamic effects associated to the interactions described by [12]. More specifically, the interaction between poachers.In a population full of indiscriminate poachers is there a benefit to a single poacher becoming selective or vice versa? This notion is explored here using evolutionary game theory [17]. 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.

Note that poachers are, in practice finite, and each has individual factors that will affect a poacher's

behaviour. An infinite population model corresponds to either an asymptotic generalisation or overall descriptive behaviour.

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

$$u_1(\chi) \text{ and } u_2(\chi).$$

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

$$
\begin{cases}
\dfrac{dx_1}{dt} = x_1(u_1(\chi) - \phi), \\[4ex]
\dfrac{dx_2}{dt} = x_2(u_2(\chi) - \phi),
\end{cases}
\tag{1}
$$

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

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

Recalling that $x_1 + x_2 = 1$ the average fitness can be written as,

$$\phi = x_1 u_1(\chi) + x_2 u_2(\chi). \tag{3}$$

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

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

4

The equilibria of the differential equation (4) are given by, $x_1 = 0$, $x_1 = 1$, and $0 < x_1 < 1$ 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 stable strategy to be an Evolutionary Stable Strategy (ESS) it must remain the best response even in a mutated population χ_ϵ. A mutated population is the post entry population where a small proportion $\epsilon > 0$ starts deviating and adopts a different strategy. Fig. 1 illustrates two potential strategies: without outside stimulation neither marble would move. In Fig. 1b however the stability can be described as "stronger": with a small nudge the marble would return to its stable position. In Fig. 1a any non-zero nudge would move the marble out of its equilibria.

(a) A diagram of a stable strategy which is not ESS.
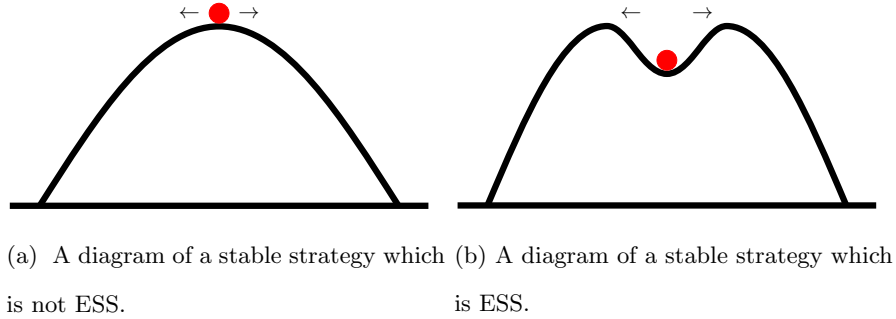
(b) A diagram of a stable strategy which is ESS.

Figure 1: Diagrams of stable strategies.

In Section 2, 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 [12]. The results contained in this paper are proven analytically, and more specifically it is shown that:

- all poachers behaving selectively is trivially unstable,

- a mixed population where selective and indiscriminate poachers learn to coexist can not hold,

- 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 into a population of only indiscriminate poachers.

2 The Utility Model

As discussed briefly in Section 1, a rhino poacher can adopt two strategies, to either behave selectively or indiscriminately. To calculate the utility for each strategy, the gain and cost 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 θ 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 [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 proportion of horn gained is $\theta = \theta_r$ (for some $0 < \theta_r < 1$). Therefore, the amount of horn gained in the general case is

$$\theta(r, x) = x(1 - r) + (1 - x)((\theta_r - 1)r + 1), \tag{5}$$

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 [13]. Thus at any given time the expected gain is

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

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. 2, 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 χ is referred to in terms of the proportion of selective poachers only, x. Therefore, the gain for a
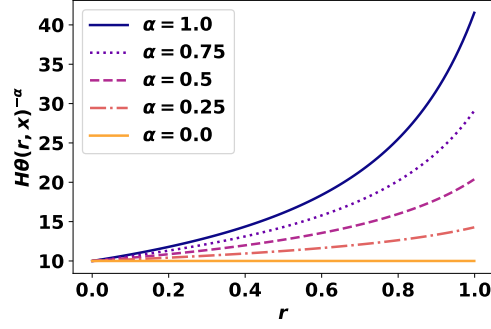
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Figure 2: $H\theta(r,x)^{-\alpha}$ for values $H = 10, \theta_r = 0.3$ and $x = 0.2$.

poacher in the population x is either

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

depending on the chosen strategy of the individual.

