# An Optimization Approach for Minimizing Extinction Risk of Endangered Species through Captive Breeding

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**Abstract:** To use captive breeding most effectively as a tool to manage endangered species we need to optimize decisions such as when to capture wild animals or release zoo-bred individuals into the wild. There has been an ongoing debate within the conservation community about the merits of captive breeding as a method to conserve threatened species. Although captive breeding is expensive, it provides a level of certainty that may not be possible with *in situ* conservation. Unfortunately for many species captive breeding is the only viable option to prevent extinction because we do not know the causes of population decline in the wild or we are unable to eliminate the problem quickly enough. To address these management issues, we constructed a first order Markov chain population model for two populations, a captive population and a wild population, and used stochastic dynamic programming to identify optimal size of translocations between the zoo and the wild. This provides a practical tool for captive breeding decision-making and suggests a number of rules of thumb for their management.

*Keywords:* Captive Breeding; Stochastic Dynamic Programming; Conservation Biology

## 1. INTRODUCTION

An ever-increasing number of species are endangered due to, threats like habitat destruction, invasive species and poaching, but more than half the time we do not know the causes for population decline [Margin et al., 1994]. If the factors that threaten a species are unknown or cannot be eliminated quickly, then captive breeding is the only viable conservation measure. Important issues in captive breeding conservation programs concern the best size of translocations between captivity and wild. In this paper we derive optimal translocation strategies and rules of thumb that can be used as a decision tool for captive breeding programs.

Reintroduction is a common conservation strategy in the developed world [Beck et al., 1994], however the success rate of reintroductions of captive bred animals is very low [1-38%, Beck et al., 1994]. Critical for the success of reintroductions are the number of animals released. In general, successful reintroduction programs were of longer duration and released more animals than unsuccessful programs [Griffith et al., 1989; Beck et al., 1994]. But exactly how many animals are enough? As building up populations of animals in captivity is time consuming and expensive it is important to know the

number of animals to release that will maximise long-term benefits. UCN/SSC Guidelines for Re-Introductions (41st Meeting of the IUCN Council, Gland Switzerland, May 1995) specifically state the necessity to use modelling to identify the optimal number of individuals to be released per year necessary to promote establishment of a viable population.

As a result of the high costs involved with captive breeding [Leader-Williams, 1991] this conservation measure has been used as a last resort and captive breeding programs are frequently initiated after the population is reduced to a very low size. However, if populations are very small, demographic stochasticity reduces the chances of successfully establishing a captive population. Population Viability Analysis [PVA, e.g. Boyce, 1992; Beissinger and Westphal, 1998] can be used to as a tool to decide which species need to be protected by means of identifying species extinction risks. However we need to couple PVA with decision theory to decide on the best time to start and design of a captive breeding program because we need to simultaneously consider captive and wild populations. To address this problem we need a set of optimal decisions because the best conservation strategy depends on the number of individuals in

the wild and in captivity. PVA's in isolation cannot be used to easily get such state-dependent decisions [Possingham et al., 2002].

We find the state-dependent strategy that minimises extinction risk in the wild with Stochastic Dynamic Programming (SDP). Ideally we do not want to manage a population forever, so our objective is only concerned with the survival of the species in the wild. SDP is a generic optimisation approach that is widely used in biology to find state-dependent optimal strategies when the state dynamics are stochastic [Clark and Mangel, 2000].

## 2. MODELING CONCEPT

### 2.1 Population Model

There are two populations, a zoo population $Z$ and a wild population $W$. The populations are bounded by the carrying capacities $K_z$ and $K_w$ because of space restrictions in the zoo or limited resources in the wild. We assume that females always have the opportunity to mate regardless of male abundance, and so we only track the number of females. We also ignore age-structure, and so the dynamics of the populations can be modelled as a first order Markov Chain. The transition matrix describes the change in population density from one year to another.

In our model birth and recruitment occurs before death. The population matrix A describing the transition of population density time from $t$ to $t+1$ is

A = RS,

which is the matrix product of the recruitment matrix R and the survival matrix S. This means that only surviving individuals have the opportunity to reproduce.

The probability of having i surviving individuals at $t+1$, given $j$ individuals at time $t$ is the binomial probability

$$s_{i,j} = \begin{cases} \binom{j}{i}\mu^{j-i}(1-\mu)^i, & if \quad 0 \le i \le j, \\ 0 & otherwise \end{cases} \quad (1)$$

where $\mu$ is the mortality rate.

