Bearded Vulture Population Viability Analysis

Workshop Report – October 2022

BEARDED VULTURE
RECOVERY
PROGRAMME


Sonja Krüger

On behalf of the participants of the *2022 Bearded Vulture Population Viability Analysis (PVA) Workshop*, this document was compiled and edited by: Waller LJ, Davies-Mostert H, Copsey J.

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1 EXECUTIVE SUMMARY

1.1 Context

In November 2020, the Conservation Planning Specialist Group (CPSG) of the IUCN Species Survival Commission was approached by the Bearded Vulture Breeding Programme and Ezemvelo KwaZulu-Natal Wildlife (EKZNW) on behalf of the Bearded Vulture Task Force (BVTF) of the Bearded Vulture Recovery Programme (BVRP) to design and facilitate a stakeholder-inclusive Population Viability Analysis (PVA). The aims of the PVA would be to i) assess interventions required to achieve the species conservation objectives as defined in the draft Southern African Bearded Vulture Recovery Strategy and Action Plan (BVRSAP); ii) revise the species targets if required based on the outcome of the PVA; and iii) identify priority conservation interventions that are necessary to ensure the persistence of the species in the wild with a particular focus on better understanding the scale of ex situ management required to support recovery in the wild.

The PVA was run considering the targets of the draft BVRSAP which are:

- Ensure the long-term survival of the Bearded Vulture population in southern Africa through halting the population decline and stabilising the population at the current population size (approximately 100 breeding pairs[1]) over the next ten years (by 2030).
- Grow the population to a realistic carrying capacity (150 breeding pairs) in the future and maintain a positive population growth rate (> λ=1).

Results from the PVA analyses would then be used to update the draft BVRSAP and reprioritise if and where needed.

The initial baseline model developed in 2020-2021, demonstrated that the population trajectory of the wild population was of grave concern and highlighted the potential role that ex situ management could play in its recovery. It also demonstrated that a reduction of mortality in situ was critical to population recovery, and that the ex situ contribution would only be viable if in situ mortality was reduced.

In 2022, a PVA workshop was run, where the baseline model was updated and the interplay between the in situ and ex situ populations investigated. A range of scenarios that would best support the Bearded Vulture population's recovery were considered. It is the results of these analyses that are presented in this report, and on which the recommendations are based.

1.2 Final recommendation statement

The Bearded Vulture is regionally Critically Endangered and it is not well represented or conserved in protected areas. Conservation measures thus need to be implemented across the species range in Lesotho and South Africa. The recommendations developed are based on the outcome of the baseline model that estimates there will only be 62 birds (20 breeding pairs) remaining in the wild in 50 years' time, should no further interventions be implemented.

[1] A breeding pair is defined as any pair attempting to produce young.

Based on the PVA workshop and model results, **it is recommended that the strategy going forward should be to focus on securing the current wild population through threat mitigation in situ coupled with supplementation from an ex situ population**. It is recommended that this is achieved by the following:

a. In situ:
   i. Actions need to be immediately intensified to reduce mortality in situ (wild population) by 15% per annum across all age classes (**this translates into preventing the deaths of approximately 6 birds a year**).
   ii. Increase productivity in situ by 5% per annum.
   iii. Concurrent with the implementation of the above actions, release sites (as part of a reintroduction/supplementation programme) should be prepared.
   iv. Within the next 5 years (2027), in situ mortality through poisoning, power lines and any other man-induced activity need to be effectively mitigated. If not, the BVTF will have to consider other release sites in the species historical range where the threats are less problematic.

b. Ex situ:
   i. There is a critical and urgent need for an ex situ (captive) population to support the recovery of the Bearded Vulture in the wild.
   ii. To effectively support the recovery of the wild population **a minimum of 32 birds are required in the captive population.** This can be achieved by harvesting 6 eggs per annum for the next 3 years, and thereafter between 2 and 4 eggs every 4 years to maintain an appropriate age structure and genetic diversity.
   iii. Should an increase in productivity in situ of 5% not be achieved, then the ex situ population needs to be increased to 42 birds, which would allow for increased supplementation back into the wild.
   iv. The captive breeding **programme is to start releasing birds in 4 years' time (approximately 2026).**
   v. The ex situ population will also function as a genetic reserve for the species.

c. Stakeholder buy-in: It is important that all stakeholders are cognisant of and in agreement with these modelling results and that buy-in is achieved from all key role-players to ensure effective roll-out of agreed upon options. It is also recommended that focussed discussions be had with relevant stakeholders to ascertain what actions will be most effective at reducing juvenile and adult mortality and how the productivity of breeding females can be increased. During the workshop, participants discussed options such as food supplementation at vulture supplementary feeding sites, reduction of disturbance at nest sites, and dedicated programmes to clear poisons from the landscape. The impact of these interventions needs to be quantitatively evaluated - if at all possible - to track progress and inform future management through determining what combinations of actions will work to produce the best results.

d. It is recommended that that the BVTF review the draft BVRSAP to incorporate the outcomes and recommendations of this report.

1.3 Required research

Due to the difficult nature of the terrain, obtaining demographic and census data on Bearded Vultures is difficult and expensive. The PVA process did, however, highlight some areas where additional monitoring and research would make valuable contributions in assisting conservation practitioners to evaluate and adapt their approaches. A research prioritisation exercise, conducted with relevant stakeholders would be helpful in working towards this.

The models indicate that **adult and juvenile mortality; proportion of breeding females; and age at first breeding were the main drivers of Bearded Vulture population dynamics**. Mortality rates used in the PVA model were obtained from a relatively small sample of tracked birds over a limited time period, and the accuracy of subsequent modelling updates would be improved with an increased understanding of in situ mortality rates and their drivers. Similarly, a better understanding (i.e., larger sample size) of the proportion of females breeding, breeding biology (including age at first breeding and last reproduction) and understanding factors that influence these parameters are also priorities.

There is also a need to evaluate the effectiveness of the interventions undertaken to promote Bearded Vulture population recovery.

1.4 Post-workshop steps

During the PVA workshop, the participants noted that there is a need to go through the actions in the Draft Strategy and Action Plan to ensure that they align with priorities that have come out of the modelling process.

2 WORKSHOP PROCEEDINGS

2.1 Conservation status of Bearded Vultures in southern Africa

The Beaded Vulture (*Gypaetus barbatus*) is classified globally as Near Threatened by the IUCN (BirdLife International 2021). In southern Africa however, it is classified as Critically Endangered (Krüger 2015). The justification for this regional classification is that the population size is estimated to be <250 mature individuals, with >90% of these mature individuals occurring in a single sub-population (*Gypaetus barbatus meridionalis)* (Krüger 2015). Further, a decline of 82.8% over the past three generations satisfies the criterion for regionally Critically Endangered, with a quantitative analysis indicating that the probability of extinction in the wild is at least 50% within the next three generations (Krüger 2015).

Globally, the species occurs in Europe, Asia and Africa (Mundy et al. 1992). The regional southern African population is geographically and genetically isolated from its nearest conspecific population in Ethiopia with genetic research, that includes the use of microsatellite data, supporting the management of the southern African population as a separate conservation unit (Streicher et al. 2018). The breeding distribution of the Bearded Vulture in southern Africa is restricted to the Maloti Mountains n Lesotho and the Drakensberg Mountains of the Free State, KwaZulu-Natal and Eastern Cape Provinces of South Africa, and associated outcrops within the foothills of these mountains.

Threats to the species are summarised in the draft BVRSAP (Krüger 2020). Primary threats to the species are listed as unintentional poisoning/trapping (Krüger 2014); direct persecution (Mundy et al. 1992, Maphisa 1997, Mander et al. 2007); collision with energy infrastructure (powerlines) (Krüger 2014) and unintentional poisoning (lead) (Krüger and Amar 2018). Secondary threats include a decline in food availability (Boshoff et al. 1983); human disturbance (Guy 1974; Kopij 2001; Vernon and Boshoff 1997; Brown 1991; Maphisa 1997); habitat loss and degradation and fires (Krüger 2005 and 2007). Potential threats are thought to include collision with energy infrastructure (wind farms) (Reid et al. 2014 Rushworth and Krüger 2014); genetic bottlenecks; unintentional poisoning (NSAIDs); climate change and trade and utilisation.

The population is not well represented or conserved in protected areas, therefore conservation measures need to be implemented throughout its range in Lesotho and South Africa (Krüger 2020). To identify and implement these conservation measures, a Bearded Vulture (*Gypaetus barbatus meridionalis*) Population and Habitat Viability Assessment Workshop Report (Krüger et al. 2006) was developed in 2006. This report was used to develop a Conservation Action Plan for the species (2006), which was reviewed in 2011 and published in 2014 in South Africa as the Biodiversity Management Plan for the Bearded Vulture (Krüger 2013) through the National Environmental Management: Biodiversity Act, 2004 (Act No. 10 of 2004). This BMP is now being reviewed, and a Southern African Bearded Vulture Recovery Strategy and Action Plan (BVRSAP) is being developed (Krüger 2020).

The recommendations from the Population Viability Analysis (PVA) on which this document reports, will be used to update the BVRSAP. The PVA was designed to answer questions that looked at evaluating species targets and clarifying the interplay between the in situ and ex situ populations and actions to manage them, to determine how they could work together most effectively to result in positive population change in the wild.

2.2 Workshop overview

In November 2020, the Conservation Planning Specialist Group (CPSG) of the IUCN Species Survival Commission was approached by Ezemvelo KwaZulu-Natal Wildlife (EKZNW) on behalf of the Bearded Vulture Task Force (BVTF) to design and facilitate a stakeholder-inclusive PVA to i) assess interventions required to achieve the species conservation objectives as defined in the draft strategy BVRSAP; ii) revise the species targets if required based on the outcome of the PVA; and iii) identify priority conservation interventions that are necessary to ensure the persistence of the species in the wild. The purpose and conservation priorities of the ex situ population as well as any interaction between the in situ and ex situ populations necessary for the long-term Bearded Vulture population sustainability (including harvest and reintroduction strategies) were also considered. The PVA was also guided by the aims of the draft BVRSAP (Krüger 2020) which are:

- To provide a mechanism to ensure the long-term survival of the species through halting the population decline and stabilizing the population at the current population size (approximately 100 breeding pairs) over the next ten years.
- To provide a mechanism to start growing the population to a realistic carrying capacity (150 breeding pairs) in the future and maintaining a positive population growth rate ($> \lambda=1$).

Central to the process followed was that of the One Plan approach (Byers et al. 2013), where all populations (in situ and ex situ) of the species are considered to determine how best to support the recovery of the species in the wild while engaging relevant stakeholders with the expertise to contribute. To do this, CPSG ran a series of workshops and meetings with these stakeholders to obtain information on knowledge of the current population parameters, threats and carrying capacity that would be used to develop a baseline model that best approximated the current population dynamics of Bearded Vultures. The aim of the first series of meetings in 2020 and 2021- which included the development of the baseline model- was to determine whether a more assertive harvesting strategy, designed to boost the founder population in captivity, would negatively impact the wild population. As part of this baseline model development, primary drivers of the in situ population were investigated.

The baseline model was then used to predict the outcome on the population of different future management scenarios in 2022. Recommendations from these analyses will subsequently be used to review management objectives and activities in the BVRSAP update, particularly those which relate to the contribution of the ex situ (captive) population to the conservation/recovery of the species to the in situ (wild) population.

This participatory process involved several small workshops, culminating in a Population Viability Analyses (PVA) workshop. Details of the PVA analysis are provided in Section 3 of this report. In Section 2, we focus on the process followed.

2.3 Process development

During 2020 and 2021, the focus of the modelling and decision-making process was to build the baseline model and provide a scientific basis for decisions regarding the future direction of the Bearded Vulture captive breeding programme. Stakeholder meetings were held to discuss model input parameters; the desired end state for the Bearded Vulture population in the wild; and what harvesting rate would be needed to build the captive population such that it would make a meaningful contribution to the wild in future. The outcome of this initial phase of modelling was a shared decision for the 2021 season to harvest the first egg from double egg clutches and take the egg from single egg clutches from an identified subset of approximately 10 nests, with a target of getting six successful hatchings to boost the captive population. A summary of the process followed in 2020 and 2021 can be found in Appendix 1, a summary of consolidated responses that were used to inform the initial modelling, in Appendix 2 and a list of participants for the various meetings in Appendix 3.

Building on this initial work, a series of meetings were held with a smaller group in 2022 (see Appendix 3) to develop the captive baseline model; consider what changes were needed (and feasible) in the wild and captivity to ensure population recovery and to develop future scenarios to inform how the ex situ population needed to develop to support the wild population recovery. These meetings culminated in the PVA workshop in May 2022. See Appendix 4 for a summary and outcomes of the 2022 meetings; Appendix 5 for the PVA workshop Agenda and Section 3 for the technical details and results of the PVA.

2.4 Workshop participants

In total, twenty three participants from the governments of Lesotho and South Africa, as well as conservation NGOs and independent individuals participated in the meetings (See Appendix 3). Participants also included members from the BVTF who had relevant expertise with Bearded Vultures. International experts actively engaged in captive breeding of Bearded Vultures for release into the wild were also consulted.

2.5 Identifying fundamental objectives

Fundamental objectives are those that stakeholders want to see achieved through any recommendations made in the Bearded Vulture PVA modelling process. When considering fundamental objectives for the Bearded Vulture, the following statements were presented to the group: *What do you care most about in making the decision? Fundamental objectives are those against which you will be evaluating the success of the plan; this is what you want to achieve (as opposed to how you are going to achieve it).*

In the first part of the process, participants spent time identifying what their concerns and aspirations were that they wanted to be considered. These were brainstormed during a virtual meeting on the 11th of May 2022. During this meeting, participants were asked to list concerns and raise aspects of the Bearded Vulture Recovery that were most important to them. These concerns are listed in Table 1.

Table 1 Concerns identified by stakeholders that they wanted addressed in the decision-making process.

Fundamental objectives resulting from stakeholder discussions
Maximise the likelihood of survival of release birds (how do we decide where to release the birds?)
Population doesn't go extinct in the wild
Reducing mortality of birds in the declining wild population
Population increases in the wild
Achieve a recovering population over 60 years (150 pairs?)
Achieve positive Regional Listing status change
Reduce the risk of extinction through multiple populations
Establish new populations where threats are absent so the likelihood of species recovery is higher
We all need to be comfortable that we are going in an agreed direction
Ensure legislative bodies are behind and supportive of the work
Change people's perceptions to recognise the value of the species in the wild
Have a back-up to loss in the wild
Standards of care for birds on release- welfare
Work to date is considered irrelevant- validity of the breeding programme
Costs associated with the breeding programme (ex situ)
Monitoring in situ (lack of or insufficient?)
Maximise knowledge of why birds not in certain places anymore

The responses provided by the participants were then consolidated and rephrased into potential objectives. These were then revisited at the beginning of the PVA workshop on 23rd May 2022. Four fundamental objectives were subsequently identified that stakeholders wanted to ensure would be achieved through any recommendations made through the PVA process (Table 2)

Table 2 Fundamental objectives for stakeholders in developing recommendations for the Bearded Vulture.

Fundamental objectives resulting from stakeholder discussions
To maximise the growth rate of the population in the wild
To secure as much of the genetic diversity from the existing population as possible
To minimise cost
To maximise the area of occupancy (at least stop further loss)

The results of the PVA modelling of scenarios were reviewed with these fundamental objectives in mind.

2.6 Summary of population viability analysis (PVA)

Section 3 provides the technical details and results of the PVA (See Model results). Here the high-level findings are summarised.

Finding 1

Confirming initial results of the modelling undertaken in 2020 and 2021, harvesting eggs from the wild into the captive population can be undertaken in a way that does not have a significant impact on the trajectory of the wild population. The wild population is thus not at risk from harvesting if done at recommended rates.

Finding 2

Mortality reduction in the wild has a considerable impact on the population, leading to a significant increase in the overall number of birds at the end of the modelled period of 50 years. Activities that reduce juvenile and adult mortality must be seen as a top priority for the population recovery of Bearded Vultures.

Finding 3

While an insurance captive population can be established from the existing 14 founder birds- to prevent significant loss of genetic diversity over time- augmentation from the wild is required. Furthermore, increasing the captive population improves the long-term genetic resilience.