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 by,

$$
\psi(r,x) = 1 - rx.
\tag{8}
$$

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 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 cannot be guaranteed that much security will be added from the saved money. However, our model assumes that there is a proportional and negative relationship between the measures.

$$
(1-r)^{\beta},
\tag{9}
$$

where $\beta \geq 0$ is a constant that determines the precise relationship between the proportion of rhinos not

7

devalued and the security on the grounds. Therefore, at any given time the expected cost for a poacher is,

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

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 γ close to zero indicates very sparse rhinos. Fig. 3 verifies the decreasing relationship between r and the cost.
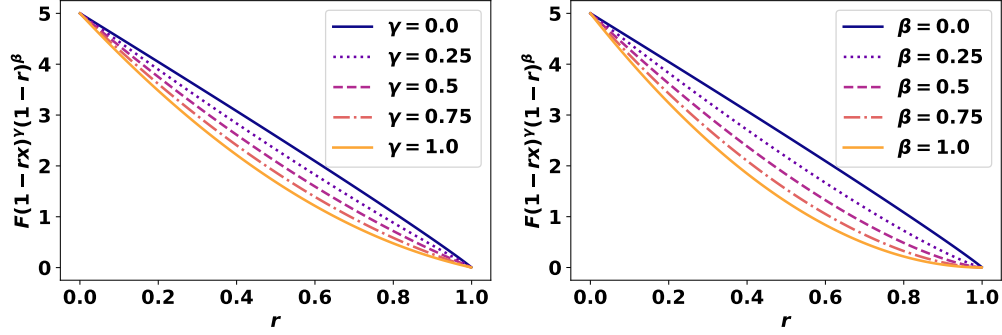
(a) For values, $x = 0.7, F = 5$ and $\beta = 0.95$.   (b) For values, $x = 1, F = 5$ and $\gamma = 0.95$.

Figure 3: $F(1-rx)^{\gamma}(1-r)^{\beta}$.

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 $r \to 1$,

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

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

$$
\begin{cases}
\frac{1}{1-r}F\psi(r,x)^{\gamma}(1-r)^{\beta} & \text{selective poacher} \\[2ex]
F\psi(r,x)^{\gamma}(1-r)^{\beta} & \text{indiscriminate poacher.}
\end{cases}
\tag{12}
$$

Combining (7) and (12) gives the utility functions for selective poachers, $u_1(x)$, and indiscriminate poachers, $u_2(x)$,

$$
\begin{aligned}
u_1(x) &= \theta(r,1)H\theta(r,x)^{-\alpha} - \frac{1}{1-r}F\psi(r,x)^{\gamma}(1-r)^{\beta}, \tag{13} \\
u_2(x) &= \theta(r,0)H\theta(r,x)^{-\alpha} - F\psi(r,x)^{\gamma}(1-r)^{\beta}. \tag{14}
\end{aligned}
$$

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 σ is 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 $0 \le x \le 1$ selective poachers is

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

Substituting (13) and (14) into (15) and using (5) and (8) gives,

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

In Section 3, the notions of stability and evolutionary stability of these two strategies, as well as a potential mixed strategy will be investigated.

3   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 distributions based on

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the equilibria of equation (4):

- all poachers are selective;

- all poachers are indiscriminate;

- mixed population of selective and indiscriminate poachers.

