AMSI HIGHER ED

Rhino Relocation Strategies for Rhino Survival

Dimitrio Sidi
Supervisor: Professor Neville Fowkes
University of Western Australia

Australian Government
Department of Education and Training

February 25, 2016

Abstract

Due to aggressive poaching (for their horns) the population levels of the black rhinoceros in South Africa have been reduced to a dangerously low level, whereby survival in the wild seems unlikely. Almost all of such species in the wild are located in Hluhluwe-iMfolozi National Park and even there the numbers are declining rapidly with the number of animals poached in the last year increasing 20% compared to the previous year. One possible strategy in order to increase the population levels of the black rhinoceros is to relocate the animal from Hluhluwe-iMfolozi to other areas such as Kruger and Pilanesberg National Parks. Evidently one needs to determine an effective strategy to do this: how many animals should be relocated per year and to which location? We use simple mathematical models to investigate an optimal strategy. The aim of the project is not to produce mathematical simulations as an end product (although such simulations will provide insight and verification) but to produce a simple practical and robust operational procedure for steering the process.

Acknowledgements

I would like to thank Professor Neville Fowkes for his guidance in setting up the initial problem and helping set the direction for this paper as well as Professor Michael Small for his help in finalising the paper.

1 Introduction

Whilst the black rhino population in South Africa stood at about 65,000 rhinos in 1970, that number has dwindled to about 2000 currently living rhinos. This 98% reduction is largely attributed to the poaching of the black rhino for their prized horns and has led to many efforts in finding a way to reduce the impact that poaching has had. Whilst in some instances such as in Kunene, the relative population density increased markedly between 1992 and 2005 once illegal poaching had been stopped (Brodie et al., 2010), in many key and important black rhino populations in South Africa, the minimum growth targets for the animal have not been met (Emslie, 2001). In order to better facilitate population growth, the management of subpopulations is required to ensure that maximum productivity and growth in all subpopulations are met (Hrabar & du Toit, 2005).

In this paper, we will focus on relocation strategies as a means of increasing the total population of the black rhino as efficiently as possible. We start in Section 2 by presenting relevant information concerning rhino biology. In Section 3 we use a simple continuum population dynamics relocation model to examine the effect of relocation from a major donor source (Hluhluwe-iMfolozi) to two other receiver locations before looking at a theoretically ideal relocation scheme in Section 4. In Section 5 we then propose a simple relocation strategy based on practical and economic considerations before summarising and making final recommendations in Section 6.

2 The life of a rhino

The black rhinoceros has a life expectancy of about 35 to 50 years out in the wilderness. The adults are usually solitary in nature, having a certain area that they tend to use as a resting place and living in what can be described as a home range. Depending on the productivity of the environment, these home ranges vary from 2.6 km^2 to 133 km^2. Whilst the black rhino is not territorial, they are known for being extremely aggressive with 50% of males and 30% of females dying from combat-related injuries (Berger & Cunningham, 1998). This combined with poaching contributes to the overall death rate of the rhinoceros that we have to consider later.

For the black rhino, the mother and calf generally stay together for about 2-3 years until the mother is ready to give birth to another calf and gives us our approximate time scales. The female rhino reaches sexual maturity at about 5 to 7 years of age whereas males reach their sexual maturity at about 7 to 8 years of age.

3 A Simple Deterministic Relocation Model

3.1 Model Equations

Let the population levels in locations $i = 1, 2 \cdots \mathcal{L}$ be $N_i(t)$ with carrying capacities K_i and net population growth rates r_i. Animals are transferred from one location i to another j at a rate of h_{ij}; $h_{ij} > 0$ if location i is the donor population and j the receiver. We simplify the situation by considering the case where we have large enough populations such that we can use a continuum approach in order to describe the population growth of the system. A logistic model is used so that the relevant equations are:

$$\frac{dN_i}{dt} = r_i N_i (1 - \frac{N_i}{K_i}) - \sum_{j=1}^{\mathcal{L}} h_{ij}, \text{ for } \ i = 1 \cdots \mathcal{L}; \tag{1}$$

evidently $h_{ii} = 0$, and r_i is the net population growth rate for a location (births, deaths due to natural causes and poaching included). Since animals are simply transferred from one location to another (not removed entirely from the stock of animals) we have

$$\sum_i \sum_j h_{ij} = 0, \tag{2}$$

which immediately implies, using (1) that the total population growth rate is given by

$$\frac{dN^{tot}}{dt} = \sum_i \left[r_i N_i (1 - \frac{N_i}{K_i}) \right] = \mathcal{F}(N_i). \tag{3}$$

Initially the population levels are prescribed and the aim is either to increase the total population growth rate at each time or to increase the total population numbers over a prescribed time period T by appropriately choosing the relocation rates h_{ij}.

