

We open this response by thanking the reviewers for their thoughtful comments and suggested. In fact, we have fully taken their comments on board and made what we hope will be considered the major modifications.

The main modification has been to the utility model itself: upon reflection we have included another component of the poaching process to the utility model. By considering the time it takes to kill a rhino this ensures a heightened risk to indiscriminate poachers as they will kill all rhinos they see they will spend more time in the park at risk of being caught. This has an immediate effect of modifying the conclusions of our first submission: all strategies can be evolutionarily stable.

Given this major modification we will now respond to each comment/suggestion below:

1 Reviewer 1

Ln 58 pg 5, repeated "of"

We have made this suggested change.

Ln 20 40, pg 6, the variables talk about "proportion of horn gained" but I think a more general way to think of the variable is "proportion of value gained from the horn". For example, de-horning clearly leads to proportion of horn, but for other management interventions such as dye it may be a proportion of devaluing rather than quantity. Think it would be useful to say something like this model holds for any management action that proportionally devalues or removes a quantity of horn from the market, we will use the word "horn gained" because we are thinking about "dehorning" but the model is more general, or something to that effect.

This has been addressed by making the suggested substitution and including the opening comment but also ensuring that unless dehorning is specifically intended that the term devaluing is used.

Eqn 5, There are many mathematically valid choices for how to write this equation, including yours, but I think this way of expressing it is less clear than some alternatives. I think it would be clearer to write this equation in one of the following ways, $(1-r) + (1-x)(1-r + r \sigma_r)$ or $1 - r + r \sigma_r (1-x)$ to me your choice of expression obfuscates the meaning and creates an awkward nested parenthesis. Of the two expressions above, the first one starts from the point of view of the proportion of poachers, the alternative equation starts from the point of view of the rhino (i.e. whole horns are harvested from both types $(1-r)$ and $r \sigma_r (1-x)$ is the additional value harvested by the indiscriminate poachers. The second is the simplest expression in my opinion, but I can see reasons for why you might prefer the former one.

Thank you to the reviewer for pointing this out: we have made the suggested change.

>> Ln 55-56 pg 6, can you avoid introducing the variable capital x. Simply say as you basically do in the following line, that x uniquely determines the proportion of both types and therefore describes the state of the population of poachers. The added variable is unnecessary unless you are going to use it heavily later.

>> Similar to the capital X comment this sentence is also confusing. Just introduce s.

We have made this suggested change.

>> Eqn 6 is confusing as to how it should exactly be thought of and how it relates to supply and demand relationships. It is not clear how fig.2 shows how "fig 2 verifies that the gain curve corresponds to a demand curve". How exactly does it do this?

Eqn 6 attempts to capture that by devaluing raw rhino horn (increasing r) its scarcity in the market increases which in turn increases its 'price'. We have attempted to clarify this further in the text.

>> Eqn 9, this is a bit strange to me, why is this an exponent? Consider that each rhino dehorned caused a unit of money that could go to security, then dollars to security is directly proportional to $(1 - r)$ so why not a constant multiple? Presumably if $\beta < 1$ this could denote a diminishing return on police efficacy

>> Eqn 8, I do not understand this equation. What is this the cost of? Searching for rhinos? Presumably this could be measured in the amount of time it took to find a rhino comparatively if you were passing on rhinos that have been devalued. If we were assuming poachers encountered rhinos randomly via laws of mass action for every time unit it took for indiscriminate poachers to find a rhino it would take $1/(1-r)$ units of time for an indiscriminate poacher to find a rhino that hasn't been devalued. Is this how equation 8 is being calculated? If so I do not follow the derivation. I'm also concerned with double counting. Your benefit function includes the added benefit from poaching rhinos indiscriminately by getting more rhinos. Please walk the reader through this equation. Is it search cost? Is this the same cost for an individual of both strategies? I'm not really sure what you are assuming here.