Finding 4

The use of captive-born birds to supplement the wild population leads to significant improvements in the population trajectory over time.

Overall, **the strategy that leads to the best results in the wild is to combine mortality reduction, increased reproduction, and population augmentation from the captive population.**

Based on the PVA results, the group compiled a "Concluding Statement" which was presented to the BVTF on the final evening of the workshop, as well as circulated to all BVTF members by email the next day.

2.7 Minimising costs: some practical considerations

One of the four fundamental objectives that were identified above was to minimise costs. Once the models and scenarios had been developed, the model group spent some time brainstorming on in situ and ex situ activities and tentative costs were identified for some of these (See Appendix VI). This information is not intended to be exhaustive, but rather could be used to contribute to future, more focussed budget discussions.

An important consideration that the model group wanted to emphasise was the considerable costs (in R millions) associated with growing and maintaining the ex situ population such that it can fulfil its role in the recovery of the Bearded Vulture, as well as ensuring that this 'investment' is protected by reducing in situ mortality. Without reducing natural mortality and increasing natural production, the augmentation of the in situ population with ex situ birds will have negligible impacts on the population trajectory over time, with considerable financial cost.

3 POPULATION VIABILITY ANALYSIS FOR THE BEARDED VULTURE

Modelling team: Brent Coverdale, Shannon Hoffman, Bill Howells, Sonja Krüger, Ian Rushworth, Jamie Copsey, Lauren Waller, Harriet Davies-Mostert (in person); Mamasheane Motabotabo, Mantsatsi Moleleki, Refiloe Maliehe, Bataung Mokhele (online).

3.1 VORTEX: A stochastic simulation of the extinction process

Demographic models present a useful tool to investigate drivers of population dynamics in wildlife populations and allow teams to interrogate the potential outcomes of alternative management options. There are many approaches to take, but all modelling exercises should begin with a clear understanding of the goal of the analysis and a clear list of questions.

To undertake the PVA for Bearded Vultures, we used the software programme VORTEX (version 10.5.5.0) https://scti.tools/vortex/ which is an individual-based simulation model for population viability analysis. In VORTEX, population dynamics are modelled as discrete, sequential events (e.g., births, deaths, catastrophes, etc.) that occur according to defined probabilities following specified distributions (Lacy, 1993). These probabilities are typically extracted from field data, the published literature, expert observations, or extrapolations from closely related species with similar life-history traits. Population growth or decline is strongly influenced by random events, so the model is run many times to obtain the distribution of possible fates under different sets of conditions.

3.2 The modeling approach and overarching questions for Bearded Vultures

The overall targets of the Bearded Vulture Recovery Programme, as stated in the Draft Bearded Vulture Recovery Strategy and Action Plan 2020, are:

Target 1. Ensure the long-term survival of the Bearded Vulture population in southern Africa through halting the population decline and stabilising the population at the current population size (approximately 100 breeding pairs) over the next ten years (by 2030).

Target 2. Grow the population to a realistic carrying capacity (150 breeding pairs) in the future and maintain a positive population growth rate (> λ =1).

The population modelling approach adopted during the Bearded Vulture PVA Workshop was initiated by consulting with key experts and stakeholders to draw up a list of key questions considered useful for improving our understanding of Bearded Vulture population dynamics. These questions were formulated in the context of understanding which conservation actions will be most effective at achieving the fundamental objectives (See Identifying fundamental objectives). The group also acknowledged the importance of achieving buy-in from all key role-players to ensure effective roll-out of agreed upon options.

Modelling conducted in 2021 indicated that the ex situ population was needed to contribute to achieving the conservation targets for the species (See Appendix 1). Workshop participants recognised that this contribution could manifest in several ways:

1. The establishment of an **insurance population** in which genetic diversity is captured and maintained in the long-term as an insurance against population extinction in the long-term.
2. An **active captive breeding programme** that serves both as an insurance population and as a source of birds to be released into the wild to:
    a. supplement the existing wild population to stabilise and ultimately reverse the population decline, or
    b. establish a new reintroduced population in a site within the former distribution range, but with fewer current threats than the existing wild population,
    c. or a combination of the above.

These options are presented in Figure 1.

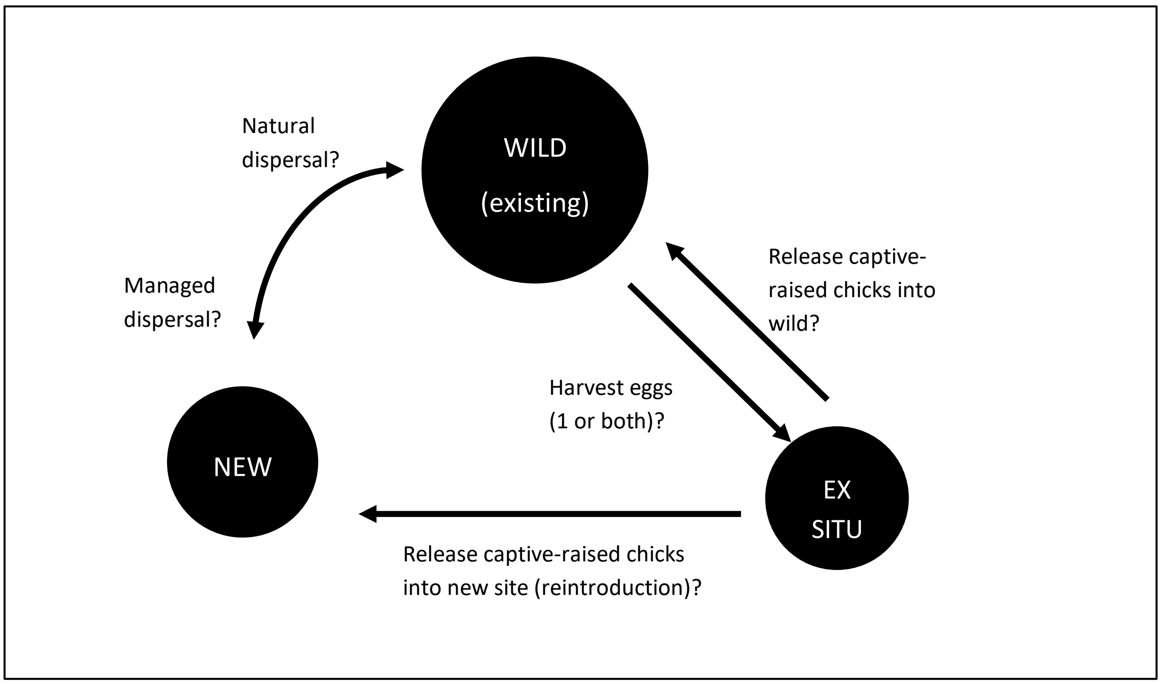

Figure 1 Graphic illustrating the potential structure of a recovered Bearded Vulture population in southern Africa.

The modelling tasks were therefore to:

1. **Develop a series of baseline models** which best approximate the current population dynamics of the in situ population, considering current knowledge of population parameters and carrying capacity.
2. **Conduct sensitivity testing of various demographic parameters** to explore where uncertainty and variation might have the biggest impacts on model outcomes.
3. Use the baseline models to **explore the influence of management options** on the wild population, predict the outcome of different scenarios, and ultimately improve decision-making in respect of population and habitat management interventions.

3.3 Conceptual model of the life cycle of Bearded Vultures

Figure 2 indicates conceptually the best understanding of the Bearded Vulture life cycle, illustrating the various life stages, how these contribute to population dynamics, and the multiple factors that may influence them. These age classes are mapping how the model works, not the biology of the birds. In the model, birds only come into existence at fledging, and the rates have been corrected to account for this. In this conceptual model, birds are predicted to start breeding at 7 years of age[2]. For modelling purposes, the definitions of the various life stages used in the model are listed in Table 3.

Table 3 Bearded Vulture life stages as defined in the Population Viability Analysis models

Age (years)	Description
–	Eggs are laid by breeding (adult) females Chicks are hatched after 52-58 days, Fledglings are produced at the age of 110–123 days
0	Fledglings fledge (t=0)
1	Fledglings become Juveniles (non-breeding)
2–6	Birds remain as non-breeding immatures and sub adults[3]
≥7	Upon reaching maturity, adult birds pair up and breed (long-term monogamy) *

*In rare cases, adult birds may form “trios”, when three birds occupy a breeding territory

Reproduction and survival are both influenced by various factors, the effects of which are likely to vary between life stages.

[2] The influence of age at first breeding was investigated though sensitivity testing

[3] It is noted that birds <7 years old can be accurately aged in the field from moulting patterns

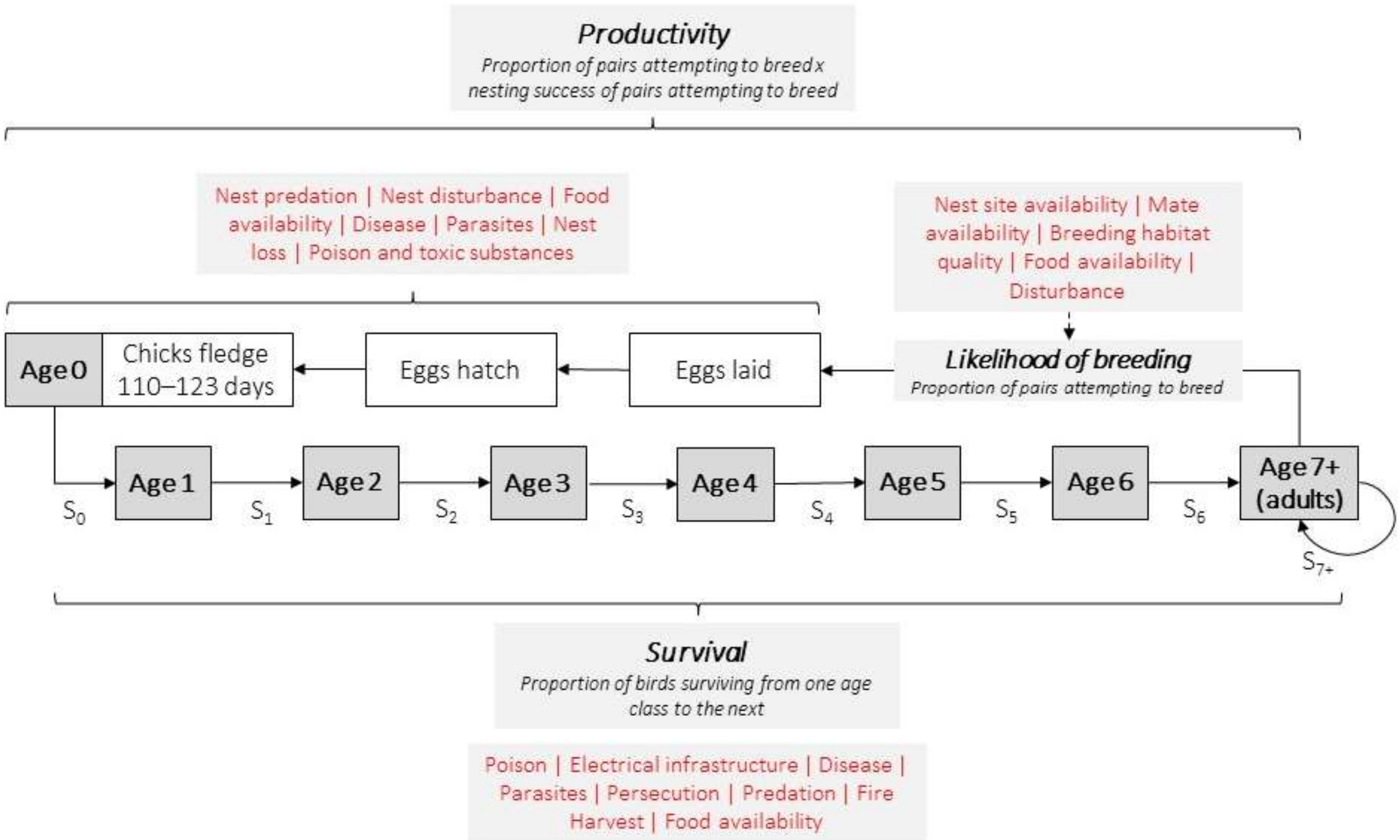

Figure 2 Schematic of the Beaded Vulture cycle, showing main life-stages (grey boxes) and potential factors influencing reproduction and survival specific to each stage (red writing). This diagram presents the life stages used in the PVA model and does not reflect traditional definitions of age classes as used in the field. There is limited field data on the production of eggs, and so Age 0 is defined as fledging in the models.

3.3.1 Notes on reproduction

Although egg laying and hatching (<0 years, see Figure 2) are important milestones in the early stages of the Bearded Vulture lifecycle, field data on the rates at which birds survive these stages are extremely sparse and difficult to collect. We therefore used fledging as Age 0 in all the models.

Some model definitions:

Breeding rate: The proportion of territorial pairs that attempt to breed each year (Murgatroyd et al., 2016; Krüger and Amar 2017).

Nesting success: The proportion of breeding attempts that successfully rear a nestling/fledgling (Murgatroyd et al., 2016; Krüger and Amar 2017).

Productivity: The proportion of monitored pairs that successfully rear a nestling, considering that each breeding attempt can only result in one nestling. This is calculated as **breeding rate X nesting success** (Krüger and Amar 2017).

3.3.2 Notes on survival

Previous attempts have been made to calculate survival rates for Bearded Vultures (Bretagnolle et al., 2004; Margalida et al., 2020; Schaub et al., 2009), however very few studies exist on survival rates in southern Africa (Krüger, 2014). In this PVA, we obtained data on age-specific mortality rates from Krüger (pers. comm.) who updated the 2012 data (Krüger, 2014) with new information from field data collected up until 2021. Due to small samples sizes, which led to significant (and – according to the experts we consulted – not likely to be biologically meaningful) inter-age variation in mortality rates, we fitted a smoothed line to the data and back-transformed this to calculate rates for each age class (Table 4 and Figure 3).

Table 4 Source of baseline mortality rates used for the wild population and adjusted Bearded Vulture mortality rates for each size class using smoothing function.

Age classes	Updated mortality rate (Krüger pers. comm.)	Adjusted mortality rates, using smoothing function
0-1	42.9%	35.3%
1-2	8.5%	25.9%
2-3	24.3%	20.4%
3-4	22.6%	16.5%
4-5	13.3%	13.5%
5-6	16.9%	11.0%
6-7	0.0%	9.0%
>7	10.3%	7.2%

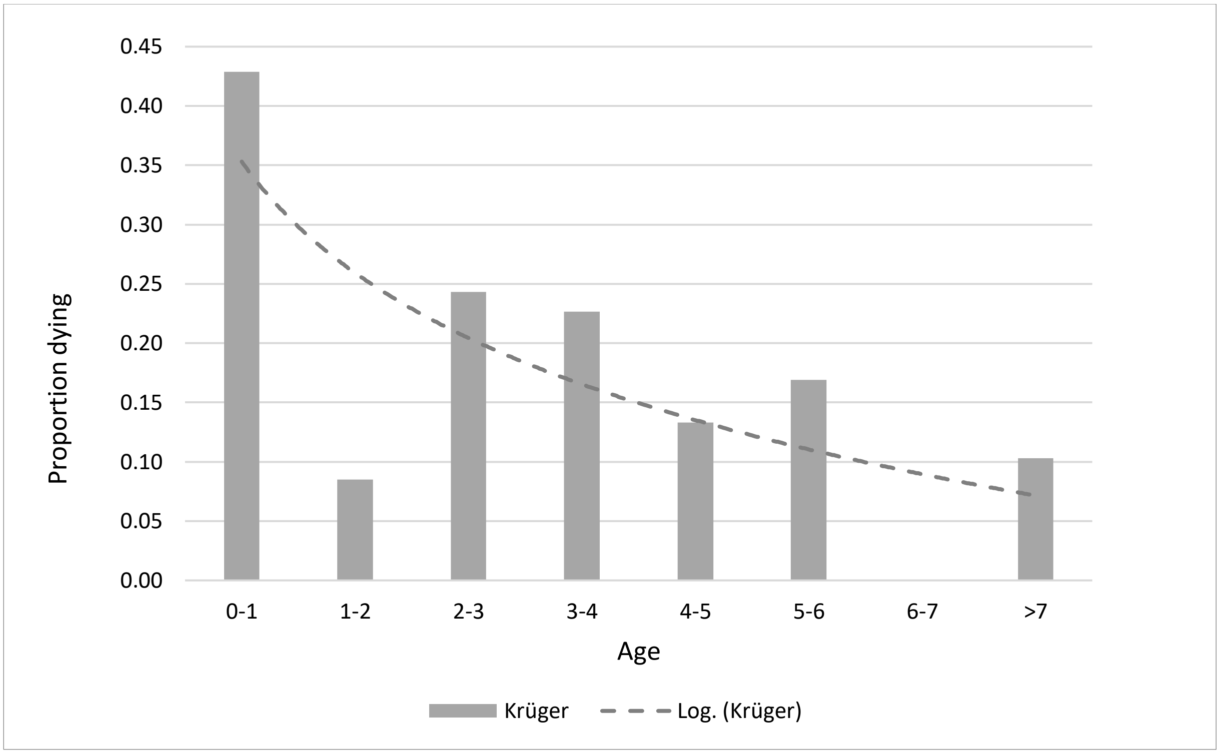

Figure 3 Age-specific mortality rates; field data (bars) and rates used in model (fitted curve, y = -0.135ln(x)+0.3531)

3.3.3 Notes on population trends over time

There have been few attempts to estimate the total population size of Bearded Vultures in wild in the past 30 years. Estimates are typically obtained by monitoring occupancy of known territories, using methods described by Krüger et al. (2014). These estimates are provided in Table 5 below.