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

3.1   All poachers are selective

Theorem 1. *Using the utility model described in Section 2, 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 of selective poachers must be greater than the utility of a poacher behaving indiscriminately in a population of selective poachers,

$$u(1,1) > u(0,1), \tag{17}$$

where

$$
\begin{aligned}
u(1,1) &= H(1-r)\theta(r,1)^{-\alpha} - F(\frac{1}{1-r})(1-r)^\gamma(1-r)^\beta \tag{18} \\
&= H(1-r)^{1-\alpha} - F(1-r)^{\beta+\gamma-1}, \tag{19}
\end{aligned}
$$

and

$$
\begin{aligned}
u(0,1) &= H(\theta_r r - r + 1)\theta(r,1)^{-\alpha} - F(1-r)^\gamma(1-r)^\beta \tag{20} \\
&= H(\theta_r r + 1 - r)(1-r)^{-\alpha} - F(1-r)^{\beta+\gamma}. \tag{21}
\end{aligned}
$$

Setting (18) to be greater than (20) gives the condition,

$$H\theta_r < -F(1-r)^{\gamma+\beta+\alpha-1}. \tag{22}$$

10

The right-hand side will always be negative for any r, on the other hand the left-hand side is always positive. Thus, (22) can never hold. □

This implies that whilst [12] identified the individual poachers acting selectively as an equilibrium it is an extremely weak equilibrium from the point of view of population stability: a slight change and the population will change.

3.2 All poachers are indiscriminate

Theorem 2. *Using the utility model described in Section 2, a population of indiscriminate poachers is evolutionarily stable.*

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

$$u(0, x_\epsilon) > u(x_\epsilon, x_\epsilon), \tag{23}$$

must hold. From (16),

$$u(0, x_\epsilon) = H(\theta_r r - r + 1)\theta(r, x_\epsilon)^{-\alpha} - F(1 - rx_\epsilon)^\gamma(1 - r)^\beta, \tag{24}$$

$$u(x_\epsilon, x_\epsilon) = H(\theta_r r(1 - x_\epsilon) - r + 1)\theta(r, x_\epsilon)^{-\alpha} - F(1 - rx_\epsilon)^\gamma(1 - r)^\beta \left(1 - x_\epsilon + \frac{x_\epsilon}{1 - r}\right). \tag{25}$$

Let the difference of (24) and (25) be denoted as,

$$\delta = u(0, x_\epsilon) - u(x_\epsilon, x_\epsilon), \tag{26}$$

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

All players being indiscriminate will be an ESS only if $\delta > 0$ for any small value of ϵ. Thus only if,

$$H\theta(r, x_\epsilon)^{-\alpha}\theta_r r x_\epsilon > F(1 - rx_\epsilon)^\gamma(1 - r)^\beta x_\epsilon \left(\frac{-r}{1 - r}\right). \tag{28}$$

11

The right-hand side of inequality (28) 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 [12], but is also a very robust and attractive equilibrium at the population level.

3.3   Mixed population of selective and indiscriminate poachers

Theorem 3. *Using the utility model described in section 2, a mixed stable population ($s = s^*$) never exists for $0 < r < 1$.*

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

$$u(1, s^*) = u(0, s^*). \tag{29}$$

From equation (16) the left-hand side is,

$$u(1, s^*) = H(1 - r)\theta(r, s^*)^{-\alpha} - F\frac{1}{(1 - r)}(1 - rs^*)^{\gamma}(1 - r)^{\beta} \tag{30}$$

and the right-hand side is

$$u(0, s^*) = H(\theta_r r + 1 - r)\theta(r, s^*)^{-\alpha} - F(1 - rs^*)^{\gamma}(1 - r)^{\beta}. \tag{31}$$

Substituting (30) and (31) into (29) gives

$$u(1, s^*) - u(0, s^*) = H\theta(r, s^*)^{-\alpha}(-\theta_r r) + F(1 - rs^*)^{\gamma}(1 - r)^{\beta}(\frac{r}{1 - r}) \tag{32}$$

$$= -r(H\theta_r\theta(r, s^*)^{-\alpha} + F(1 - rs^*)^{\gamma}(1 - r)^{\beta-1}) = 0. \tag{33}$$

Condition (33) can never hold for $0 < r < 1$ because both terms of the sum are positive. Thus a mixed stable

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186 equilibrium is never stable. □

187 In this section we have analytically studied the stability of all the possible equilibria. We have proven

188 the instability of any population with selective poachers, and the evolutionary stability of the indiscriminate

189 behaviour. All of these theoretic results have been verified empirically, and the data for this has been archived

190 at [9].