>> Eqn 11, Handling time of killing and processing a rhinos and the increased risk of being caught due to killing more rhinos (dehorned rhinos) do not appear to be factored into the model. As a result I question whether the main result is an artefact of this model set-up. I'm not sure I follow how an discriminant poacher gets any benefit from their actions in this model (with the exception of H). I don't think supply and demand is the main reason managers argue for this strategy, so the effect of H is less important to explore than handling time and risk to poachers, in my opinion. From a game theoretic sense, unless I am missing something, it is obvious that increases in H with r wouldn't affect the stable strategies because all individuals are affected by the price of the value of horn equally. So only through risk of exposure and added costs through handling time of killing less valuable rhinos can one argue for dehorning, which this paper doesn't explore.

>> Eqn 11 confuses me as I thought time would be the unit of cost of searching for rhinos, as can be seen from my comment above I thought something like these equations would be the costs. Basically I was expecting equation 11 to be the costs. It seems like we have similar thoughts. Ψ actually seems to just be proportional to the number of rhinos being poached, but you call it the cost, which is confusing to me. Am I missing something here?

We have reflected on these raised points extensively and have explicitly addressed them. Indeed, as was, the model did not account for the time related to killing and processing rhinos which in the case of the indiscriminate poachers would correlate with an augmented risk.

This has now been modelled using a stochastic walk, this has been explained in the text and a diagram has also been included.

The reviewer was completely correct in their insight about the conclusions and a new theoretic result has been obtained that describes the conditions for which devaluation will lead to selective poachers.

We thank the reviewer for very helpfully pointing this out and feel that this has greatly improved the paper including the conclusions that detail the factors that influence selective behaviour.

>> When introducing H I think you need a reference for its choice. Below are some modelling papers where supply and demand affecting poaching

- [Economics of Antipoaching Enforcement and the Ivory Trade Ban](https://www.jstor.org/stable/1244594?seq=1#page_scan_tab_contents) - [Protecting the African elephant: A dynamic bioeconomic model of ivory trade](http://www.unece.lsu.edu/responsible_trade/documents/2008/rt08_33.pdf)

>> There are many papers modelling poaching in the rhino trade system. You might want to consider going through them a bit more systematically and describing how your work sits within the broader rhino horn modelling literature (possibly in the discussion). Here are some examples (but there are many more) to seed your search

- [Debunking the myth that a legal trade will solve the rhino horn crisis: A system dynamics model for market demand](<http://www.saeon.ac.za/enewsletter/archives/2015/october2015/images/0300.pdf>)
- [Identification of policies for a sustainable legal trade in rhinoceros horn based on population projection and socioeconomic models.](<https://www.ncbi.nlm.nih.gov/pubmed/25331485>) - [Trading on extinction: An open-access deterrence model for the South African abalone fishery](http://www.scielo.org.za/scielo.php?script=sci_arttext&pid=S0038-23532016000200019)
- [How many to dehorn? A model for decision-making by rhino managers](<https://www.cambridge.org/core/journals/animal-conservation-forum/article/how-many-to-dehorn>)

>> It would be good to cite the anthropogenic Allee effect in either line 42 of the intro or in the discussion as this is one of the main hypothesised drivers in the mathematical modelling literature on what causes rhino horn to be so valuable. The theory is mathematically described in

- [High prices for rare species can drive large populations extinct: the anthropogenic Allee effect revisited.](<https://www.ncbi.nlm.nih.gov/pubmed/28669883>)

>> and first biologically hypothesized here

- [Rarity Value and Species Extinction: The Anthropogenic Allee Effect](<http://journals.plos.org/plosbiology/article?id=10.1371/journal.pbio.0040415>)

>> Ln 20 43 pg 3. The issue of opportunistic exploitation is highly

relevant to the game you present. In fact I think it may be the logic behind a lot of what's driving your results. It's not exactly the same because the authors think of opportunistic exploitation as a multi-species problem, but it is very similar because you could think of dehorned and horned rhino as two species. The basic idea is that while hunting for one type you will kill the other if it's there and easy to kill without much added cost. Ln 20 -43 seems like a natural place to talk about this, but it could be talked about later in the discussion

- [Opportunistic exploitation: an overlooked pathway to extinction](<https://www.sciencedirect.com/science/article/pii/S0169534713000712>)