Table 5 Abundance estimates for Bearded Vultures from 1991 to 2021.

Year	Qualifier*	Number of breeding pairs	Number of breeding adults	Trios	Number of non-breeding adults	Total population estimate	Source
1991	-	204	408	-	175	583	Brown, 1992
2006	-	145	290	-	174	419	Krüger et al., 2006
2012	Minimum	115	230	3	155	368	Krüger, 2014
2021	Minimum	103	206	3	125	305	Krüger pers. comm.

* Where a range of estimates are provided, the "minimum" estimate is presented

3.4 Development of broad baseline models and questions

Prior to the workshops, the following modelling questions were formulated to create a range of potential management intervention scenarios to be explored through modelling (See Appendix II for background as to how these questions were formulated):

1. Can we build a **one-population baseline simulation model** with sufficient detail and precision that can accurately describe the observed dynamics of the southern African Bearded Vulture population in the wild?
2. What are the primary demographic drivers of the wild population?
3. Which demographic parameters have the most significant influence on the population trajectory?
4. How will having 150 breeding pairs change the extinction risk, compared to now?
5. Can we build a **two-population baseline simulation model** with sufficient detail and precision that links the in situ and ex situ populations to evaluate the effectiveness of various management strategies according to their contribution to the overall targets stated above?
6. How big does the ex situ population need to be to retain the requisite gene diversity (GD) over time (i.e., an effective **insurance population**)?
7. How big does the ex situ population need to be to retain sufficient GD over time (insurance population), whilst also producing a sufficient source of birds for release into the wild?
8. Given the current population trajectory in the wild, how many individuals must be released into the wild population, at what intervals and over what period, to achieve a stable population of 150 breeding pairs by 2070?
9. If supplementation can achieve a stable population, how big does the ex-situ population need to be to produce the required number of birds?
10. What is the best strategy for establishing an ex-situ population (i.e., harvest pressure) that is large enough to produce supplemental birds? What are the relative impacts of different strategies on the wild population?
11. How large will the in situ and ex situ populations need to be to retain 95% of current genetic diversity in the population?
12. How big does the population need to be to retain 95% of current genetic diversity over 100, 150 and 200 years?
13. Can we build a three-population baseline simulation model to mimic the effect of establishing a reintroduced population in a new site?
14. How many founder birds will be needed to establish a new population?

In preparation for the workshop, five basic model structures were developed that captured a range of options for consideration by the modelling team (Figure 4, Table 6):

1. **Baseline**. This model comprises a single population representing the wild population, using data from the field supplied by Sonja Krüger. No supplementation was modelled.
2. **Captive**. This model comprises a single captive population using ex situ data from the Bearded Vulture Breeding Programme, Brink et al. (2020), and data from captive facilities in Europe (Alex Llopis, pers. comm.). No supplementation was modelled.
3. **Insurance**. This model comprises two populations (wild and captive), linked through one-way flow from the wild population to the captive population. Vital rates for each population were the same as for the **Baseline** and **Captive** models.

4. **Augmentation**. This model comprises two populations (wild and captive), linked through two-way flow between them. Vital rates for each population were the same as for the **Baseline** and **Captive** models.
5. **Reintroduction**. This population comprises three populations (wild, captive, new), linked through harvest from the wild population into the captive population, and subsequent harvest of captive-bred birds into the new population at a time when the captive population could sustain such harvest.

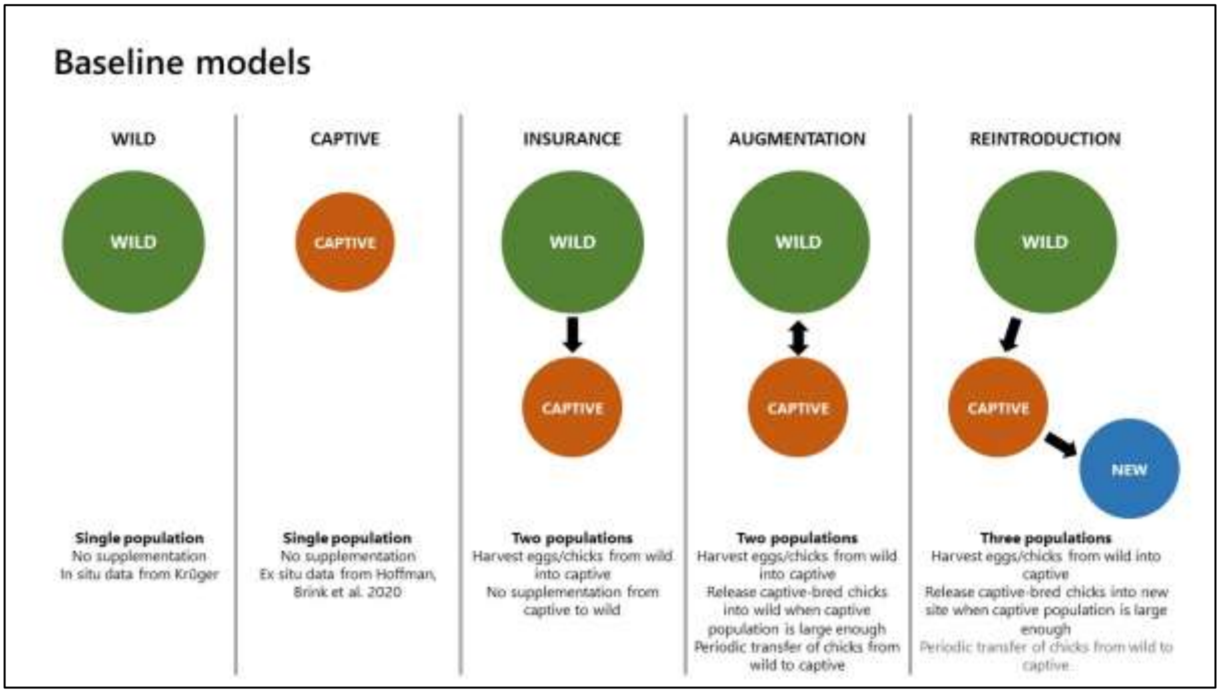

Figure 4 Details of five baseline models developed in preparation for the PVA process.

Table 6 Range of possible population interactions to explore.

		Recipient		
		Wild	**Ex situ**	**Reintroduced**
Source	**Wild**	Release of wild harvested captive-reared chicks into the wild	Eggs harvested from wild into captivity (this is done according to the protocol set for the season, and could be either the first or second egg of a 2 egg clutch and the only egg of a 1 egg clutch).	Release of wild harvested captive-reared chicks into the new population Natural dispersal from wild population to newly established site
	Ex situ	Release of captive bred juveniles into wild	Maintain population of captive bred birds for insurance population or for breeding	Release of captive bred juveniles into new population
	Reintroduced	Swapping of birds between populations to achieve GD targets Natural dispersal from new population back into existing wild population	Harvest of eggs from reintroduced population to bolter ex situ gene diversity	Release of wild harvested captive-reared chicks into the wild

3.5 Input parameters for baseline models

The study population for this PVA is taken as the entire southern African population of Bearded Vultures, which includes a wild (in situ) population, a captive (ex situ) population, and a potential new, reintroduced population.

Estimates for parameters used in the baseline models were obtained from the literature or from experts, with some of these being standard across all models (see section 3.7), and others specific to individual models, as outlined below.

3.6 Standard input parameters across all baseline models[4]

- **Duration and number of simulations**

All simulations were run for 50 years with 500 iterations using VORTEX. The Bearded Vulture has a generation length of ~16 years, and so the model duration represents ~3 generations.

[4] References provided for decisions when these were available, otherwise decisions were based on expert opinion provided by S. Krüger, pers. comm.

- **Definition of extinction**

Extinction was defined as occurring when only one sex remains.

- **Inbreeding depression**

Inbreeding depression was not incorporated into any baseline models.

- **EV (reproduction) to be concordant with EV (survival)**

In the absence of data to the contrary, it was assumed that environmental variation would affect both reproduction and survival, and the default value of 0.5 was used.

- **Types of catastrophes**

The baseline models did not include any catastrophes.

- **Monogamous, polygamous, or hermaphroditic population**

Bearded Vultures are assumed to mate for life and are therefore classified as long-term monogamous breeders.

- **Age at first reproduction for males and females**

The median age at first reproduction was assumed to be 7 years for both males and females.

- **Maximum breeding age**

Maximum breeding age was modelled at 32 years in all the baseline models.

- **Sex ratio at birth**

Very limited information is available for sex ratio at birth. An even sex ratio was chosen as the default (proportion of males at birth = 0.50). In a European reintroduction breeding programme, the sex ratio of newly hatched chicks was not significantly different from 50%.

- **Density dependent breeding**

As no data exist to show/disprove the presence of density dependence, and because the wild population is believed to be occurring at densities much lower than carrying capacity, density dependent reproduction was not included in the baseline models.

- **EV in % breeding**

Not enough data exist to calculate inter-annual variation in breeding due to environmental variation, and therefore we adopted the approach taken in the 2006 PHVA to include a value of 10% in the baseline model. This value was chosen due to the observed low variability in breeding attempts each year.

- **Mortality rates in the wild**

Mortality rates were estimated from field data collected from a sample of 24 tracked birds between 2000 and 2020 (Sonja Krüger pers. comm.). Age specific mortality rates were deduced by fitting a logarithmic curve to rates determined from field data (see 0. and Figure 3).

- **% Males in breeding pool**

As Bearded Vultures are long-term monogamous breeders, we considered females to be the limiting sex, and assumed that 98% of males were in the breeding pool (with the remaining 2% forming part of trios) (Krüger, pers. comm.).

- **Initial population size, population age distribution and carrying capacity**

These all varied between populations. Please see model-specific details in section 0 below.

- **Trend in carrying capacity**

No trend was set for carrying capacity in the baseline models.

- **Harvest/supplementation**

No harvest or supplementation was included in the wild model, although these were integrated into various other models.

3.7 Specific input data for expanded models

3.7.1 WILD model

- **Number of populations: one**

The baseline model of the wild population included one population. The population ranges over Lesotho and three provinces within South Africa (KwaZulu-Natal, Eastern Cape, and Free State) and is considered to be a single, interacting population.

- **Percentage adult females breeding**

In the WILD model, Time 0 is defined as the time of fledging. This variable is the same as the breeding rate defined in section 0 above – i.e., the proportion of pairs that attempt to breed. Recent estimates suggests that just 59.88% ± 24.92% of females attempt to breed each year (Krüger and Amar, 2017). Slightly higher rates than this were used by Brink et al., 2020, 72% ± 20% although the source was not provided (Krüger, 2014). The team agreed to use the lower (more pessimistic) rates in the models.

- **Distribution of broods**

We assume 23% of breeding females produce 0 broods and 77% produced 1 brood (Brink et al. 2020).

- **Mean number of offspring per breeding female**

Although Bearded Vultures will often lay two eggs, only one chick ever fledges in the wild. We specify an exact distribution of number of offspring per female per brood, at 1 offspring = 100% and 2 offspring = 0%.

- **Mortality rates**

We used a smoothed function against real-world mortality rates collected from a sample of tracked birds (see section 0 for details).

- **Initial population size**

Minimum current estimates of breeding pairs in the different areas were collated from the database and adjusted based on personal observations (Table 7). Adopting a precautionary approach, we used the minimum estimates in all models.

Table 7 Estimates used to determine the initial population size under different levels of monitoring certainty.

These estimates include 2020 data and include a review of data at all 260 sites over >20 years to standardise decision making across all the years. The "minimum" estimate counts as active only those nest sites where pairs were confirmed to be breeding. The "best" estimate counts as active all sites where breeding was confirmed and assumed based on the presence of individuals or pairs in the territory. The "maximum" estimate includes an additional 15 nest sites that were potentially active but were not monitored.

	Minimum	Best	Maximum
Number of breeding pairs[1]	76	103	118
Number of breeding adults	152	206	236
Trios	3	3	3
Single adults	36		
Total adults	191	209	239
Immatures (60% of adults)[2]	114	125	143
Total population[3]	305	334	382

[1] For the total number of active breeding pairs we can be confident about 76.

[2] The population estimate is based on the ratio of adults: non-adults of 1:0.6(Brown 1997, Krüger et al. 2014).

[3] The best population estimate (N=334) is only 15 pairs more than the minimum estimate.

- **Population age distribution**

The wild population was assumed to have a stable age distribution.

- **Carrying capacity**

The carrying capacity is unknown and so was set at 700 individuals.

3.7.2 CAPTIVE model

- **Number of populations: one**

The CAPTIVE baseline model included one population. This population is currently located as the captive breeding facility at the African Bird of Prey Sanctuary, Lynfield Park, KwaZulu-Natal.

- **Percentage adult females breeding**

A much higher percentage of females breed in captivity than in the wild. Following Brink et al., (2020), we use a rate of 100% ± 5%.

- **Distribution of broods**

Given that no breeding has yet taken place in captivity in southern Africa, there is no data available on the likely distribution of broods, although there is good data from captive facilities in Europe. These facilities are divided into two types: zoos and private facilities have lower fledgling production rates than specialist facilities. Workshop participants agreed that it would be realistic to model an improvement in chick production in captivity over time. We therefore used data from captive facilities in Europe to calculate the distribution of broods, starting from lower rates (modelled on the average rate of 0.60 fledglings per pair) and improving to rates found at specialist facilities (0.9 fledglings per pair) over a period of 10 years. To mimic these rates of fledgling production, we used the proportions indicated in Table 8.

Table 8 Fledgling proportions used in the model.

Number of fledglings produced	Low	High
0	0.4	0.2
1	0.6	0.7
2	0.0	0.1
Total	1.0	1.0

In VORTEX, we used equations[5] to manipulate the distribution of broods and brood size to obtain the distribution of fledgling rates during the first 10-year period of the CAPTIVE model as indicated in Table 9.

Table 9 Distribution of broods and brood size to obtain the distribution of fledgling rates during the first 10-year period of the CAPTIVE model generated in VORTEX.

	Proportion of broods of size:		
Year	**0**	**1**	**2**
1	0.400	0.600	0.000
2	0.378	0.611	0.011
3	0.356	0.622	0.022
4	0.334	0.633	0.033
5	0.312	0.644	0.044
6	0.290	0.655	0.055
7	0.268	0.666	0.066
8	0.246	0.677	0.077
9	0.224	0.688	0.088
10	0.202	0.699	0.099

These rates were used in all subsequent models and combinations of models that included the CAPTIVE baseline model.

- **Mortality rates**

For captive birds, we used mortality rates from Brink et al. (2020), as indicated in Table 10.