In order to understand the critical issues we will highlight a simpler example in which we have just one donor location ($i = 1$) and two receiver locations ($i = 2, 3$). In the South African context we will identify $i = 1$ with Hluhluwe-iMfolozi, and the two receiving locations $i = 2, 3$ as Kruger and Pilanesberg National Parks. Also to further focus the study we will examine the case in which the total number or animals donated by the supplier location $i = 1$ is fixed (perhaps determined by external considerations such as available resources for transportation) at the value h. Thus if $\alpha(t)$ is the proportion of animals going to location $i = 2$, then we have

$$h_{12} = \alpha(t)h, \ h_{13} = (1 - \alpha(t)))h, \tag{4}$$

and the issue is how one should choose the proportion of animals relocated from location 1 to location 2 (i.e. $\alpha(t)$) so as to maximise the total population growth rate either at each instance of time or over a prescribed time interval.

3.2 Nondimensionalisation

Using the location $i = 1$ as a datum with the time scale corresponding to this population we have:

$$N_i = K_1 N_i', \; r_i = r_1 r_i', t = t_0 t' \text{ where } t_0 = 1/r_1 \tag{5}$$

where the scaled parameters (r_i', K_i') determine the relative viability of the locations for rhino reproduction. Note that we've chosen to scale the numbers of animals according to the carrying capacity of the donor population $i = 1$, and have chosen the time scale corresponding to this same donor location. The equations become:

$$\begin{aligned}
\dot{N}_1' &= r_1' N_1'(1 - N_1'/\mathcal{K}_1) - (h_{12}' + h_{13}') \\
\dot{N}_2' &= r_2' N_2'(1 - N_2'/\mathcal{K}_2) + h_{12}' \\
\dot{N}_3' &= r_3' N_3'(1 - N_3'/\mathcal{K}_3) + h_{13}'
\end{aligned}$$

with $r_1' = 1$ and $\mathcal{K}_1 = 1$. The important dimensionless groups are

$$\mathcal{K}_2 = \frac{K_2}{K_1}, \; \mathcal{K}_3 = \frac{K_3}{K_1}, \mathcal{R}_2 = \frac{r_2}{r_1}, \mathcal{R}_3 = \frac{r_3}{r_1}, \tag{6}$$

and we will drop primes in the work to follow.

4 A theoretically ideal relocation scheme

One can see from the result (3) that a (mathematical) optimum total population growth rate at each instance of time would be realised by relocating animals according to a population growth rate maximisation scheme:

$$\max(\sum_i \left[r_i N_i (1 - \frac{N_i}{\mathcal{K}_i}) \right]) \text{ with } \sum N_i = N^{tot}(t) \text{ prescribed.} \tag{7}$$

With such a scheme at each interval of time the animals $N^{tot}(t)$ are redistributed between locations so as to ensure the largest possible population growth rate.

The above maximum growth rate optimisation problem (7) is best solved by introducing a Lagrange multiplier λ and is given as

$$\max_{(N_i,\lambda)} \left[\sum_i \left(r_i N_i (1 - \frac{N_i}{\mathcal{K}_i}) \right) - \lambda (\sum_i N_i - N^{tot}(t)) \right].$$

The solution is given by

$$\lambda = \frac{\sum \mathcal{K}_i - 2N^{tot}(t)}{\sum \frac{\mathcal{K}_i}{r_i}} \text{ with } N_i = \frac{\mathcal{K}_i}{2r_i}(r_i - \lambda), \tag{8}$$

and the maximum possible overall population growth rate can thus be determined corresponding to any prescribed $N^{tot}(t)$, see Figure 1 left. Assuming this optimal scheme is adopted one can