We thank the reviewer for their extensive recommendations, which have been referenced in the introduction and discussion as suggested. The only suggested article that was not included is "Debunking the myth that a legal trade will solve the rhino horn crisis: A system dynamics model for market demand". In addition to the recommended papers, we have added reference to:

1. Lawson, K., & Vines, A. (2014). Global impacts of the illegal wildlife trade: The costs of crime, insecurity and institutional erosion. Chatham house.
2. Crookes, D. J., & Blignaut, J. N. (2016). A categorisation and evaluation of rhino management policies. Development Southern Africa, 33(4), 459-469.
3. Gao, Y., Stoner, K. J., Lee, A. T., & Clark, S. G. (2016). Rhino horn trade in China: An analysis of the art and antiques market. Biological Conservation, 201, 343-347.

>>> Ln 46, pg 3, space after period

We have made this suggested change.

>>> Ln 42 pg 3 of intro, it doesn't make sense to talk about quadrants without a figure to refer to with quadrants in it, or to say the poachers win (win at what).

We have included Figure 1 to refer to with quadrants in it.

>>> Eqn 1 these are also often called replicator equations in the evolutionary dynamics literature

We now address the equations as replicator equations and we included the relevant reference.

>>> Lines 36 38, not really. This is only true if parks are very small and there is relatively small amounts of travel time to get between the parks. Perhaps use the hedging phrase 'may also provide insights at the macroeconomic level.' I also think a discussion of travel time might be warranted here and what assumptions must be made for this model to hold in the macroeconomic case.

We have used a hedging phrase suggesting that it could be of macroeconomic interest but highlighted the non negligible effect of travel time.

\section{Reviewer 2}

\begin{verbatim}

>> I think the most problematic assumption is that rhino population dynamics is assumed to be stable through time. Obviously, this won't be the case and

that could change everything because the increasing rarity of rhino could increase the price of horn, devalued or not, and therefore the relationship between costs and benefits that would be challenging to predict. I think addressing this question could definitely increase dramatically the novelty of this study, which will be beneficial from an ecological and a modelling point of views.

Whilst the rhino population dynamics are not modelled explicitly we agree this would be an interesting avenue to consider, we have included this in the discussion. However, we feel that for the purpose of analysis considered at this stage assuming the dynamics of the rhino population and thus the cost/benefit to the poachers is sufficiently captured by the supply/demand model. Whilst not considered specifically the rarity of rhino is considered by the $(1 - r)$ term and the behaviour of the poachers. This can also be seen in some of the new scenarios that have been included.

>> The authors have also identified some situations where selective strategy could be more beneficial than indiscriminate. I think it could be interesting to look at the literature in which kind of situations we really are, and if these conditions found theoretically can be really encountered on the field.

Establishing the real life process of poacher behaviour in a comparable manner to the model is not possible. However, the model aims to not replicate reality exactly, but to show insight into the feasibility of the game of devaluing rhino horns, and what factors have more influence. For example, our model shows that disincentive factors when used with the correct level of devaluation, can nudge the poacher to behave selectively, in fact more so than supply and demand variation. Examples of disincentive factors, with references, are now mentioned in the second and third paragraph of the discussion, for example, monetary fines.

>> Regarding the length of the paper, I am not 100% sure that the analysis for situations where everyone has selective or indiscriminate strategy really brings something. This highlights that this study is maybe not deep enough, because classically, these analyses would be moved in supplementary materials. I understand the point of showing the difference with mixed strategies, which won't be stable, but I still think these analyses on pure strategies are not very insightful.

Thank you for this comment which encouraged us to reflect on the length of the paper, as a result we have modified the model to only consider a disincentive (when set to 0 this corresponds to the previous model) and furthermore only a single theoretic result is presented. This specifically offers insight regarding the conditions required for selective poachers to subsist.

>> Finally, from a presentation point of view, I think that figure 1 is not needed

We have removed this figure.

>> Figure 2 and 3 could be merged.

>> Legends and axes names need to be improved to make the figures readable without going back to the text.

Figure 3 has been replaced with another Figure relevant to the new model and the axes and legends are now hopefully clear.

>> I think that a summary figure of the selected strategies (without disincentive) could be also an interesting addition.

We have included a figure that describes the strategies as requested.