[5] **Distribution of broods:** 0 broods =(Y=1)*40+(Y=2)*38+(Y=3)*36+(Y=4)*34+(Y=5)*32+(Y=6)*28+(Y=7)*26+(Y=8)*24+(Y=9)*22+(Y>9)*20; 1 brood = balance. **Distribution of number of progeny per female:** 1 offspring =(Y=1)*60+(Y=2)*61+(Y=3)*62+(Y=4)*63+(Y=5)*64+(Y=6)*66+(Y=7)*67+(Y=8)*68+(Y=9)*69+(Y>9)*70; 2 offspring: =balance.

Table 10 Mortality rates for captive birds used in the models, obtained from Brink et al. (2020).

Age (years)	Mortality	SD in mortality
0–1	7.57%	25.06%
1–2	1.11%	4.03%
2–3	1.11%	4.03%
3–4	1.11%	4.03%
4–5	1.11%	4.03%
5–6	1.11%	4.03%
6–7	1.11%	4.03%
>7	3.30%	3.07%

- **Initial population size**

In mid-2022 the captive population contained 14 birds (Shannon Hoffman, pers. comm.). Please see details of the founding population structure below in Table 11.

- **Population age distribution**

A specified age distribution was used for the initial captive population, based on the structure of the existing captive population, as indicated in Table 11.

Table 11 The specified age distribution used for the initial captive population, based on the structure of the existing captive population.

Age (years)	Females	Males	Total
1	3	3	6
2	0	0	0
3	1	2	3
4	1	0	1
5	1	0	1
6	0	0	0
>=7	2	1	3
Total	**8**	**6**	**14**

- **Carrying capacity**

Set at 32 birds.

3.7.3 INSURANCE model

- **Number of populations: two**

This model contains two populations and links the wild and captive populations by harvesting eggs from the wild into the captive population for the purposes of establishing an insurance population. Movement of birds is managed through the translocation option in harvest and supplementation.

- **Initial population size and age distribution**

This model uses population sizes and age distributions for the baseline wild (n=305) and captive (n=14) models.

- **Carrying capacity (K)**

The wild population K was set at 700, and the captive population K at 32.

- **Harvest and supplementation**

The populations are linked through harvest from the wild population into captivity.

3.7.4 SUPPLEMENTATION model

- **Number of populations: two**

This model contains two populations and links the wild and captive populations by harvesting eggs from the wild into the captive population and releasing captive-born fledglings back into the wild population. Movement of birds is managed through the translocation option in harvest and supplementation.

- **Initial population size and age distribution**

This model uses population sizes and age distributions for the baseline wild (n=305) and captive (n=14) models.

- **Carrying capacity (K)**

The wild population K was set at 700, and the captive population K at 32.

- **Harvest and supplementation**

The populations are linked through two-way flow between both populations.

3.7.5 REINTRODUCTION model

- **Number of populations: three**

This model contains three populations, linked through translocations. Eggs harvested from the wild are taken into captivity and captive-born chicks are released into a new site in the historical range where the species has gone locally extinct, but where threats have been mitigated.

- **Mortality rates**

Baseline mortality rates in the new population were set at 90% (i.e., 10% lower) of those in the wild population. The justification for this was that reintroduction to a new site would only be considered if mortality rates at the new site were lower than those in the current population.

- **Initial population size and age distribution**

This model uses population sizes and age distributions for the baseline wild (n=305) and captive (n=14) models, and the new population starts at n=0.

- **Carrying capacity (K)**

The wild population K was set at 700, the captive population K at 32, and the new population K at 500.

- **Harvest and supplementation**

The populations are linked through harvest from the wild population into captivity, and from captivity into a new population at a time when the captive population can sustain such harvest for release.

3.8 Summary of variable input parameters for baseline models

Table 12 provides a summary of the various input parameters used in the five baseline model structures.

Table 12 Summary of the various input parameters used in the five baseline model structures (WILD, CAPTIVE, INSURANCE, SUPPLEMENTATION, REINTRODUCTION).

Input parameter	Model				
	WILD	CAPTIVE	INSURANCE	AUGMENTATION	REINTRODUCTION
Number of populations	1	1	2	2	3
Description of populations	Wild	Captive	Wild Captive	Wild Captive	Wild Captive New
% adult females breeding	59.88% ± 24.92%	100% ± 5%	As per Wild and Captive	As per Wild and Captive	As per Wild and Captive
Distribution of broods	0: 23% 1: 77%	0: 40% in Y1 down to 20% in Y10 1: 60% in Y1 up to 80% in Y10	As per Wild and Captive	As per Wild and Captive	As per Wild and Captive
Mean number of offspring per breeding female	1: 100& 2: 0%	1: 60% in Y1 up to 70% in Y10 2: 0% in Y1 up to 10% in Y10	As per Wild and Captive	As per Wild and Captive	As per Wild and Captive
Mortality rates for different age classes	0-1: 35.3% 1-2: 25.9% 2-3: 20.4% 3-4: 16.5% 4-5: 13.5% 5-6: 11.0% 6-7: 9.0% >7: 7.2%	0-1: 7.6% 1-2: 1.11% 2-3: 1.11% 3-4: 1.11% 4-5: 1.11% 5-6: 1.11% 6-7: 1.11% >7: 3.3%	As per wild and captive	As per wild and captive	As per wild and captive. **New** population mortality rates 10% lower than current wild population
Initial population size (N)	N_W=305	N_C=14	N_W=305 N_C=14	N_W=305 N_C=14	N_W=305 N_C=14 N_N=0
Population age distributions	Stable age	Specified age	Stable age Specified age	Stable age Specified age	Stable age Specified age None
Carrying capacity (K)	K_W=700	K_C=32	K_W=700 K_C=32	K_W=700 K_C=32	K_W=700 K_C=32 K_N=500
Harvest	None	None	Wild	Wild, Captive	Wild, Captive
Supplementation	None	None	Captive	Wild, Captive	Captive, New

3.9 Sense-checking the WILD baseline

To test whether the WILD baseline model was a reasonable reflection of current population dynamics, the model was run from a starting initial population size of N=368, the most pessimistic population estimate from field data in 2012 (Krüger, 2014), to test whether the trajectory followed observed population estimates. This produced the following population response (Figure 5) which was deemed to be sufficiently close to our understanding of the actual population trajectory to proceed. Other model outputs are provided in Table 13.

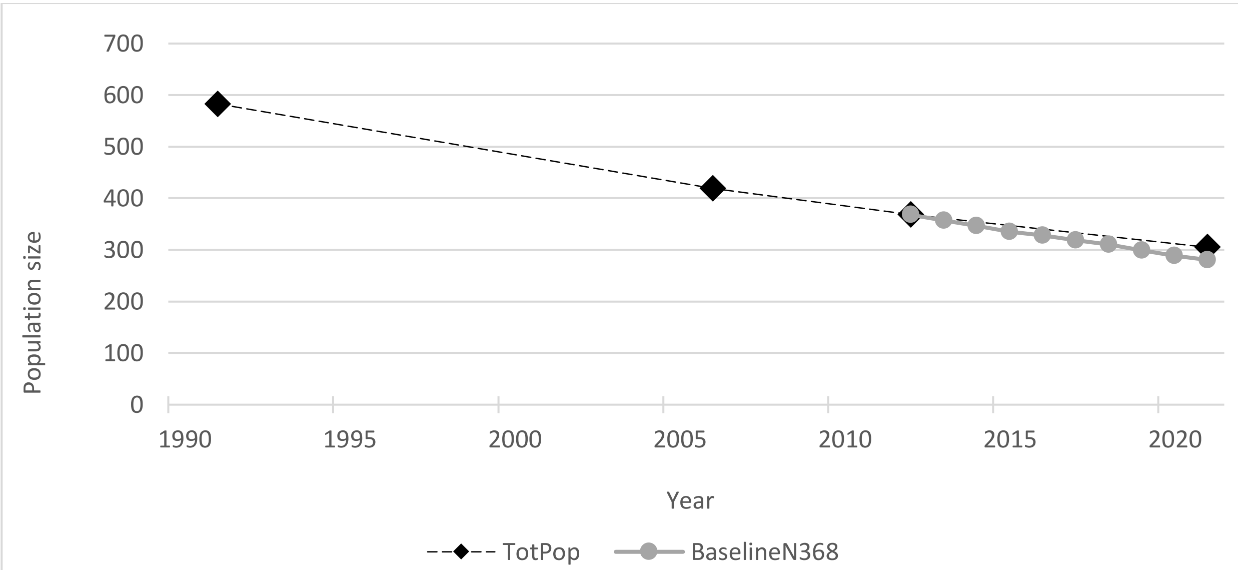

Figure 5 Comparison of the output of the Wild baseline model of the Bearded Vulture population in southern Africa (grey line, representing modelling projections back-cast from 2012) and abundance estimates from field observations (black rhombuses, dotted line).

Table 13 VORTEX output data from the Wild baseline model (500 iterations) of the Bearded Vulture population in southern Africa, over 50 years.

Parameter	Deterministic growth rate - r	Stochastic growth rate - r	SD r	N-extant	SD N-extant	GD
Wild baseline	-0.0301	-0.0351	0.0885	75.30	43.01	0.9703

3.10 Demographic sensitivity testing

Sensitivity tests enable us to explore which components of the model have the greatest impact on model projections. Such tests are useful for identifying influential assumptions and key knowledge gaps. Sensitivity tests are run by carrying values of different parameters – one at a time – to explore how model projections vary.

The WILD baseline model was used as the basis of a series of sensitivity tests to explore the relative impacts of different values of population parameters on the population growth rate (*r*) and projected final mean population size (*N*) of surviving populations after 50 years. The parameters examined and ranges tested are outlined in Table 14.

Table 14 Parameters and rates used in demographic sensitivity tests of the wild population.

Parameter tested	Base value	Values tested	Scenario codes
Definition of extinction	One sex remains	N<35 individuals	ST_ExtN35
EV (reproduction) to be concordant with EV (survival)	0.5	0.25; 0.75	ST_EV25, ST_EV75
Age at first reproduction for males and females (years)	7	6[6]; 8	ST_AR6, ST_AR8
Maximum breeding age (years)	32	22; 27	ST_BR22, ST_BR27
Sex ratio at birth (proportion males)	0.5	0.4; 0.6	ST_SR40, ST_SR60
% females breeding	60%	-10%; +10%	ST_FBr90, ST_FBr110
EV in % females breeding	10%	5%; 15%	ST_EVFBr5%, ST_EVFBr15%
Juvenile mortality	35.3%	-20%; -10%; +10%; +20%[7]	ST_JM-20%, ST_JM-10%, ST_JM+10%, ST_JM+20%
Adult mortality (all ages >7)	7.2%	-20%; -10%; +10%; +20%	ST_AM-20%, ST_AM-10%, ST_AM+10%, ST_AM+20%
Mortality off all age classes	Various	-10%; -15%; -20%	ST_M-10%, ST_M-15%, ST_M-20%

The influence of different vital rates on the final population size after 50 years is shown in Figure 6. The following factors had the most significant impacts on model outputs:

*Adult mortality
*Juvenile mortality
*Proportion of breeding females
*Age of first reproduction

Unfortunately, it is difficult to obtain accurate estimates of these vital rates and so this leaves a large degree of uncertainty in the model outputs overall. It also provides useful guidance for future demographic research on Bearded Vultures.

[6] Adjusted adult mortality rates to start from 6 years
[7] There are relative to the baseline percentages; for example, if the baseline is 30%, a 10% reduction will give a mortality rate of 27%

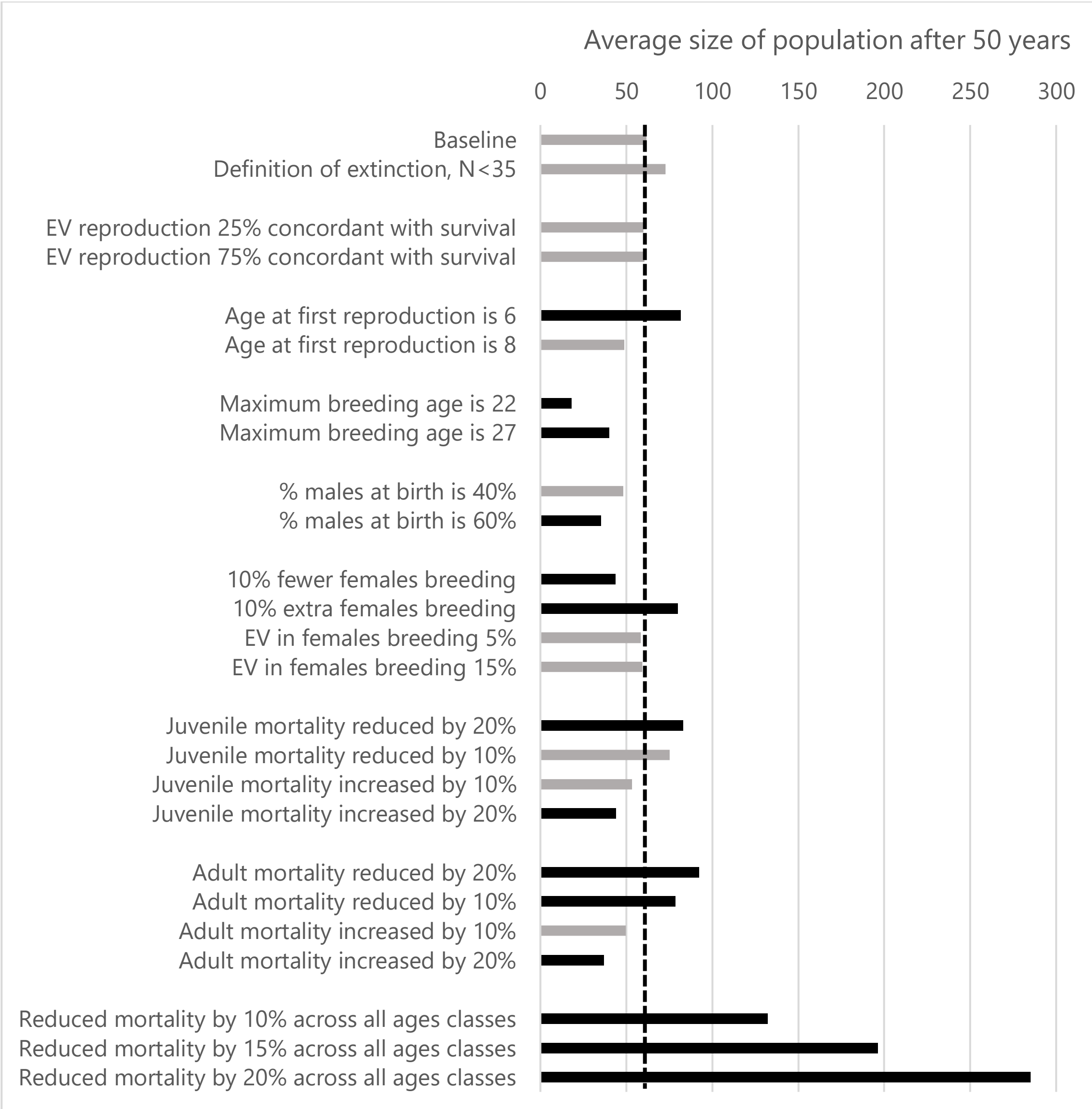

Figure 6 The influence of various Bearded Vulture population parameters on model outputs (final population size) after 50 years. Details of parameter values are provided in Table 3.12. Dashed line represents final population size for the baseline model. Black bars reflect deviations of >25% from the baseline.

3.11 Model selection during the workshop

At the workshop, participants were presented with the five candidate baseline models and asked to consider which combinations of baseline models to explore to test different management scenarios. They settled on three core models, and requested that various scenarios were explored, relating to mortality rates, carrying capacity, productivity and harvest and supplementation strategies. These are presented in Table 15.

Table 15 Baseline models selected by workshop participants for the purposes of exploring various scenarios.