We assume that the sex ratio is constant with the probability $f$ to give birth to a female newborn. Females can have between 0 and $i_{max}$ newborns that survive to recruitment. There is a probability distribution, $l_i$, that a female has $i$ newborns ($i = 0, ...., i_{max}$), where $l_i$ is derived from Poisson distribution with the mean $\lambda$, truncated at $i_{max}$ and renormalized.

Now we can calculate the binomial probability, $b_{i,1}$, that a female has $i$ female newborns as follows

$$b_{i,1} = \begin{cases} \sum_{j=1}^{i_{max}} l_i \binom{j}{i} f^i (1-f)^{j-i} & if \quad 0 \le i \le i_{max} \\ 0 & otherwise \end{cases} \quad (2)$$

The probability that $j$ females have $i$ newborns can be obtained recursively from the first column and the previous column

$$b_{i,j} = \begin{cases} \sum_{k=0}^{j} b_{k,j-1} b_{i-k,1} & for \quad i \le k \\ 0 & otherwise \end{cases} \quad (3)$$

At high population densities the reproduction is limited by $K$ such that $\sum newborns + females \le K$. This is the only place where density dependence enters the model. Given $b_i$ we can calculate the transition probability that the population density changes from $t$ to $t+1$ due to reproduction as:

$$r_{m,n} = \begin{cases} b_{m-n,n} & if \quad n \le m < K \\ 1 - \sum_{i=n}^{K-1} b_{i-n,n} & if \quad m = K \\ 0 & if \quad m < n \end{cases} \quad (4)$$

### 2.2 Stochastic dynamic programming (SDP) model

The model is concerned with optimising management decisions involving captive breeding in zoos or parks. The following general questions are addressed: (1) At what population size should a wild life manager start breeding an endangered species in captivity. (2) Planning the captures, i.e how many individuals should we take out of the wild? (3) Planning the releases, i.e. how many individuals should we release into the wild?

The SDP model has three states, the number of individuals in the zoo ($n_z = 0, ...., K_z$), the number of individuals in the wild ($n_w = 0, ..., K_w$) and the time over which the management plan will be optimized ($t = 0,....T$). The change in density over time in both populations follows from Markov chain population matrixes, $A_w$ and $A_z$, where $A_w$ is based on higher fecundity and higher mortality rates than $A_z$.

Each time step a wild life manager can either do nothing or transfer $n$ individuals from the wild into the zoo (captures) or vice versa (releases). The maximum number of captures or releases depends on the carrying capacities in the zoo and in the wild. If we define releases as negative captures the

SDP model evaluates the consequences of all possible captures (decision variable $d = -K_z, \ldots, 0, \ldots K_z$). We set an objective function $V$ at the end of the time horizon ($t = T$) that maximises the probability of survival $\varepsilon$ years after the captive breeding programs ceases.

$$V\left(n_w, n_z, T\right) = 1 - a'_{0,n_w},\qquad(5)$$

where $a'_{i,j}$ is an element of the transition matrix $A$ raised to the power $\varepsilon$. $V$ minimizes the extinction probability $\varepsilon$ time steps in the future, thus rewarding solutions resulting in higher population sizes. Ideally $\varepsilon = 128$ years. However with some parameter settings the wild population is virtually extinct long before 128 years. In that case we set $\varepsilon = 32$.

Transferring individuals between the zoo and the wild imposes certain costs on the populations. The SDP model considers the following cost in terms of decreased survival and increased mortality: (1) We assume that as a result of stress and disorientation individuals transported from the zoo to the wild and vice versa do not breed in the year of translocation. In the real world, it is not impossible that translocated individuals will breed but the effects of translocation on fecundity are largely unknown, so in this paper we assume the worst-case scenario. (2) Only a fraction of wild individuals targeted for capture survive the transfer to the zoo because individuals may die from injuries during the capturing procedure or from stress during the transport itself. Similarly, not all individuals translocated from the zoo to the wild survive. (3) In addition, there might be a cost to the wild population as a whole because captive breeding programs may create an uncontrolled demand of live individuals of the species in question because some people think they can make a good profit from selling them to zoos [Clayton et al., 2000]. We assume that all aforementioned costs apply only for one year. This implies that appropriate government actions against illegal hunting take effect within one year and that the genetic makeup between zoo and wild animals is basically the same. The latter assumption might be violated for some species particular after long periods of captivity but including long-term effects would increase the state space very much and the magnitude of long-term effect are largely unknown for most species anyhow.