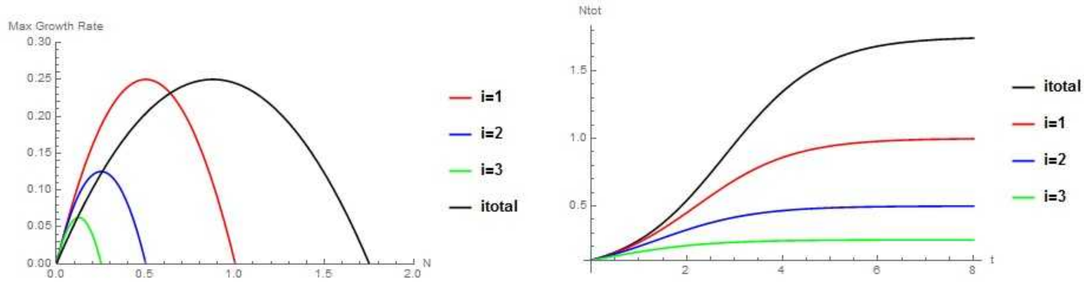

Figure 1: The theoretical maximum possible population growth rate obtained by re-location. We have 3 locations with different capacities. The black curve corresponds to the total population over all three locations. The other locations' populations are also displayed and the variables were set at $\mathcal{K}_1 = 1, \mathcal{K}_2 = 0.5, \mathcal{K}_3 = 0.25, r_1 = 1, r_2 = 1, r_3 = 1$. *Left* Growth rate as a function of N^{tot}. *Right* $N^{tot}(t)$ over time.

substitute for N_i in terms of $N^{tot}(t)$ into the N^{tot} equation (3) to obtain an ordinary differential equation for the best possible total population pattern of growth. This result is shown in Figure 1.

There are several key features to note as we move forward. Firstly we note that the population growth is at a maximum when the population state is at half the carrying capacity in all locations. In other words

$$\left[\frac{dN^{tot}}{dt}\right]_{max} = \sum_i [r_i K_i/2] \text{ with } N_i = \frac{K_i}{2}. \tag{9}$$

This is to be expected from a logistic growth model and gives us a goal in terms of how to maximise the overall rhino population growth. Secondly, it is clear that if two locations have different carrying capacities (and in fact, also if they have different net growth rates), relocating to one location may increase the overall growth rate much more significantly than relocating to the other. We will carry these two pieces of understanding forward as we attempt to produce a more practical relocation process.

We now develop a relocation regime whereby we aim to get all three locations to the ideal population of half their carrying capacity. At every iteration, we want to relocate animals such that we are maximising the increase we get in the overall growth rate. Suppose then that we have a donation rate of h per year and that we are free to move these h rhinos in any way we like across the two locations i=2,i=3. The maximum increase in the population growth rate can be achieved by proceeding along a path given by $\nabla\mathcal{F}$ in N_i space from the initial starting point N_i^0. If the total donation rate is fixed at h then the required h_{ij}'s are given by $h\nabla\mathcal{F}/|\nabla\mathcal{F}|$ at any time. Now if the initial values are given by $(N_2^0,\ N_3^0)$ then this results determines the path in the $N_2 - N_3$ plane that achieves the maximum population growth rate from this initial starting point. This strategy can be extended to larger values of i.