Model	Number of populations	Scenarios tested	Harvest and supplementation options
2.1 **Insurance model** with reduced mortality and staggered harvest	2	Mortality reduced for all ages classes by 10%, 15%, or 20%	Harvest 6 fledglings from the wild into captivity every year for 3 years, then 4 fledglings every 5 years[8] No movement from captive to wild.
			No harvest from the wild (i.e., wild and captive populations start from current state, with no movement of birds between them)
2.2 **Insurance model** with reduced mortality, consistent harvest	2	Mortality reduced for all ages classes by 10%, 15%, or 20%	Harvest 6 fledglings from the wild into captivity every year for first 8 years
		Captive carrying capacity increased to K=64	
3.1 **Supplementation model** with staggered harvest	2	Mortality reduced for all ages classes by 15% or 20%	Harvest 6 fledglings from the wild into captivity every year for 3 years, then 4 fledglings every 5 years Release all captive bred fledglings back into the wild from year 4[9]
		Captive carrying capacity increased to K=42 or K=64	
		Improved productivity: % adult females breeding = 63% AND distribution of broods, 0=15.3%, 1=84.7%	
4.1 **Reintroduction** model	Workshop participants felt that options for reintroduction into a completely new site should be considered in future only if the scenarios in **Error! Reference source not found.** failed to lead to population recovery and threats in the new site had been robustly assessed and mitigated. We therefore did not explore the REINTRODUCTION model any further.		

3.12 Model results

Detailed outputs of all models are provided in Appendix VIII

3.12.1 INSURANCE 2.1 models with staggered harvest

Figure 7 provides the results of the scenarios tested for the INSURANCE 2.1 model. In this model, eggs are harvested from the wild to supplement the captive population, which can hold a maximum of 32 birds. Six eggs are harvested each year for the first 3 years, and thereafter 4 eggs are harvested every 5 years. No captive birds are released back into the wild but are held as an insurance population for future release should this be required.

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[8] Harvest function for Age 0 birds of both sexes: =((Y<4)*(IUNIFORM(1;3)))+(((Y>3)*((Y%5-3)=0))*(IUNIFORM(1;2)))

[9] Harvest function for Age 0 birds of both sexes: =CEIL(J*0.5)-1

The basic model (Figure 7, A) shows that harvesting eggs into a captive population leads to a slightly smaller wild population after 50 years. The overall metapopulation (i.e., wild + captive) has slightly more birds (N=81 vs N=61).

When mortality rates are reduced across the board (Figure 7, B), we see significant improvements in population size at the end of the 50-year period. All these improvements occur in the wild population since the captive population is capped at a carrying capacity of K=32.

The third graph (Figure 7, C) shows that very similar numerical results can be achieved even if there is no movement of birds from the wild into captivity (i.e., the captive population grows from its current founder stock of 14 birds). Population sizes at the end of the 50-year period are slightly larger than with harvest, because there has been no removal of birds from the wild.

Figure 7 (D) compares the genetic outcomes of harvesting or not harvesting, in a model that include a 15% reduction in mortality across all age classes. This clearly shows that, although the population trajectories are not significantly affected (Figure 7, C), there are large genetic differences in the captive population depending on whether it is supplemented by wild birds or not.

Key results from the INSURANCE 2.1 model scenarios:

1. **Harvesting from the wild does not have a significant influence on the population trajectory of the wild population.**
2. **A captive population can be maintained as an insurance for future reintroductions if needed.**
3. **Mortality reductions in the wild population can lead to a significant increase in the overall number of birds at the end of the 50-year period.**
4. **Although a captive population could be established from the existing 14 founder birds, the genetic diversity of the captive population will decline unless there are periodic additions of wild birds into the captive population.**

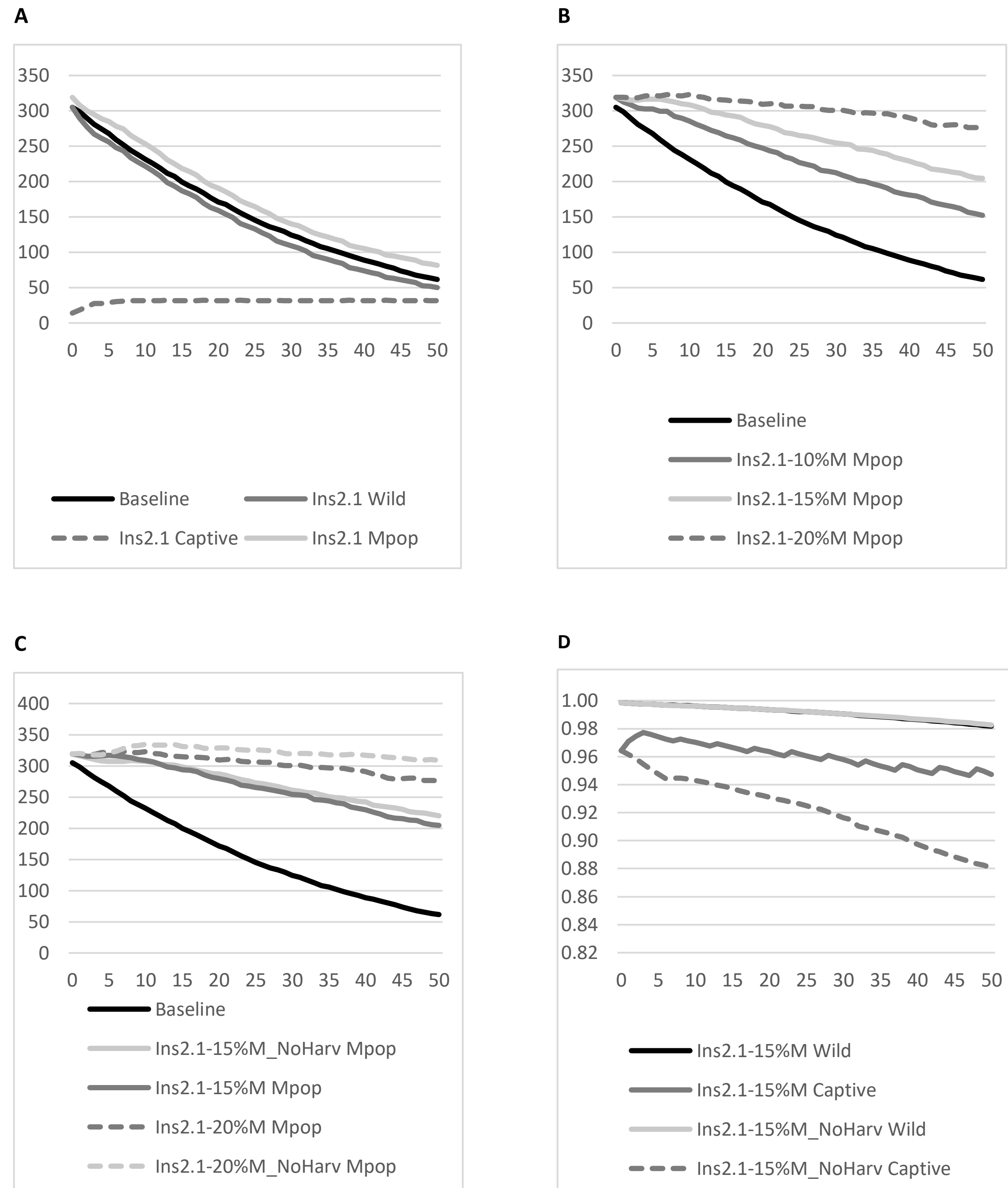

Figure 7 Outputs of scenarios explored using the INSURANCE 2.1 model. Figure legends indicate the models used, where Mpop = Total population; the % M refers to the % that all mortality changed from the baseline; NoHarv = model run with no exchange between populations.

3.12.2 INSURANCE 2.2 models with consistent harvest for first 8 years

Figure 8 provides the results of the scenarios tested for the INSURANCE 2.2 model. In this model, eggs are harvested from the wild to supplement the captive population, which can hold a maximum of 32 birds. Six eggs are harvested every year for the first 8 years, and thereafter no further harvests are undertaken. No captive birds are released back into the wild but are held as an insurance population for future release should this be required.

The trajectories presented in Figure 8A are very similar to those in Figure 7A, suggesting that an aggressive wild harvest in the first 8 years will not lead to significantly different outcomes for the population.

Like the Insurance 2.1 model, reductions on mortality across the board will lead to significant improvements in population trajectory, with the biggest improvements at a 20% reduction (Figure 8B).

Increasing the carrying capacity of the captive population to K=64 does nothing to influence the trajectory of the wild population but increases the overall number of birds because there are more birds in captivity, where mortality rates are lower (Figure 8C). However, a larger captive population has better long-term genetic outcomes, as clearly shown in Figure 8D.

Key results from the INSURANCE 2.2 model scenarios:

1. **An initial aggressive harvesting from the wild does not have a significant influence on the population trajectory of the wild population.**
2. **Mortality reductions in the wild population can lead to a significant increase in the overall number of birds at the end of the 50-year period.**
3. **The larger the captive population, the better the long-term genetic outcomes.**

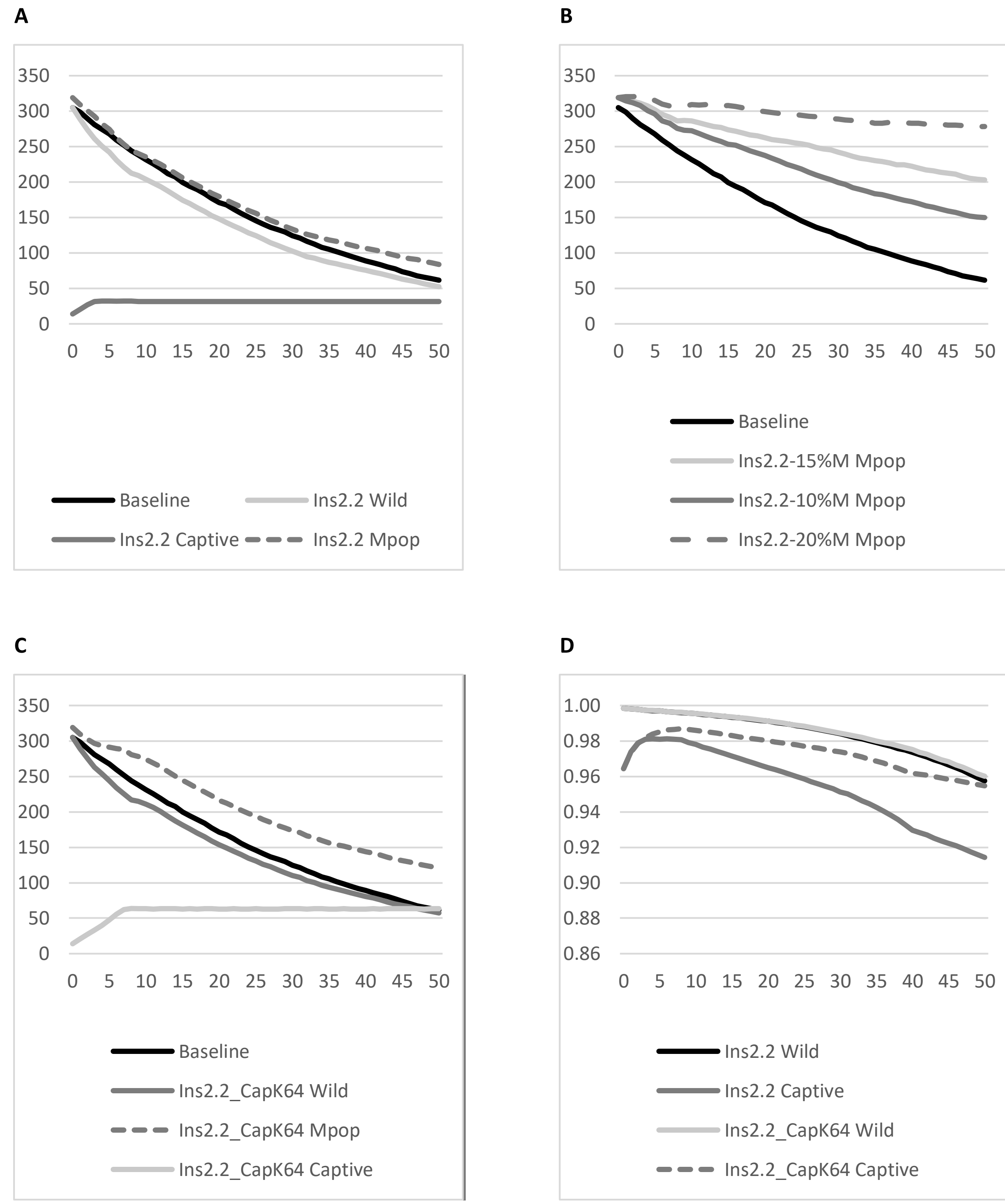

Figure 8 Outputs of scenarios explored using the INSURANCE 2.2 model. Figure legends indicate the models used, where Mpop = Total population; the % M refers to the % that mortality changed from the baseline.

3.12.3 SUPPLEMENTATION models

The last set of models explored the effects of two-way translocations between the wild and captive populations. In these scenarios, the captive population acts both as an insurance population but also as a source of birds that are used to augment the wild population. The results from these scenarios are presented in Figure 9.

The supplementation of the wild population from captivity leads to significant improvements in population projections against the baseline, with three times the number of birds in the metapopulation at the end of 50 years (Figure 9**Error! Reference source not found.**A). The trajectories improve even f urther when the carrying capacity of the captive population is increased to K=42 and K=64. This effect is not simply an increase in the number of birds in captivity but also because more birds are being produced and released into the wild (Figure 9B).

As with the previous models, a reduction in mortality across all age classes has significant effects on population outcomes, with the population coming close to stabilising with a 10% reduction, and experiences big increases at 15% and 20% reductions (Figure 9C).

When reduced mortality rates are combined with an increase in productivity, the population achieves a positive trajectory very easily (Figure 9D). The best performing model was one that combined a reduction in mortality of 20%, with a 10% increase in productivity, and a captive population of 64 birds. This model results in 549 birds in the wild at the end of the 50-year simulation.

Key results from the AUGMENTATION 3.1 model scenarios:

1. Using captive-born birds to supplement the wild population leads to significant improvements in population trajectory over time.
2. The larger the captive population, the greater the outcomes for the wild population.
3. Reductions in mortality in the wild very quickly result in stabilisation of population trajectories.
4. The best results in the wild are achieved with a combined strategy of mortality reduction, increased productivity, and population supplementation from the captive population.