Mortality costs are modelled by means of the ratio $\alpha$ ($\alpha$ = reduced survival/natural survival). The factors can range from 1 to 0, with lower values indicating high costs. So the new mortality $\mu_{new} = 1 - [(1-\mu)(1-\alpha)]$. We calculated three additional Markov chain matrices: $A_{rel}$ for released individuals, $A_{capt}$ for captured individuals, and $A_{w-h}$ for the non-captured individuals of the wild population.

The programming equation is as follows:

$$V\left(n_w, n_z, t\right) =$$

$$\max_{d} \begin{cases} do \quad nothing & if \quad d = 0 \\ release & if \quad d < 0 \\ capture & if \quad d > 0 \end{cases} \qquad(6)$$

where $d$ is the number of captured or translocated individuals, and

"do nothing" =

$$\sum_{i=0}^{K_z}\sum_{j=0}^{K_w} V\left(t+1, i, j\right) a_{j,n_w}^{w} a_{i,n_z}^{z}$$

"release" =

$$\sum_{i=0}^{K_z}\sum_{j=0}^{K_w}\sum_{k=d}^{0} V\left(t+1, i, j-k\right) a_{j,n_w}^{w} a_{-k,-d}^{rel} a_{i,n_z+d}^{z}$$

"capture" =

$$\sum_{i=0}^{K_z}\sum_{j=0}^{K_w}\sum_{k=0}^{d} V\left(t+1, i+k, j\right) a_{j,n_w-d}^{w-h} a_{k,d}^{cap} a_{i,n_z}^{z}$$

The superscripts indicate the transition matrix, eg. $a_{i,n_z}^{z}$ is the probability $n_z$ females of the zoo population in year $t$ become $i$ females in year $t+1$. (Note that releases are considered as negative captures)

## 3.  CASE STUDY

In the model we consider a maximum of 50 females in the wild and 20 females in the zoo. These population boundaries are rather small, but the use of larger values of $K_w$ and $K_z$ results in long running times (e.g. a run using $K_w = 150$, and $K_z = 30$ lasts over 9 days on a 700 MHz PIII).

We parameterise our model with data on Arabian oryx because in the literature we could find data on most of the parameters used in the model. In the following we summarise the range of vital rates published for this species and derive the parameter values of two scenarios used in the SDP (Table 1). The per capita growth rates population growth rates of the two scenarios are consistent with population growth rates found in Arabian oryx sanctuaries [Abu Jafar and Hays-Shahin, 1988; Ostrowski et al., 1998; Spalton et al., 1999; Marshall and Spalton, 2000].

- **Recruitment**: In the model we assume that off-spring reproduction in the wild is smaller than in the zoo. Under optimal conditions females can give birth to a single calf once per year, which

has a 92.5% [Vie, 1996] -75% [Mace, 1988] chance to survive the first year of life. Assuming a sex ratio of 1:1 [Mace, 1988; Vie, 1996; Spalton et al., 1999] and a newborn survival rate of 0.92 and 0.82 we get $\lambda = 0.46$ and 0.41, that is the per capita annual increase in the female population.

- **Mortality**: Annual mortality of adult Arabian oryx ranges between 4-15 % [Abu Jafar and Hays-Shahin, 1988; Mace, 1988]. We assume that the wild mortality rate increases up to 40% due to poaching [Spalton et al., 1999]. In the second scenario we examined how the optimal strategy would change if poaching mortality could be reduced to 20%.

- **Translocation costs**: According to Ostrowski (personnel communication) the losses due to capturing and transferring Arabian oryx into captivity and vice versa are very small with mortality ranging between 0 and 5 %. As far as we know fixed costs are not documented for Arabian oryx. However, the conservation community is concerned with potential detrimental effects that capture of individuals from the wild can have on the survival of the species as a whole [Rabinowitz, 1995; Struhsaker and Siex, 1998]. For example, Clayton et al. [2000] describe that the recently initiated captive breeding program of babirusas in Sulawesi (Indonesia) triggered a large demand for live babirusas and a substantial unauthorized trade in live animals. For the sake of parsimony we assume that the fixed costs equal the variable translocation costs.