191 Theorems 1, 2, 3 are illustrated in Fig. 4 which shows the numerical solutions to (4) using (13) and (14)

192 with $x_1 = x$. This is done using numerical integration implemented in [6]. As evidenced from the scenarios

193 considered, all populations converge to being all indiscriminate.
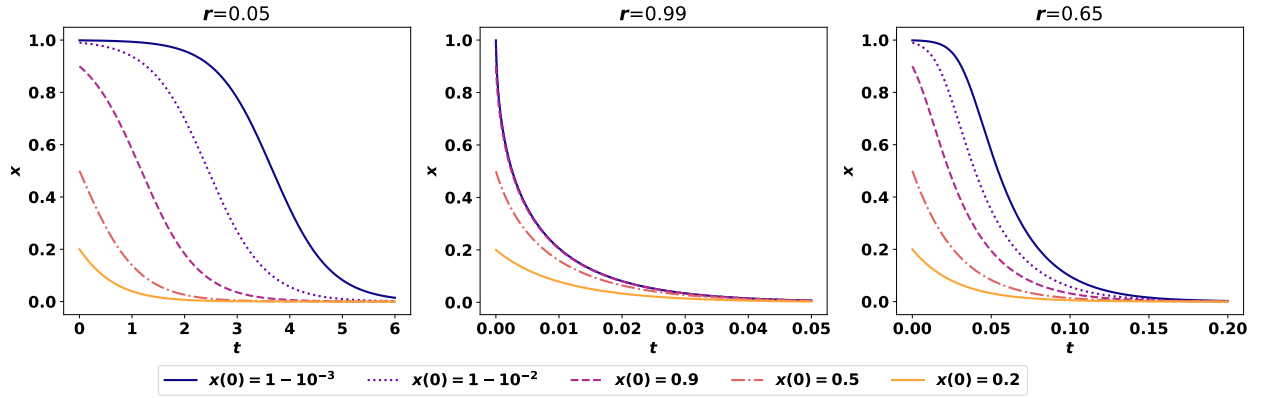
Figure 4: The change of the population over time with different starting populations. For $F = 5, H = 50, \alpha = 2, \beta = 2, \gamma = 1, \theta_r = 0.6$.

194 Note that these results essentially follow by comparing equations (13) and (14), which show that $u_1(x) \leq$

195 $u_2(x)$ for all x. Consider the reverse scenario,

$$u_1(x) > u_2(x) \tag{34}$$

$$F\psi(r,x)^\gamma(1-r)^{\beta-1} < -H\theta(r,x)^{-\alpha}\theta_r \tag{35}$$

196 which gives the required contradiction. This shows that the utility model used implies that given the choice

197 of acting selectively or indiscriminately, in any given environment, it will always be a rational deviation to

198 act indiscriminately.

199 In the following section a disincentive to acting indiscriminately will be introduced. This can be interpreted

200 in many ways:

13

- more severe punishment for indiscriminate killing of rhinos;

- educational interventions that highlight the negative aspects of indiscriminate killing;

- the possibility of a better alternative being offered to selective poachers.

4   Disincentive for indiscriminate behaviour

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

$$\tilde{u}_2(x) = u_2(x) - \Gamma \tag{36}$$

where $\Gamma > 0$ is some constant representing a disincentive only applied to indiscriminate poachers. This leads to the following modified form of (15):

$$\tilde{u}(s, x) = u(s, x) - (1 - s)\Gamma. \tag{37}$$

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:*

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

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

$$\tilde{u}(1,1) > \tilde{u}(0,1), \tag{39}$$

where

$$\tilde{u}(1,1) = H(1-r)^{1-\alpha} - F(1-r)^{\beta+\gamma-1}, \tag{40}$$

and

14

$$\tilde{u}(0,1) = H(\theta_r r + 1 - r)(1-r)^{-\alpha} - F(1-r)^{\beta+\gamma} - \Gamma. \tag{41}$$

²¹⁴ Setting (40) to be greater than (41) gives the condition,

$$\theta_r H - F(1-r)^{\gamma+\beta+\alpha-1} < \frac{\Gamma(1-r)^\alpha}{r}. \tag{42}$$