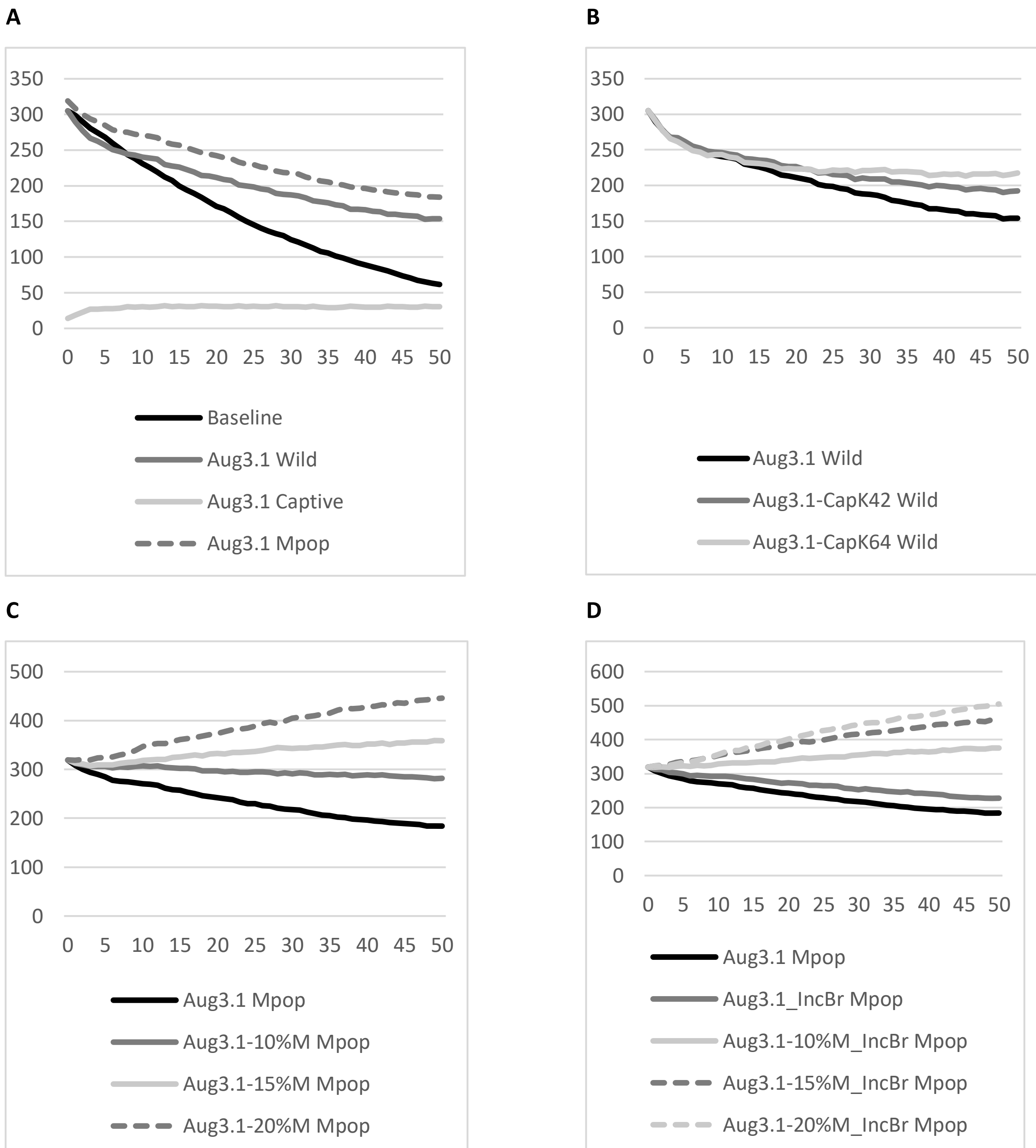

Figure 9 Outputs of scenarios explored using the AUGMENTATION 3.1 model. Figure legends indicate the models used, where Mpop = Total population; the % M refers to the % that all mortality changed from the baseline; IncBr = increase in breeding rate. A – baseline AUGMENTATION model; B – comparing changes in carrying capacity of the captive population; C – effects of decreasing mortality across all ages classes by 10-20%; D – effects of a combination of reduced mortality and increased productivity.

3.13 Key population drivers: knowledge gaps and priorities for action

Based on the sensitivity tests using the WILD baseline model, the main drivers of population dynamics for the Bearded Vultures in the wild are:

Mortality rates at all ages. Changes in mortality rates have significant effects on the outcomes of the models, as illustrated by the summary results in

1. . Unfortunately, our estimates of mortality have been obtained from a relatively small sample of tracked birds, and this means that all the outputs from the modelling process should be interpreted with caution.
2. **Productivity.** The challenge of observing nesting in the Bearded Vultures' mountainous habitat, mean that estimates of the number of females breeding are likely to be both inaccurate and imprecise. Re-visits to active nests and monitoring a large sample of nests are not always feasible, and so we also do not know how many eggs become fledglings. Productivity is a key driver of population dynamics and so further work to obtain more accurate and precise estimates is a priority.
3. **Basic reproductive biology.** The age of first and last reproduction is also a strong driver of population dynamics, and any contraction of a bird's breeding period over its lifetime tends to significantly reduce the viability of the population in the long-term. In addition, while it is known that in growing populations, females can breed at the age of 5 years, in very dense populations (e.g., in the Pyrenees), they do not start breeding on average until they are 11–12 years old. So, while birds may be at the age of sexual maturity, the age at which they start breeding can be quite different and depends on many factors (A. Llopis pers. comm. 22 Oct 2022). Studies to better understanding basic breeding biology are therefore important.

4 CONCLUSION

This report presents the results of a PVA for the southern African population of Bearded Vultures facilitated by the IUCN's Species Survival Commission's Conservation Planning Specialist Group. This independent process used international best practice and VORTEX software to develop a series of baseline models against which the effectiveness of different interventions could be tested.

The baseline model indicated that the wild population, at the current rate of decline with no additional interventions, would decline to 62 birds (20 breeding pairs) in 50 years. To prevent the species from going extinct in southern Africa and to achieve the goals of the Bearded Vulture Recovery Strategy and Action Plan (150 pairs by 2070), the Bearded Vulture Recovery Programme must achieve the following:

- A reduction in mortality of 15% across all ages (i.e., prevent the deaths of just 6 birds per year);
- Increased productivity in the wild of 5% (i.e., increase the proportion of females that breed and increase the number of chicks that survive until fledging); and
- Harvest 6 eggs from the wild population for the next three years to build a captive flock of 32 birds (large enough to conserve >90% of the remaining genetic diversity of the wild population and produce sufficient chicks for release back into the existing wild population); thereafter harvest between 2 and 4 eggs from the wild every 4 years to maintain an appropriate age structure and genetic diversity within the captive population.

By 2026 the captive breeding programme will be ready to release birds, therefore the BVTF will need to intensify actions in the next 4 years to reduce mortality in the wild population by 15% and to identify and prepare safe release sites. If mortality cannot be reduced by 15% and productivity increased by 5%, then the captive population would need to be increased to 42 birds, which will allow for increased supplementation back into the wild.

The immediate focus will be on securing the current wild population through threat mitigation (i.e., addressing existing poisoning, power line and any other man-induced mortality, while preventing any future increase in these and other threats) and supplementation (release of captive-bred birds within the current range). If mortality within the current range cannot be adequately reduced in the near future, the BVTF will have to consider the option of re-establishing a new population within the historical range of the species where the threats are less problematic. The option to establish additional populations, if considered, is one that would benefit from further discussions with recovery teams working in Europe where multiple sites are used to reduce the probability of extinction across the range.

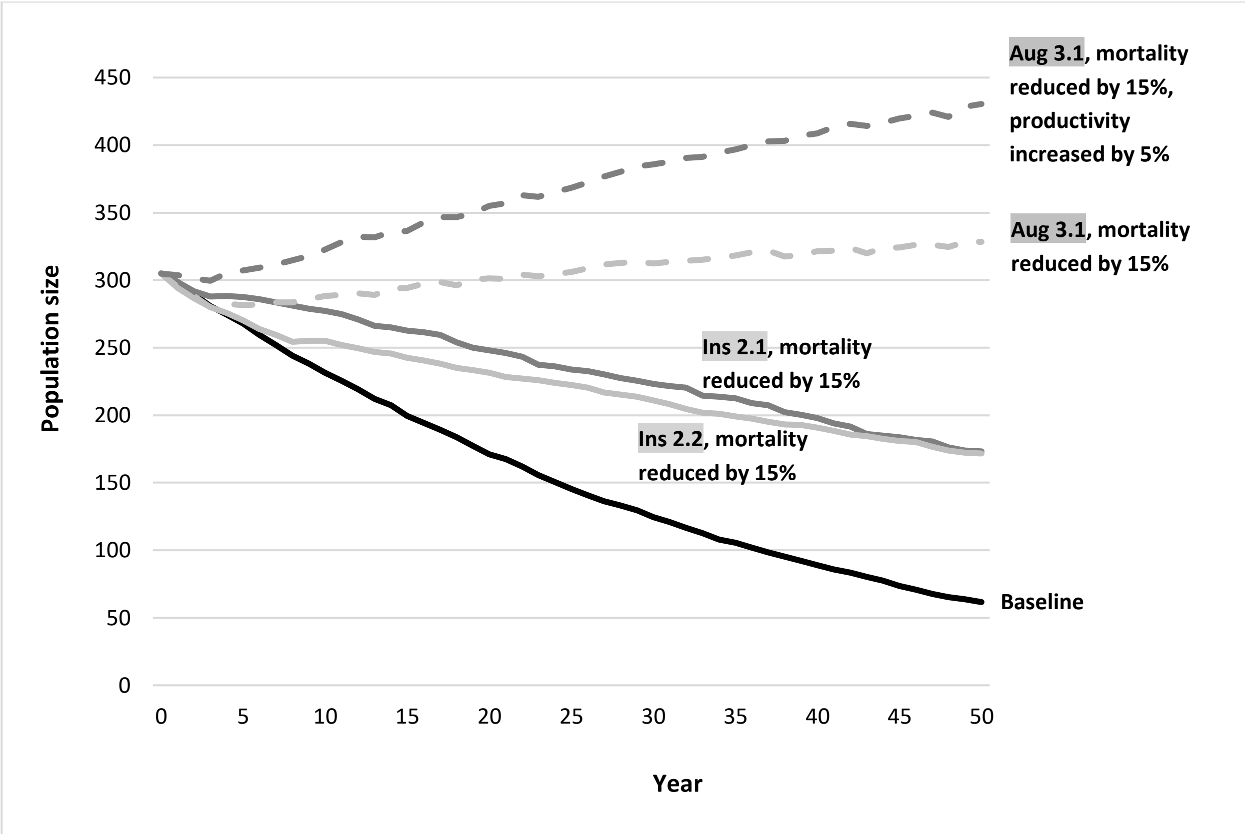

Figure 10. Graph showing the most promising population trajectories from modelled scenarios. Please refer to Table 12 and Table 15 for more details on the scenarios.

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6 APPENDICES

APPENDIX I: Summary of IUCN Conservation Planning Specialist Group-facilitated modelling and decision-making process for Bearded Vulture captive breeding, 2020–2021

Background
By mid-2020 the Breeding component of the BVRP had been going for over 5 years. It has been proven that eggs can be harvested, chicks can be reared, and much has been learnt about the husbandry needs of the species. However, the team has also learnt about the practical challenges. For many reasons it was clear that it was time to either take the project to the next level or stop it. But – to make such a big decision the team needed to ensure that the decisions were based on good data using internationally accepted methods with the guidance of the best experience in the field.

To facilitate this process the following steps were followed:

STEP 1
Recruitment of Jamie Copsey (CPSG – IUCN Facilitator) and Dr Harriet Davies-Mostert (EWT)
Multiple meetings were held between a core team of Jamie, Harriet, Ian Rushworth (EKZN Wildlife) and Dr Judy Mann (BVBP Chair) to determine the steps to be taken to fulfil the goals described above. The role of this core team was to keep the process going until (1) a short-term decision for the 2021 harvest had been reached, and (2) the role of the *ex situ* population in the overall recovery programme has been reviewed and defined.

STEP 2
The Model Input - 8 December 2020
Attendance
Jamie Copsey; Harriet Davies-Mostert; Judy Mann; Ian Rushworth;
Kerryn Morrison
Sonja Krüger; Brent Coverdale
Shannon Hoffman; Ben Hoffman; Bill Howells
Mantsatsi Moleleki; Mamasheane Motabotabo; Mammeli Makhate
Chris Kelly; Willeen Olivier; Andre Botha; Linda van den Heever

Recording link:
https://us02web.zoom.us/rec/share/pdYKoLw6IV7NJiXIAHFSw4OHo0PWR90Z0hz7sEbjatgjqqDztzFBC2u2KHqGtLFK.DEoCPcNLkYrIUvHA
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Summary
The CPSG process was outlined, and a route forward for the BV project was discussed. All agreed that an updated PVA model on the species was needed to guide future decisions.

STEP 3
Input from all stakeholders on desired end state - 10 December 2020
(Summary of consolidated responses available – See Appendix 2)

STEP 4
Modelling undertaken by Dr Harriet Davies-Mostert (EWT)

STEP 5
Presentation of the baseline model - 16 February 2021
Attendance
Jamie Copsey; Harriet T. Davies-Mostert; Ian Rushworth; Judy Mann; Sonja Krüger; Brent Coverdale; Shannon Hoffman, Bill Howells; Chris Kelly; Ben Hoffman; Alex Llopis Dell; Willeen Olivier; Mantsatsi Moleleki; Mamasheane Motabotabo

Outcome
The long-term trajectory of the species was very similar to that projected in the 2006 modelling process. This suggested that both *in situ* and *ex situ* interventions are urgently required. It was agreed that to ensure that the *ex situ* component could be undertaken a change in the harvest strategy was needed, however a decision on the required changes to the strategy was not possible without further information from the model.

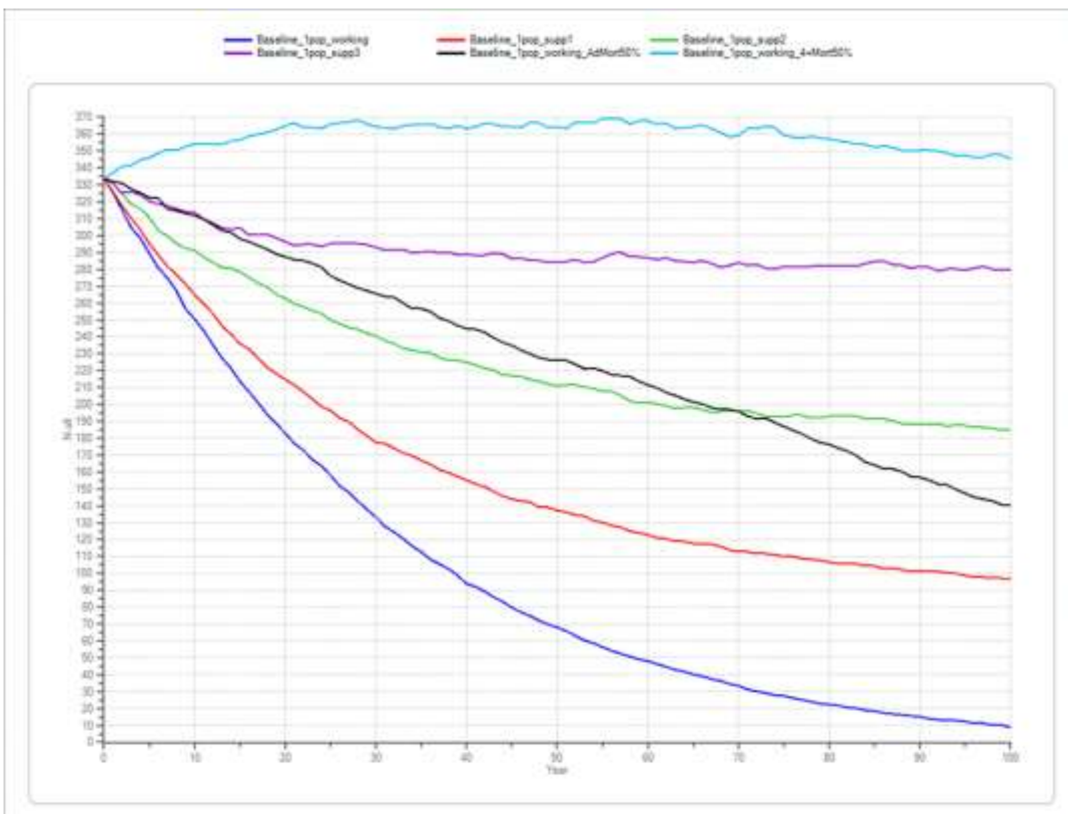

Figure 1. Multiple scenarios for the 100-year future of the Bearded Vulture. The baseline (scenario without supplementation or any additional in situ interventions, blue line) is compared to various interventions and combinations of interventions (supplementation and reduction in mortality).

Breeding Programme Committee Meeting
22 April 2021
Outcome – a decision on the 2021 harvest strategy was needed urgently to enable the season to proceed.

STEP 6
Presentation of the impact of supplementation modelling – 10 May 2021

First stage: Presentation and discussion of the baseline model for the future trajectory of the species in the wild and reviewing some future intervention scenarios to gain a sense of the relative contribution that *ex situ* management could make to the long-term stabilisation/increase in the wild population.

Second stage: Continued discussion and consideration of the potential impact of varying levels of harvesting effort on the wild population to establish different scales of ex situ population, with a particular focus on the likely impacts of modifying 2021/2022 harvesting numbers.