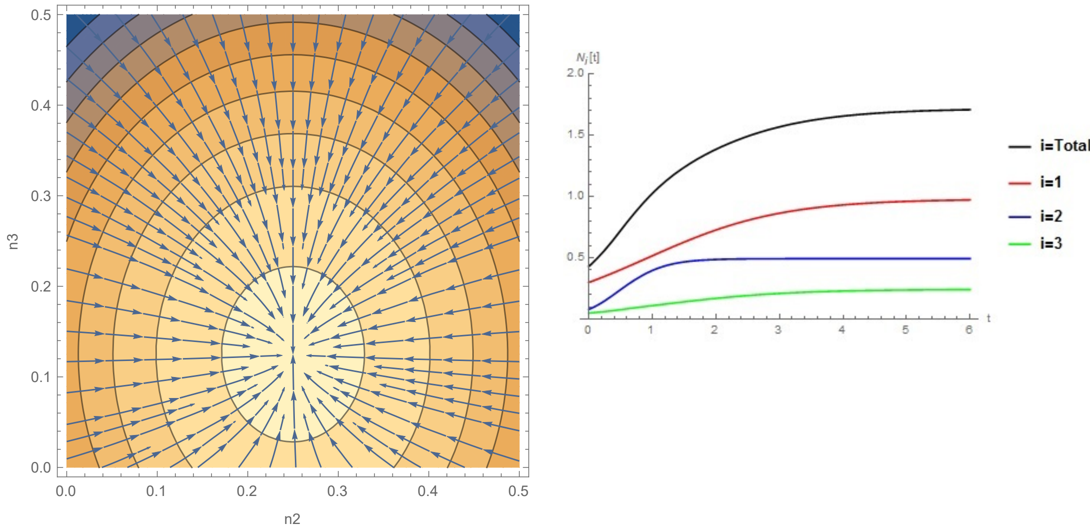

Figure 2: *Left* The vector field $\nabla\mathcal{F}$ in $N_2 - N_3$ space giving the ideal relocation paths in order to maximise population growth at each iteration of relocation. $Right N_i(t)$ over time under the relocation regime. The graphs were created using the following values $\mathcal{K}_1 = 1, \mathcal{K}_2 = 0.5, \mathcal{K}_3 = 0.25, r_1 = 1, r_2 = 3, r_3 = 1, n_1(0) = 0.3, n_2(0) = 0.08, n_3(0) = 0.05$.

5 Practical and Economic Considerations of the Relocation Strategy

The above optimal solutions are based on easy relocation assumptions. There are costs associated with relocation which have not been taken into account yet. The first of these that we will consider is an economic cost; for example it may not be feasible or economically possible to transport animals to several locations in relatively small numbers as would be required if the above optimal solutions were adopted. Under such a limitation we will determine the best possible solution in the case in which animals are relocated from one population to just one single location at each time interval; thus $h_{1j} = 0$ for $j \neq k$ and $h_{ik} = h$. In this case the optimal solution will zig-zag towards the global optimal solution prescribed earlier (9). As such we have a relocation regime such that:

- the various population levels approach the maximum reproduction rate values given by half the carrying capacity over time.
- animals are transferred to the most productive area first.

Such a regime is graphically displayed in Figure 3. As such, we now have a relocation regime that is dependent on the current population levels at each location, the relative carrying capacities and net population growth rates at each location. Note that one limitation of this revised relocation regime is that within a distance of order h of the optimal solution, we will produce an oscillation about the optimal solution. The start of this can be seen by the arrows in Figure 3. As such when

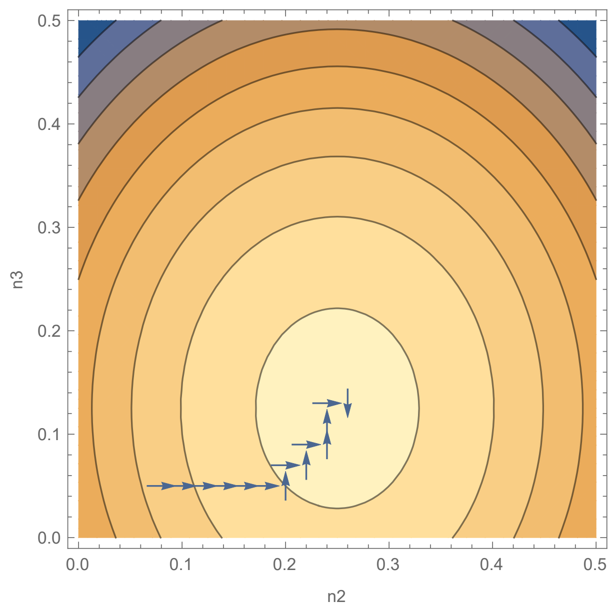

Figure 3: A relocation regime beginning at (0.08,0.05) in $N_2 - N_3$ space where the arrows represent where we should relocate to at any given iteration in order to maximise the population growth

we get to within h of the optimal solution, we will have to relocate the exact number of animals to get us to the optimal solution in order to avoid such oscillations.