**Table 1**: Parameters used in SDP model. We assume that all costs such as capturing mortality, fixed capturing costs, and release mortality = 0.05, $K_z = 20$, and $K_w = 50$ females; and sex ratio $f = 0.5$.

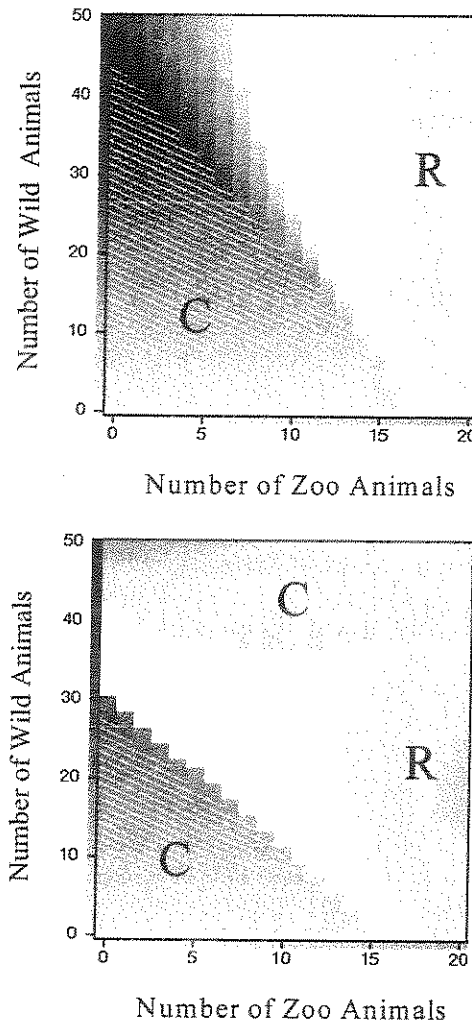| Parameters | Run1 | Run2 |
|---|---|---|
| Zoo population: | | |
| Mean no offspring $\lambda_z$ | 0.46 | 0.46 |
| Mortality $\mu_z$ | 0.1 | 0.1 |
| Growth rate $r_z$ | 0.32 | 0.32 |
| Wild population: | | |
| Mean no offspring $\lambda_w$ | 0.41 | 0.41 |
| Mortality $\mu_w$ | 0.4 | 0.2 |
| Growth rate $r_w$ | 0.85 | 1.13 |

## 4. RESULTS



**Figure 1.** Optimal number of translocated animals as a function of population numbers in the wild and the zoo. The grey intensity is proportional to the number of translocated animals so that white = 0 and dark grey = 50. C indicates captures, R indicates releases, and stripes indicate that $d = n_w$. Upper graph $r_w = 0.83$; lower graph $r_w = 1.13$.

Here we only present "stationary decisions", which means we stepped so far backward in time until the decisions were the same for previous and following time steps. The results of the two runs presented in this paper (Table 1, Figures 1 and 2) are representative for 2 different result classes identified through a whole range of parameter combinations. The results can be classified based on whether the per capita growth rate in the wild $r_w > 1$ or $r_w < 1$.

Figure 1 illustrates the number of captured and released animals as a function of population numbers in the zoo and the wild. The actual number of

translocated animals is not so important as this critically depends on the rather speculative translocation costs and the carrying capacity of the zoo, $K_z$. It is more relevant to ask: "How much should we fill up the zoo?" To address this question we plotted the expected zoo population after the decision, $E(n_{z,t+1})$ (taking mortality and transloca-tion cost into account), as a proportion of $K_z$ ($E(n_{z,t+1})/K_z$, Figure 2), given the number of captured animals $d < n_w$. Including cases where $d = n_w$ would bias the results to smaller values just because $d$ is limited by $n_w$. The model results can be summarised by rules of thumb; some rules are case specific, some rules apply for both cases.
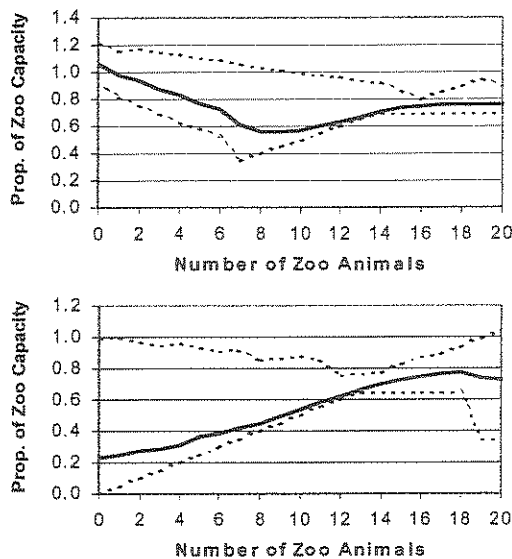