²¹⁵ □

²¹⁶ This immediately leads to the following important remark:

²¹⁷ **Theorem 5.** *Using the modified utility model described, if all rhinos have been dehorned a population of*
²¹⁸ *selective poachers is not stable.*

²¹⁹ *Proof.* All rhinos being dehorned implies that $r = 1$. Substituting this into (38) gives,

$$\theta_r H < 0, \tag{43}$$

²²⁰ which is not possible. □

²²¹   Theorem 5 is due to the fact that given two options, if all rhinos have been dehorned then all poachers
²²² will need to act indiscriminately to have any source of utility. Theorem 4 states that a mixed population
²²³ can be stable with a disincentive, as opposed to Theorem 3 which states that a mixed stable strategy does
²²⁴ not exist for $0 < r < 1$. This is illustrated in Fig. 5 where the evolutionary dynamics are represented for a
²²⁵ number of scenarios.

²²⁶   Note that now the manager has control over the point of convergence by controlling r, as shown in Fig. 6
²²⁷ where a difference in the value from $r = 0.7$ to $r = 0.5$ changes the point of convergence from a mixed to a
²²⁸ selective one. Moreover, the manager can also manipulate how fast the population convergences, as shown
²²⁹ in the difference from $r = 0.5$ to $r = 0.2$. Fig 7a shows the equilibrium for x for a number of different values
²³⁰ of r, and indicates that having a large r pushes poachers to behave indiscriminately. However all selective
²³¹ poachers can save at most, the r proportion of dehorned rhinos, so a low r is not ideal. As demonstrated
²³² in Fig 7b, a higher value of H also has a non-ideal effect on the poachers, as one would expect. Thus, high
²³³ values of H and r lead to more indiscriminate poachers.

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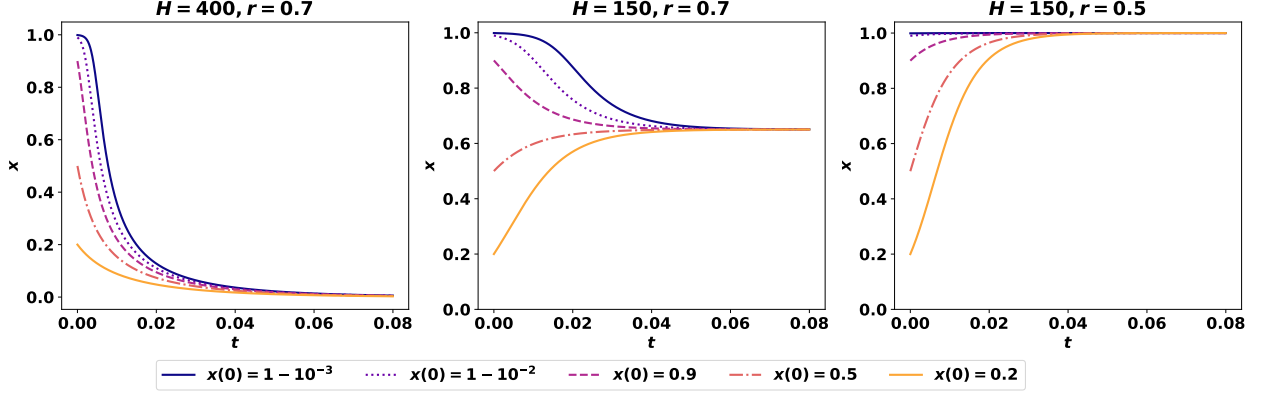234 The insights gained from the results are discussed in Section 5.