At this stage, it is worth noting that whilst the current population at any time can be easily measured, the carrying capacity and net population growth rate within a location is not only harder to quantify but can change over time depending on factors such as rainfall, soil fertility and browse availability (Hrabar & du Toit, 2005). As such, it is important to make observations on just how these two variables affect the characteristics of our relocation regime.

In order to make such observations, we look at several cases where we vary the carrying capacity and net population growth rate of the two locations such that we have the case where we have:

Case 1: two similar receiver locations.

Case 2: a significantly different carrying capacity, $\mathcal{K}$.

Case 3: a significantly different net population growth rate, r.

Case 4: different carrying capacities and different net population growth rates in the two locations.

Looking at Figure 4 in case 3, if the net population growth is clearly higher in one location, for example i=2, than the other, the relocation regime will be such that in a majority of cases, we would be looking at relocating rhinos to location 2 until that location almost reaches half its carrying capacity before relocating rhinos to the other location. When we look at Case 2, we see that the optimal growth point occurs at a different coordinate to Case 1 because of the different values for the carrying capacities. However in terms of optimal relocation strategies and determining where

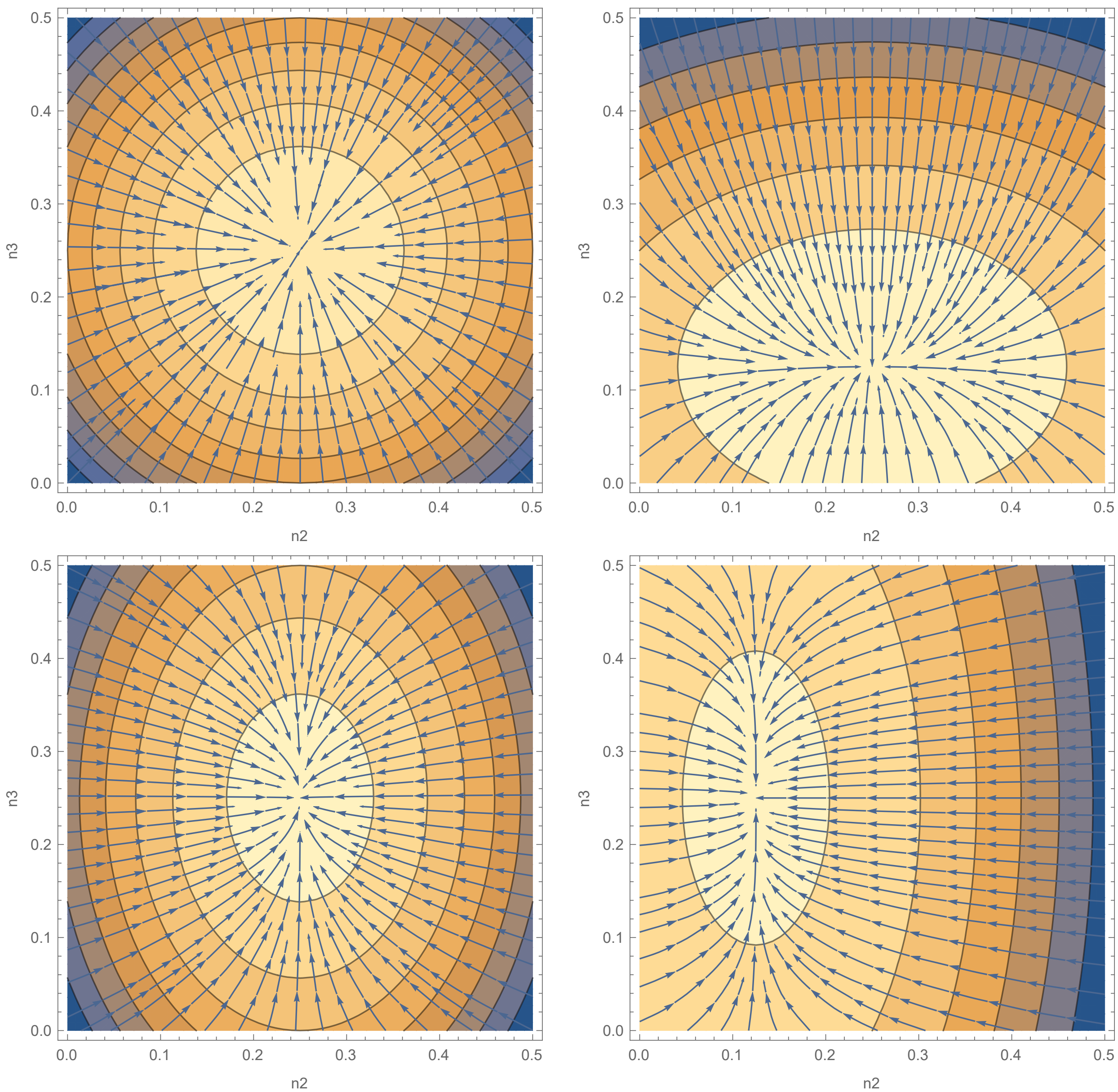