Attendance

Jamie Copsey; Harriet T. Davies-Mostert (Modelling); Ian Rushworth; Judy Mann; Sonja Krüger; Brent Coverdale; Shannon Hoffman, Bill Howells; Chris Kelly; Ben Hoffman; Alex Llopis Dell; Willeen Olivier; Mantsatsi Moleleki; Bataung Mokhele representing Mamasheane Motabotabo

Recording link: https://us02web.zoom.us/rec/share/8rsukYhWh1RgXN3yqqcSn-o9kAnAZTttnSfpWsP65u11hbWYvoen4tmGwbfbRZgY.PBqvcuPuDz8RQTH2?startTime=1620637462000

Outcome
General agreement that the 2021 harvest objective was to ensure enough eggs were harvested to have confidence that six young could be added to the captive population to begin building what is required to meaningfully contribute to the wild population in the future and establish a safety net in the shorter term. Agreement that the approach to harvesting birds over the last few years has been insufficient to result in the required scale of future supplementation releases. The strategy needs to change.

Model Results as a PDF Available on request

STEP 7
Decision making process – 13 May 2021

Attendance
Jamie Copsey – IUCN (Facilitator); Harriet T. Davies-Mostert (Modelling); Ian Rushworth; Judy Mann; Sonja Krüger; Shannon Hoffman, Bill Howells; Chris Kelly; Ben Hoffman; Alex Llopis Dell; Willeen Olivier; Mantsatsi Moleleki; Bataung Mokhele on behalf of Mamasheane Motabotabo.

Aim

Restatement of objective and the context and run through the additional PVA work to determine impact on the wild population of a more assertive harvesting strategy, at least this year (and potentially looking ahead four years which would in principle allow the achievement of the target captive population size). Critically review each of the alternatives, identifying the various pros/cons of each, and through this discussion aim to reach an agreement for the 2021 harvesting season only.

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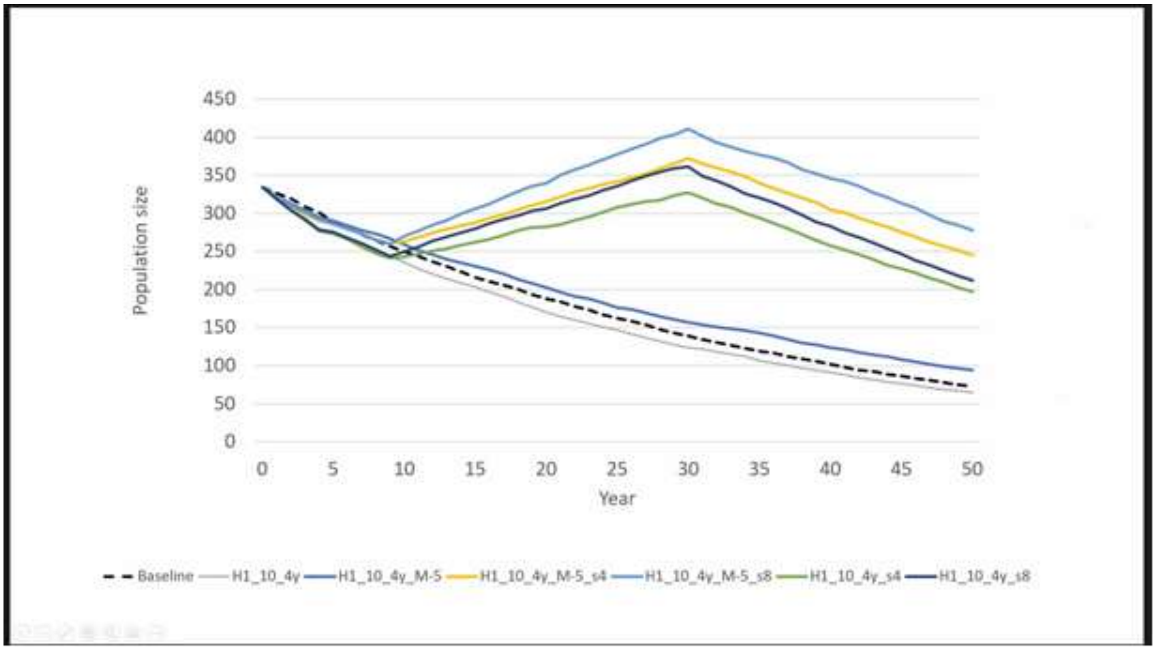

Figure 2. Modelling results of multiple scenarios of supplementation to the Bearded Vulture population. Even an 'assertive' harvest strategy (zero production of ten nests per year for four years, grey line) would have a limited effect on the population outcome; this impact would be compensated for by the benefit of future releases, assuming the breeding programme is able to successfully raise breeding pairs. However, in situ mortality needs to be reduced by significantly more than 5% across all age categories to sustain the population.

Outcome

The following was recommended:

Harvest first egg from double egg clutches and take the egg from single egg clutches from an identified subset of about 10 nests, with a target of getting six successful hatchings.

Where single eggs are taken then a dummy egg should be placed in the nest (there are specific criteria for size and weight and this needs to be carefully guided by the European experience).

Principles:

There appears to be some genetic basis for single egg breeders (data from Europe) so it is important to harvest some eggs from single-egg pairs to ensure full representation of the population genetic diversity in the captive population, even though this may have a marginally larger impact on the breeding output of the wild population.

If there is a clear surplus of viable nests to access, then, all else being equal, choose nests with two egg clutches over nests with single egg clutches.

Given the cost and risk to life from climbing and Covid (for 2021), even single eggs should be removed, however single chicks must not to be taken, though the smaller of two chicks could be taken if two live chicks are on the nest at the time of climbing.

The main risk of desertion or predation by ravens relates to the climbing event, rather than the egg removal event, so if the disturbance has been created to climb to a nest, then it makes sense to take even a single egg to minimise the number of nests disturbed.

For single egg clutches do not take pipping eggs; if there is one chick and the second egg is pipping then fine to take pipping egg.

Monitoring of productivity across the population will be particularly critical this year to establish whether this approach is having any measurable impact on the population. This monitoring will also help inform inclusion of new sites in 2022+ to both take pressure off known breeders AND ensure wider genetic representation in captivity. This proposal is only for this year and would be re-evaluated in advance of the 2022 season.

Monitoring of climbed nests to be undertaken in collaboration by Shannon Hoffman and Sonja Krüger.

Remaining Work

It is now essential, before momentum is lost, to complete the captive model and review and precisely define the scale and role of the *ex situ* population in the overall recovery programme of the Bearded Vulture. This should happen before the end of June so that the BV Recovery Strategy can be revised accordingly.

It is clear from Figure 2 that captive breeding and release buys time but the *in situ* mortality must be drastically reduced if the species is to survive. The next phase in this project should focus on *in situ* mortality reduction.

OTHER ACTIVITIES

AGREEMENTS

In addition to the modelling the following agreements have also been worked on:

Bilateral Agreement with Lesotho (11 Versions) November 2020 Waiting for MTEC The MOA between Kingdom of Lesotho and RSA regarding the BVRP (housing the BVBP) needs to be accepted and signed (Mamasheane Motabotabo and Ian Rushworth) *Under discussion with Lesotho to send to South Africa to be ready by May*

BV Task Force ToR (9 versions) May 2020 Pending

BP Steering Committee ToR (12 versions) April 2020 Agreed

Recovery Strategy and Action Plan

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BP Steering Committee ToR (12 versions) April 2020 Agreed
Recovery Strategy and Action Plan

MINISTERIAL VISIT

A visit from the Lesotho Ministry of the Environment was hosted by the Bird of Prey Sanctuary in March 2020.

APPENDIX II: Bearded Vulture recovery discussion (10 December 2020): consolidated responses

Received from Sonja Krüger, Shannon Hoffman, Ben Hoffman, Brent Coverdale, Andre Botha

DATE: 10 December 2020

BEARDED VULTURE RECOVERY DISCUSSION (8 December 2020)

Please add your responses below under the sub-titles highlighted in yellow. The responses here were captured at the workshop.

What does success look like? (What should be the goals (SMART) of the recovery programme)

The two tables below provide opportunities for you to add your thoughts on the conservative and optimistic measures of success for the species. These details will provide the framework in which we can develop the PVA models. Please add a row of information to reflect your own views on what we should be aiming for at a minimum as well as at an ideal level.

Conservative/ minimum goal elements

How far into the future should we be looking?	What status would we like to imagine for the species at this time frame?	What level of risk of extinction are you willing to tolerate?	Any other information/ comments
In Situ			
2050 (or 2 generations from current year) (Also 30 years and 2045 stated)	Maintain current range (2 countries/ three states) Positive growth rate within the existing range BVs widely distributed across the current breeding range and all pairs that hold territories, actually breeding. Population Stabilization	Range: 0% - <50%	Can we create a population in the historic range, to act as the genetic reservoir as opposed to a captive flock? Should we change the timeline from what was originally stipulated in the first PVA? And if we do, should we not also change our methodology to achieve our outcome. Is the current breeding population breeding normally?
Ex Situ			
2025	Ex situ – the complete captive group of 20 to 30 unrelated birds be obtained (8 current) and progeny being released, and release methodology confirmed.	0%	

Optimistic/ ideal goal elements

How far into the future should we be looking?	What status would we like to imagine for the species at this time frame?	What level of risk of extinction are you willing to tolerate?	Any other information/ comments
In Situ			
2070 Three generations	Occupancy of the entire historic and current known viable range (sites)in Southern Africa	Range: 0-10%	What is the entire historic range? This must then allow for adaption to future threats
Ex Situ			
2024	The complete captive group of 20 to 30 unrelated birds be obtained (8 current) and first progeny being released	0%	

Some are not comfortable that 100 pairs are sustainable in the long run. Maintaining what we have is not sufficient

Current proposed goals

The proposed goals are:

i) Ensure the long-term survival of the Bearded Vulture population in southern Africa by halting the population decline and stabilising the population (i.e., $\lambda=1$) at the current population size (approximately 100 breeding pairs) over the next ten years (i.e., by 2025).

ii) Grow the population to a realistic carrying capacity (150 breeding pairs) in the next 50 years, i.e.,, by 2070)

iii) Maintain a positive population growth rate ($\lambda>1$).

General questions and issues

- What is the current decline in the population and the likely causes?
- Are the timeframes for the species conservation goals realistic/achievable?
    - We may need to redefine the goals and timeframes based on realistic assumptions and through an iterative process which feeds into the strategy. The 'stabilise in 5 years' goal will have to be achieved prior to the first releases of captive-bred birds
    - How sure are we of the continuity in terms of running both in situ and ex situ programmes over the next 2–3 decades? Do we have individuals earmarked and available to be groomed to take responsibility for the running of these activities when current project staff depart? Is there a capacity-development process in place to address this?
    - What is the continued viability of the programme in view of funding and other resource constraints?

- The current rate/intensity of harvest from the in situ population is not producing a collective group of programme birds that are productively age compatible to produce optimum progeny levels for release.
- The captive population currently is not large enough to produce the progeny numbers necessary to have an impact on the dwindling wild population.
- The current breeding location is proving hot for the birds and a second cooler site within the species' home range is being pursued. To take this step, we need full programme commitment behind the captive requirement in the programme.
- How would we re-measure the population size at the listed goal date, if not by re-counting the absolute figures as have been done here?
- If VORTEX modelling is based on a rather negative 'rate of extinction' measure, how do we as a group ensure that we maintain a positive outlook in our process that includes an element of 'hope', without which humans cease to function effectively?
- There is not enough monitoring of the wild population due to funding and capacity constraints. All nests need to be located and monitored every year (4 visits pa minimum)

What questions would we like the PVA to answer?

OVERARCHING

- **Prioritisation of actions**: What future management actions are likely to have the most positive impact on Bearded Vulture populations? The longevity of the captive breeding process requires multiple in situ actions to be undertaken simultaneously.
- **Range states:** Although this is a joint initiative across two countries, do you think we should also model the Lesotho and South Africa nests as two separate models as well? (What if we are hit with another covid pandemic?). Harriet Davies Mostert suggested no.

IN SITU DEMOGRAPHICS

- Can we build a series of simulation models with sufficient detail and precision that can accurately describe the observed dynamics of Bearded Vulture populations?
    - *The* answer *to this question determines whether we should fairly base all future conservation decision-making on the outcomes of this single process.*
- What are the primary demographic factors influencing population trends in Bearded Vultures?
- The reproductivity of the in situ breeding population is low.
    - There seems to be a high proportion of occupied territories, where adult birds are not attempting to breed or produce offspring. We need to investigate, in as many ways possible, the reasons behind this and work to rectify the problem.
- What is the current impact of climate change on the species?
    - In view of current projections, this should be a significant concern that could negate all the work done to date as well as that planned. A single cataclysmic climatic event could have a significant impact on the population overall.
- What are the most significant knowledge gaps with respect to drivers of Bearded Vulture trends? (**Research priorities**)
- There are vacant breeding sites that could be colonised- there is space

SUPPLEMENTATION

- Given the realistic potential to reduce adult mortality and increase juvenile survival in the wild, is it necessary to supplement the population (from ex situ population) to achieve the goals?

- If not realistic to reduce mortality, is it **<u>acceptable</u>** to compensate through supplementation?
- If so, how many individuals do we need to release each year (from wild harvesting, raising, and releasing) and for how many years to achieve the desired impact on the wild population to either 1) stabilise the current in situ population, and/or (2) grow the population to 150 pairs?
- What is the sustainability of release in terms of long-term in situ population trends – are we just flooding?

CAPTIVE BREEDING REQUIREMENTS

- What is the purpose of the ex situ population? If it's for a genetic reservoir, then the composition is important.
- How big does the genetic reservoir have to be:
    - If no supplementation is undertaken?
    - If supplementation is undertaken?
- The longevity of the flock without looking at multiple facilities.
    - Can we model additional breeding facilities to make up a meta-population in captivity that would reach the targets? This is not really a modelling issue but does impact resource requirements.
- If ex situ birds are required for supplementation, how large does the breeding programme need to be to produce the number of birds required?
    - Noting that:
        - Not all captive birds that reach maturity will successfully pair
        - Not all offspring produced will be suitable for release
        - This will assist in determining the size/how many facilities will be required and give some indication of the cost associated therewith.

HARVEST

- What intensity of harvest can the current in situ population withstand? What is the impact to the wild population of a more aggressive harvest if such is required?
- Will we harvest eggs only, or also chicks?
- If we were to harvest the primary chick or full clutch of 5 nests per annum for three years, could the wild population sustain the impact?
- What harvest strategy has the least short- and long-term risk to the in situ population? (Single egg, both eggs, chicks, fledglings/young of the year). (What is the best least-risk/greatest-benefit harvest strategy?)
    - **Note:** Need to consider short term risk because there is no guarantee that the breeding programme will be successful (financial, disease, husbandry and release issues); assuming the breeding programme can successfully release birds then the short-term risk of population impact needs to be offset against the longer-term positive benefits of releases into the wild within the current range.
- What is the impact of decreasing first-year mortality through the removal of fledged birds and then releasing them back into the wild?
    - **Note:** This reduces the resource requirements of harvesting nests and possibly increases the scope. This should be modelled to see the impact versus harvest and then supplementation.
- What is the relationship between actual nests and those which can be harvested? This is vital before a more aggressive harvest protocol can be looked at. This is critical to model the ex situ impact.

    - **Note:** Some nests are more important than others. Access does not mean distance having to be walked to etc, but rather can a climber get to the pothole. Some nests will require few resources, others will require a lot.

REINTRODUCTION

- Is it necessary to consider the establishment of a reintroduced population within the historical range? (Versus just supplementing the current population)
- What is the cost-benefit of doing this?

IMPACT OF THREATS

- What is the implication of Lesotho and Eastern Cape progressing with wind farm development within the current range? (Without and with supplementation). Does this change the relative importance of supplementation versus reintroduction as a conservation strategy?
    - The fact that the Lesotho and SA governments are considering or have already approved wind farms in the current range lead to initial considerations of the need to establish a reintroduced population outside of areas suitable for wind energy development.
    - From a modelling perspective, could we assume all other population parameters are the same with increased age-specific mortality?
- Habitat loss
    - Plantation development is still occurring in the eastern cape (100k ha). Birds don't forage over plantations and the housing density will also have an impact. This will cause an overall decline in foraging habitats. Some can be compensated for by changing the availability of food in the landscape or around nest sites
- The baseline model needs to consider how threats might change over the next X years. The system is dynamic, and we can't assume constant mortality etc.
- What are the predicted impacts of threats (**Priority threats**)
    - While mitigating what we believe the treats to be, we must remain open to other possibilities especially as random events (i.e., catastrophes) could have a marked effect on this very small group of birds. Contaminants for example: do we really understand their source?