Figure 2. Expected zoo population after decision at two different per capita growth rates in the wild: upper graph $r_w = 0.83$; lower graph $r_w = 1.13$. The solid lines indicate the average and the dotted lines the range of $E(n_{z,t+1})/K_z$ at any given $n_z$ (Only data included when $d < n_w$)

Rules that apply for both cases, i.e. if the zoo population has a positive expected growth rate, and expected growth rate in the wild can be either posi-tive or negative:

- **Release:** Zoo animals are only released if $n_z > 2/3 \ K_z$ (Figure 1).
- **Capturing:** If wild population $n_w$ and zoo population $n_z$ were small the entire wild popula-tion was transferred into captivity (striped areas in Figure 1). The higher $n_z$ and $n_w$ the smaller the proportion of wild animals captured.

Case 1: If the zoo population has a positive ex-pected growth rate but the wild population has a negative expected growth rate,. $r_w < 1$:

- When there are none or only a few animals in the zoo the optimal decision is to fill up the zoo to $K_z$.

- With increasing number of zoo animals $E(n_{z,t+1})/K_z$ decreases to an average of 0.5 (lowest value = 0.35) until the zoo is half full; then $E(n_{z,t+1})/K_z$ increases and asymptotes at 0.8. In other runs minimum and asymptote values were different.

Case 2: If both populations are expected to grow, $r_w > 1$:

- In most cases the optimal decision is to have a zoo population, even if the wild population is growing. With some parameter combinations not presented here it is always optimal to have a zoo population.
- The wide range of $E(n_{z,t+1})/K_z$, especially if $n_z$ is small, indicates that the optimal decision is much more complex compared to $r_w < 1$.
- With increasing number of zoo animals $E(n_{z,t+1})/K_z$ increases from 0.2 and asymptotes at approximately 0.8 .

## 5. DISCUSSION

The goal of this paper is to assist wildlife managers in designing captive breeding and reintroduction programs. A key result is the important role of cap-tive breeding in minimising the extinction risk of a species in the wild if we can be sure that the zoo population will fare better than the wild population. If the wild population is small the entire wild population is transferred to a captive breeding fa-cility, even if the population in the wild is growing. As a consequence of demographic stochasticity, a small wild population has a high probability of be-coming extinct, so the best strategy is to increase population numbers as quickly as possible through captive breeding. Note that the model does not con-sider environmental stochasticity such as the prob-ability of droughts, or catastrophes like disease outbreaks, which would increase the extinction risk of small populations even further.

The optimal strategy contrasts the common practice of conservationists responding to a problem after it has already reached the point of catastrophe, ie. when the population of a species concerned is re-duced to only a few individuals. Founding a captive breeding program with a handful of animals can also be successful, but it is safer to start managing a population earlier.

The optimal strategy suggests that releasing ani-mals should not compromise the zoo population. So at any point in time only one or two animals are released. As a result of the high $r_z$ the released ani-

mals are replaced quickly and can be released the following year. Therefore, the optimal release or relocation strategy stretches the release effort over several years, ultimately releasing a large number of animals.

The model assumes that the growth rate of populations in captivity is higher than in the wild. This assumption is violated for species that are very difficult to breed in captivity such as canids [Gindberg, 1994]. The optimal strategy seems to be determined by $r_w$ and $r_z$ rather than the actual combination of vital rates. Therefore, we believe that the model results have implications for conserving a wide range of species even though the parameters are derived from a single species. In future work we are going to test the generality of our results examining a much wider parameter range.

## 6. ACKNOWLEDGEMENT

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