Figure 4: Plots in $N_2 - N_3$ space of the different cases along with vector plots of $\nabla\mathcal{F}$ in order to display the characteristics of the relocation regime. *Top Left* Case 1 where $\mathcal{K}_1 = 1, \mathcal{K}_2 = 0.5, \mathcal{K}_3 = 0.5, r_1 = 1, r_2 = 1, r_3 = 1$. *Top Right* Case 2 where $\mathcal{K}_1 = 1, \mathcal{K}_2 = 0.5, \mathcal{K}_3 = 0.25, r_2 = 1, r_1 = 1, r_3 = 1$. *Bottom Left* Case 3 where $\mathcal{K}_1 = 1, \mathcal{K}_2 = 0.5, \mathcal{K}_3 = 0.5, r_1 = 1, r_2 = 2, r_3 = 1$. *Bottom Right* Case 4 where $\mathcal{K}_1 = 1, \mathcal{K}_2 = 0.25, \mathcal{K}_3 = 0.5, r_1 = 1, r_2 = 2, r_3 = 1$.

we should allocate animals, the carrying capacity does not appear to affect the relocation regime as much as the location's net population growth does. This is more obvious when we compare Case 3 and Case 4. Whilst the ideal population state is achieved at (0.25,0.25) for Case 3 and (0.125,0.25) for Case 4, the general characteristics and shape of the vector plots of $\nabla\mathcal{F}$ are essentially the same. We can then make the following conclusions from this:

1. the carrying capacity determines the ideal population state that we want to reach.

2. the net population growth rate at each location determines where we should predominantly relocate animals to first (if we start with low populations relative to the carrying capacity in all receiver locations).

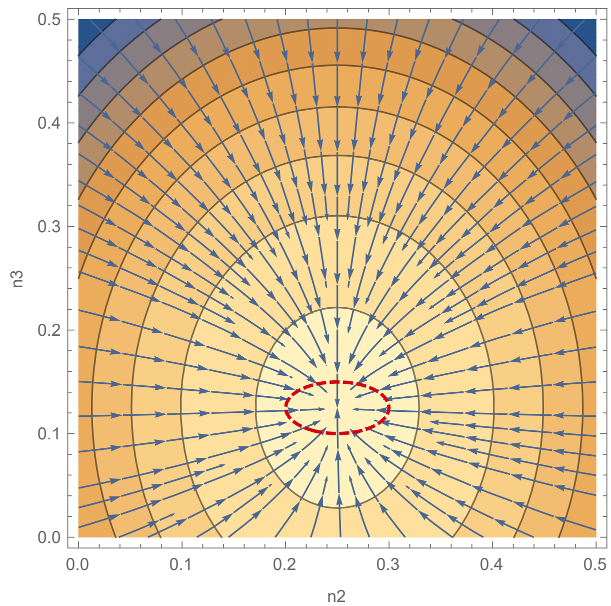

Figure 5: The elliptically shaped dotted line represents an uncertainty in the carrying capacity of the receiver locations and an uncertainty in our target population state. The demonstrated figure uses an uncertainty of 10%