Figure 5: The change of the population over time with different starting populations with a disincentive. For $F = 50, \alpha = 2, \beta = 2, \gamma = 1, \theta_r = 0.5, \Gamma = 300$.
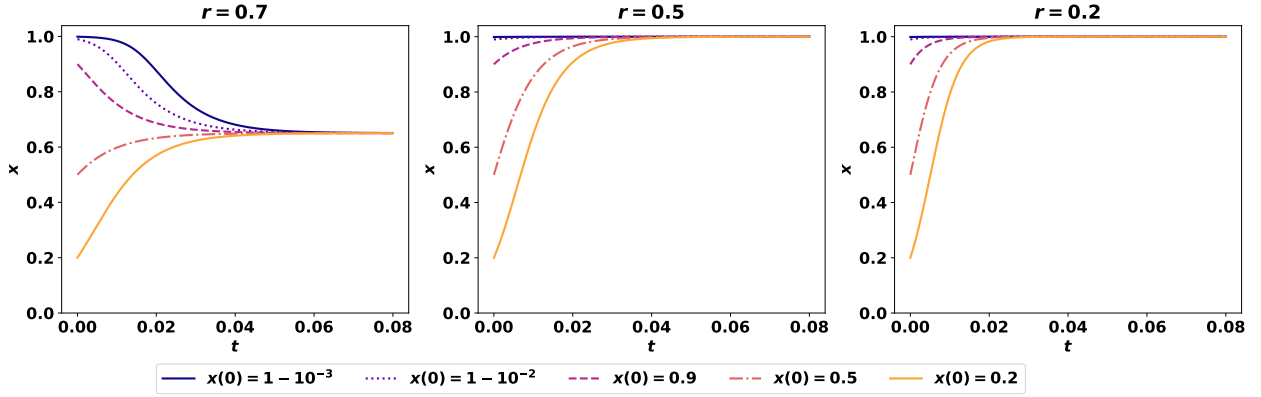

Figure 6: The change of the convergence point with different values of r with different starting populations with a disincentive. For $F = 50, H = 150, \alpha = 2, \beta = 2, \gamma = 1, \theta_r = 0.5, \Gamma = 300$.

5 Discussion and Conclusions

236 In this work the dynamics of a selective population were explored. It was proven that being selective is not
237 a best response even in a population where everyone is behaving selectively. More specifically, even a mixed
238 population with a small percentage of the population behaving selectively will not persist. Thus, a poacher
239 would never adopt a selective strategy over an indiscriminate one.
240   Using a realistic and generic utility model it was found that the only strategy that was proven to be stable

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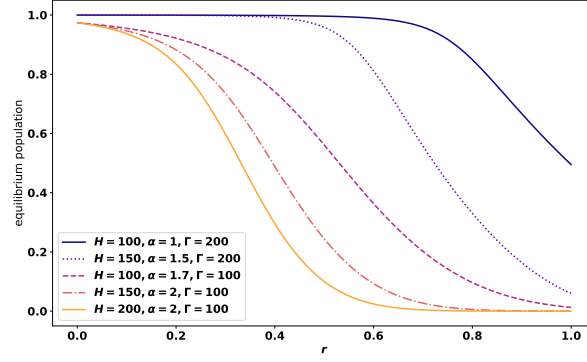
(a) Effect of r for $F = 50, \beta = 2, \gamma = 1, \theta_r = 0.6$.
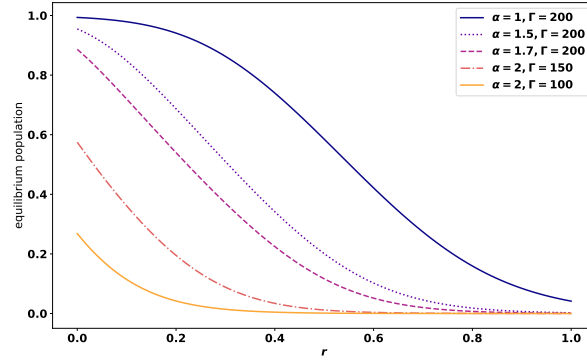
(b) Effect of H for $F = 50, r = 0.6, \beta = 2, \gamma = 1, \theta_r = 0.6$.

Figure 7: Equilibrium behaviour with a disincentive.

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, so approaches which aim to reduce demand (as suggested in [4]) would have more potential.

The disincentive factor can have several interpretations. According to [3], 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 disturb 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.

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.

Authors' contributions

All authors conceived the ideas and designed the methodology. NG and VK developed the source code needed for the numerical experiments and generating the data. All authors contributed critically to the drafts and gave final approval for publication.

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Data Accessibility

The data generated for this work have been archived and are available online [9].

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