When we consider applying our relocation regime to the real world, as mentioned before, there is a degree of difficulty in placing a value on the carrying capacity and net population growth rate for a particular location. These are variables that can change over time and therefore a degree of uncertainty needs to be taken into account when we look to use any values for these variables. With the aid of the basic conclusions that we reach above, we can better understand what the effect of having uncertainties in our values is. Uncertainty in the carrying capacities of our receiver locations means that we would create an ellipse of ideal population states that we would aim for as opposed to just one particular point. This is illustrated in Figure 5. As discussed before, the carrying capacity does not affect the directions of our vector plots significantly (rather it is the net population growth rate that does so). As such, far away from the target ellipse, our relocation principles would not change drastically when uncertainty in the carrying capacity is introduced. It is only within and very close to this target ellipse that we can expect some difficulty determining a relocation strategy. On the other hand, the effect of having uncertainties in the net population growth rate is minimal for our zig-zag regime for cases far away from our tagret population state as long as we can identify which location has a higher growth rate relative to the other. In cases where there is no obvious choice in which location has a higher growth rate, or we near the target population state, we would then consider how close the current population state is to half the carrying capacities of their respective locations and decide based on that.

Another important practical consideration is what is called the Allee effect. If the population density is low enough, through mechanisms such as mate shortage, a small population may fail to have a positive growth rate and as such its population would decrease over time until they reach extinction (Courchamp et.al, 2006). This is something we need to be wary of when relocating animals between parks. The population density for any one subpopulation needs to be above some minimum threshold to avoid the Allee affect, called Allee's number (Mponda 2013). The evidence on the prominence of the Allee effect for black rhino populations has not been conclusive (Hrabar & du Toit, 2005) and further work needs to be done on finding Allee's number for the black rhino. As such we display plots in Figure 6 to illustrate what this may mean for our relocation model only as a guide. Mathematically, we can represent the Allee effect by modifying the governing logistic equation (1) to

$$\frac{dN_i}{dt} = r_i N_i (1 - \frac{N_i}{K_i})(\frac{N_i}{\mu_i} - 1) - \sum_{j=1}^{\mathcal{L}} h_{ij}, \text{ for } \quad i = 1 \cdots \mathcal{L}; \tag{10}$$

where μ refers to the Allee number. This would modify equation (3) to

$$\frac{dN^{tot}}{dt} = \sum_i \left[r_i N_i (1 - \frac{N_i}{K_i})(\frac{N_i}{\mu_i} - 1) \right] = \mathcal{F}(N_i). \tag{11}$$

When comparing Figure 2 and figure 6 the location of the point with the maximum growth rate has shifted (no longer being exactly half the carrying capacity), but the characteristics of the vector field are quite similar. The general principles and conclusions we reached before remain the same but now we have the added intricacy of needing the population at any location to be at least above some particular value. This is perhaps most relevant in the early stages of relocation where we may need to invest in relocating a larger number of animals.

A biological cost that we also need to consider is the ability of the black rhino to adjust to being relocated. This would effect our system in two ways: firstly animals from the donor location needs to adjust to having its population harvested; secondly animals that are relocated need to adjust to their new surroundings. On the first note, it has been noted that rhinos appear slow in recolonising a harvested area especially between rhinos of the same-sex. For example if a number of females were removed from one area within a park, it takes some time for females from a neighbouring area to repopulate the harvested area (Linklater & Hutcheson, 2009). This means that harvesting would affect the efficiency with which the resources within the park are being used and is especially an issue when the donor park starts reaching its carrying capacity. This creates a pseudo-carrying capacity for a period of time until the remaining rhinos in a park are able to repopulate the harvested area, thereby affecting the population dynamics. On the second note, it is expected that relocated animals may not adapt to their new environment straight away and that there may be a time delay before these animals contribute to the population dynamics of their new environment. This time delay factor is something we could add to the governing equations for our receiver locations.

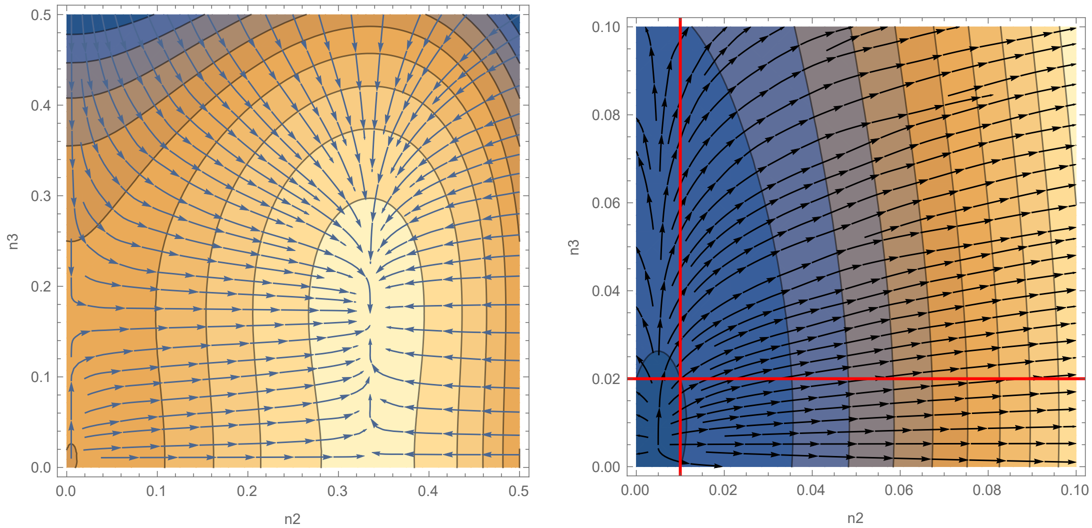

Figure 6: Plots in $N_2 - N_3$ space of the case in Figure 2 with an Allee effect included where we set $\mu_2 = 0.01$ and $\mu_3 = 0.02$. The red line indicates these Allee numbers and values below these create a forbidden zone for our relocation model. *Left* Scale is equal to that in Figure 2. *Right* A closer look at the forbidden boundary values.

6 Recommendations for Relocation and Future Work

In summary, we can create a fairly effective relocation scheme for a system with one major donor source and multiple receiver sources through the following principles:

1. the ideal situation is to have all locations be at half their carrying capacity or thereabouts.

2. relocate animals from the donor source to the location that will increase the overall population growth rate the most.

3. ensure that at any time, no location has less animals than the required Allee number.

We also noted in Section 5 that in cases where we are unable to accurately determine the carrying capacity or net population growth rate of an area, there are some basic guidelines that we can use in order to carry out our relocation regime. These guidelines were that:

1. uncertainties in the carrying capacity of our receiver locations create an ellipse of population states that we aim for.

2. the effect of uncertainties in the net population growth rate of our receiver locations can be minimised through a combination of working out which location has the higher growth rate and which population if further from half its carrying capacity.

Whilst we have discussed a lot of different practical considerations in Section 5, further understanding can be drawn by producing some simulations of the above relocation regime with real data from the conservation parks in South Africa. Scope for further work also exists in taking a closer look at the population dynamics of our donor location under harvesting. Such work includes looking at getting a better understanding of the age group demographics that need to exist within a park's population in order for it to be sustainable and how such demographics are affected by harvesting. Another aspect of harvesting that can be looked at is comparing the effectiveness of our relocation regime if the number of animals harvested from the donor source is non-constant as has been suggested in other works (Emslie, 2001). As it stands however, the above relocation strategy appears to have solid mathematical grounding whilst also being practical when considering the situation in South Africa.

References

[1] Brodie, J et al. 2010, 'Population recovery of black rhinoceros in north-west Namibia following poaching', Animal Conservation, no. 14, pp. 354-362

[2] Emslie, R 2001, 'Workshop on biological management of black rhino', Pachyderm, no. 31, pp. 83-84

[3] Hrabar, H & du Toit, J 2005, 'Dynamics of a protected black rhino (Diceros bicornis) population: Pilanesberg National Park, South Africa', Animal Conservation, no. 8, pp. 259-267

[4] Berger, J & Cunningham, C 1998, 'Natural Variation in Horn Size and Social Dominance and Their Importance to the Conservation of Black Rhinoceros', Conservation Biology , Vol. 12, No. 3, pp. 708-711

[5] Courchamp, F et al. 2006, 'Rarity Value and Species Extinction: The Anthropogenic Allee Effect', PLoS Biol, Vol. 4, No. 12, pp. 2405-2410

[6] Mponda, F 2013, 'Management of rhino removals to maximise the reproductive potential of the rhino population', Mathematics in Industry 2013 Report

[7] Linklater, W & Hutcheson, I 2010, 'Black rhinoceros are slow to colonize a harvested neighbours range', South African Journal of Wildlife Research, Vol. 40, No. 1, pp. 58-63