Some specific notes about model parameters

Reproductive rates:

- This section of input asks for parameter values that specify reproductive rates. Note that you decide when in the development of the next generation the "birth" is defined to occur. For mammals, you would probably use parturition as the point at which offspring are tallied. For oviparous species, however, <u>you can start to tally offspring at egg-laying, or at hatching, or at fledging.</u> Whenever you define an individual's life to begin, you must <u>make sure that the first year mortality rates you specify in the next input section are appropriate for the choice you made about when to start recording offspring</u>. For example, if you tally offspring starting at hatching, then the clutch sizes you specify on this page will be in terms of the number of hatches, and your first year mortality will be from hatching through the subsequent 12 months<u>. If you choose to start offspring at fledging, then the clutch size will be specified in terms of the number of fledglings, and survival will be from fledging onwards.</u>

Population size:

- The summarized data below is taken from the “Master Schedule” (from EKZNW, Dr Sonja Krüger) of in situ breeding season monitoring results for the last four years (2017 to 2020). This may help us to extract workable numbers to determine practical and achievable targets for species conservation planning and modelling. Unless the previous years are vastly different, this should give us an idea of the current population numbers.

Year	***Inspectable Units (checked known nest sites) ****	***Occupied Territories***	***Pairs Showing Breeding Activity***
2017	*69*	*24*	*15*
2018	*130*	*48*	*22*
2019	*59*	*25*	*21*
2020	*76*	*31*	*19*

**Most of these nests are the same nests monitored annually*

This is the best-known information, subject to monitor error and doesn’t reflect every nesting pair in the population.

APPENDIX III: Full list of stakeholders that participated in each meeting and workshop

(Workshop facilitators identified in bold and italics).

	Organisation	8th Dec 2020	16th Feb 2021	10th May 2021	13th May 2021	28th April 2022	3rd May 2022	11th May 2022	22 May 2022		23rd May 2022	24th May 2022	
		Virtual Meetings							PVA Day 1	Task Force Feedback	PVA Day 2	PVA Day 3	Task Force Feedback
Sonja Krüger	EKZNW	X	X	X	X		X	X	X	X	X	X	X
Ian Rushworth	EKZNW	X	X	X	X		X	X	X	X	X	X	X
Brent Coverdale	EKZNW	X	X	X									
Shannon Hoffman	African Bird of Prey Sanctuary	X	X	X	X		X	X	X	X	X	X	X
Bill Howells	Member: BVBP Steering Committee (and Raptor Specialist, retired)	X	X	X	X		X	X	X	X	X	X	X
Ian Cockbain	Chairman: BVBP Steering Committee (and African Raptor Trust)						X	X	X	X	X	X	X
Àlex Llopis Dell	Vulture Conservation Foundation		X	X	X	X	X						
Mamasheane Motabotabo	MTEC	X	X					X	X				

Mantsatsi Moleleki	MTEC	X	X	X	X				X		X		
Refiloe Maliehe	MTEC								X		X		
Mabari Lebamang	LHDA									X			X
Mammeli Makhate		X											
Willeen Olivier	DFFE (TFCA)	X	X	X	X					X			
Lebohang Tlhatlosi	MTEC									X			X
Mosiuoa Bereng	LHDA									X			
Bataung Mokhele	MTEC			X	X				X				
Andre Botha	EWT	X								X			
Ben Hoffman	Member: BVBP Steering Committee (Raptor Rescue)	X	X	X	X								X
Chris Kelly	Wildlife Act	X	X	X	X								
Anel Olivier	Wildlife Act												
Lina van den Heever	BirdLife South Africa	X											
Judy Mann	SAAMBR	X	X	X	X								
Kerryn Morrison	EWT	X											
Jamie Copsey	CPSG	X	X	X	X		X	X	X	X	X	X	X
Harriet Davies-Mostert	EWT	X	X	X	X	X	X	X	X	X	X	X	X
Lauren Waller	EWT-CPSG					X	X	X	X	X	X	X	X
Total each session		**17**	**14**	**14**	**13**	**3**	**9**	**9**	**12**	**13**	**10**	**8**	**11**
Total excluding facilitators		**15**	**12**	**12**	**11**	**1**	**6**	**6**	**9**	**10**	**7**	**5**	**8**

APPENDIX IV: Summary of the meetings and PVA workshop held in 2022

Thursday 28th April 2022 (1hr)	This virtual meeting was held to discuss the demographic parameter data available from a European ex situ facility for Bearded Vultures that had a longer time series of breeding Bearded Vultures in captivity than what was available in South Africa. This was to ensure that the modelling of the captive South African Bearded Vulture population was as accurate as possible for the development of the captive baseline model. Additional discussion was had on release site suitability.
Tuesday 3rd May 2022 (1.5hrs)	Given it had been some time since the model subgroup had met, the group was reminded about the objectives of the modelling tasks; the in situ baseline model was revisited; the results of the sensitivity testing as well as the impacts of various harvesting strategies. The key points (as raised in the 10 May 2021 meeting) were re-emphasised. It was noted that there was agreement on: that removing of 6 or 8 individuals in the wild would not have a negative impact on in situ wild population trajectory, this has been done for the 2021 and 2022 season that we are not drafting a new plan, but rather using the PVA results to inform/ adjust the revision of the Bearded Vulture Recovery Strategy and Action Plan that we are planning for the longer term, and we need to confirm the purpose of the captive population This work fits into the following objectives of the draft BVRSAP: Objective 11 of the Draft Southern African Bearded Vulture Recovery Strategy and Action plan: To support vulture conservation through cross-cutting actions that contribute to addressing knowledge gaps; Result 11.3: Establish a genetic reservoir of the southern African population of *G. barbatus* in captivity. Actions: 11.2.5 Establish a captive population of 20-30 unrelated founder birds using sound genetic and demographic criteria (includes developing funding proposals, collecting eggs) 11.2.8 Breed viable chicks in captivity for reintroduction projects The Purpose of the Bearded Vulture Breeding Programme which is *'to build and maintain an ex situ genetic reserve, and to supplement the existing in situ population or restore populations where extinct'*. It was confirmed that the purpose of the ex situ population was a three -pronged one: a genetic reserve; to supplement the wild population and to provide a

	source of founders for reintroduction into a new site. In order to do this, the following would need to be discussed further: Genetic reservoir: *How much genetic variation and over what time period was this desired?* Supplementation: *Is this to maintain genetic diversity, to result in a positive increase in the population, or to stop the population from going extinct?* Reintroduction to a new site: *What would be the population targets and over what time scale?* The meeting concluded agreeing that a subsequent discussion was needed with the modelling subgroup to ensure that all concerns of the modelling subgroup were captured and that the group produced a set of fundamental objectives that they cared most about satisfying.
Wednesday 11th May 2022 (2hrs)	This virtual meeting was held with model subgroup to discuss and agree on fundamental objectives for the PVA. The following were agreed to: Maximise growth rate of the population in the wild Secure as much of the genetic diversity from the existing population as possible Minimise cost Maximise area of occupancy (at least stop further loss)
Monday 23rd – Wed 25th May 2022 (3 days)	During this in-person PVA workshop, the baseline in situ and ex situ model was presented, discussed and finalised. Scenarios identified and modelled in order that recommendations for the captive population's contribution to the Bearded Vulture Recovery Strategy and Action Plan could be identified.

APPENDIX V: PVA workshop agenda

MONDAY 23RD MAY

Timing	Topic	Description	Format	Lead
08:45	Introduction from the Lodge	Welcome, Health & Safety brief, presentation on Silver Hill Lodge's contribution to Bearded Vulture Conservation.	Talk	Quinn Clark
09:05	Introduction to the process	Outline of the process to be followed over the next three days, including working agreement.	Presentation	Jamie
09:20	What do you hope to get out of this process?	As well as sharing introductions from participants present, we take this opportunity to discuss personal desires for the workshop to follow.	Discussion/ Individual activity	Jamie
09:45	Providing context: An overview of the plan in place	The purpose of this process is to critically review specific aspects of the current Bearded Vulture recovery plan. In this presentation we provide an overview of this plan to clarify what aspects we will be feeding into within this decision-making process	Presentation	Sonja
10:00	Clarifying agreed fundamental objectives	Before this workshop stakeholders met to begin to clarify what their core concerns were that need to be addressed through this decision-making process. Here we revisit these 'fundamental objectives' to ensure we are not missing anything and that everyone agrees.	Discussion	Lauren
11:00	**BREAK**			
11:20	An overview of Population Viability Analysis (PVA). Introduction to the baseline model.	To ensure everyone is aware of the use of PVA within a decision-making process, we introduce the tool. Run through the first baseline model (a): single model of wild population Discuss the values that have been used to develop the baseline model and get agreement on these figures.	Presentation	Harriet
13:00	**LUNCH**			

13:45	Additional baseline structures	(a) Wild (mortality reduction) (b) Captive baseline (c) Insurance (d) Augmentation (e) Reintroduction We will work through each of these models; explain the basis for each model and re-run based on the participant's inputs.		
14:45	Review baseline models	Are there models (from above) that the group want to go into more detail; and/or are there additional models that the group wants to run		
15:45	**BREAK**			
15:45	Discussion on Metrics	Quantify/qualify objectives	Discussion	Jamie
16:30	Review and forward-thinking	Here we summarise the key points from the day, identify the work to be undertaken tonight, and orientate ourselves to what we will focus on tomorrow.	Summary discussion	Jamie
17:00	**END**			
19:00		Feedback to Vulture Task Team		

TUESDAY 24th MAY

Timing	Topic	Description	Format	Lead
09:30	Baselines Models	Teaching agreement	Discussion	Jamie/Harriet
10:15	Break			
10:30	Scenarios	Run scenario categories: are there any we can remove?	Discussion	Jamie/Harriet
11:15	Scenarios	Develop scenarios within categories	Discussion	Jamie
12:15	VORTEX	Develop and run the scenarios through VORTEX	Discussion	Jamie/Harriet
13:00	**Lunch**			
14:00	Scenarios	Short list scenarios: how do they perform against biological observations	Discussion	Jamie
15:00	Metrics	Identifying metrics for other objectives, brainstorm as to how we can measure them	Discussion	Jamie
15:30	Break			
15:45	Continue work on metrics…			

WEDNESDAY 25th MAY

Timing	Topic	Description	Format	Lead
9:00	Model	Discussion on model outputs and agreement on scenarios	Discussion	Harriet
11:00	Developing Recommendations	Develop workshop recommendations based on results of the PVA	Discussion	Lauren
13:00	**Lunch**			

14:00	Bearded Vulture Recovery Strategy	Discussion on draft Bearded Vulture Strategy Actions and how they align to fundamental objectives	Discussion	Lauren
16:00	Next Steps	Discussion on next steps following completion of this workshop and agreement on deadlines	Discussion	Lauren
19:00		Feedback to Vulture Task Team		

APPENDIX VI: In situ and ex situ draft costs

In situ costs		
Supplementary feeding:	Drop off carcasses at known feeding (nest) sites (new activity)	
	Formal feed sites	100-300 Kg
	For bone	R 30 k p.a
	Petrol	
	Hours	
	Per year total per site	R 100k
Powerline mitigation		
Project management (fixed cost)		
Education costs (including materials)		
Poison Intervention (not incl trainer costs, only real costs):	Fixed salary cost	
	Cost per training course	R20 k
Ex situ		
Facility Cost:	Operations	R 900k p.a
	Egg dropped off, incubating, rearing (per bird)	R 250k
	Capital	R 3.4 mil
	Vet support	R 20k p.a
Harvesting		R 2.3 mil
Breeding season and harvesting cost:	per egg	R 40 - R50k
	6 eggs p.a (assumes 50:50 fly:land)	R 400k
Supplementary Costs (all costs per pair)		
Hacking person time costs	R 45k x 2 months	R 90k
Hack (to prep)		R 20k
Visits to prep site:		
transport/petrol	R 3k x 4	R 12k
Accommodation		R 15k
Boxes (2 birds)		R 1.5k
Vehicle (costs for 1 month during release)		?
Hide (from which to observe site)		R 120k
Camera in hack hole		R 100k
Scope and binoculars		R 20k
Food (for 2 birds for 1 month)		R1.5k
Tracking (per pair per year)		R125k
Publicity		R 5k
Education		

APPENDIX VII: PVA Model Workshop Group – Concluding Statement

- The IUCN's Species Survival Commission's (IUCN SSC) Conservation Planning Specialist Group (CPSG) provided independent facilitation for this PVA, using international best practice for this process
- The Baseline models for wild and captive populations have been developed
    - These models indicate the current status of the population trends (in the absence of additional mitigation measures)
    - We are confident that these models reflect reality reasonably well
- The outcome of the baseline model for the wild population has shown that this population is in an extremely worrying decline:
    - 62 birds in 50 years' time i.e.
    - 20 breeding pairs
- This is a desperate situation - What can be done?
- Models have indicated that to prevent this species from going extinct, the following actions are all required:
    - reducing deaths in the wild
    - increasing the number of females that breed
    - increasing the number of chicks that survive until they leave the nest,
    - harvesting eggs from the wild population to build a captive flock that is large enough to conserve the genetic diversity of the wild population and produce chicks for release back into the existing wild population

- To achieve the BV Strategy goals (150 pairs by 2070), the following actions are required:
    - Reducing mortality by 15% across all ages
        - This translates into preventing the deaths of an additional 6 birds a year
    - Increasing productivity in the wild by 5%
    - A minimum of 32 birds in the captive population which would require:
        - Harvesting of 6 eggs for the next 3 years
        - Thereafter between 2 and 4 eggs every 4 years to maintain genetic diversity
    - In the next 4 years, to intensity actions in the wild to reduce mortality by 15%. In 4 years' time, the captive population will then start to release birds
    - If we cannot increase productivity by 5%, then we need to increase the captive population to 42, which allow for increased supplementation back into the wild
    - During this time, release sites will be prepared
    - At this stage, the focus will be on securing the current wild population through threat mitigation and supplementation.
    - The team identified that, within the next 5 years, we need to be on top of poisoning, power lines and any other man-induced mortality. If not, the Task Force will have to consider other release sites in their historical distribution where the threats are less problematic.

WAY FORWARD

The team identified that there is a need to go through the actions in the Draft Strategy to ensure that they align with the priorities that have come out of the modelling process.

01 August 2022 - Modelling to be completed (All)

31 August 2022 - PVA report to be completed (Harriet)

14 September 2022 - Bearded Vulture Strategy to be updated with PVA results (Sonja)

15 October 2022 - BVTF and BVBP to provide comment on the revised Strategy

Before Nov BVTF - BVTF and BVBP comments to be incorporated (Sonja)

APPENDIX VIII: Detailed outputs of all models.

Each model was run 500 times, and results are provided for stochastic growth rate (stoch-r), standard deviation in stoch-r, probability of extinction (PE), the average number of birds in extant populations (N-extant), the standard deviation of the number of birds in extant populations (SD(N-extant), the average number of birds across all populations (N-all – this includes those that went extinct), the standard deviation in number of birds across all populations (SD(N-all)), genetic diversity (GD), and the standard deviation in genetic diversity (SD(GD)) at the end of 50 years. For models with more than one population, results are provided for each component of the overall population (Wild, Captive, New), and for the population overall (Meta).

Scenario	Population	stoch-r	SD(r)	PE	N-extant	SD(N-ext)	N-all	SD(N-all)	GeneDiv	SD(GD)
BASELINE MODELS										
Baseline	Wild	-0.0359	0.0907	0.002	61.72	38.93	61.60	38.99	0.9638	0.0201
Captive	Captive	0.0280	0.0700	0.000	31.37	1.35	31.37	1.35	0.8892	0.0248
Ins2.1	Wild	-0.0409	0.0938	0.002	50.18	34.89	50.09	34.91	0.9562	0.0289
	Captive	0.0462	0.0852	0.000	31.48	1.22	31.48	1.22	0.9444	0.0124
	Meta	-0.0214	0.0729	0.000	81.57	34.92	81.57	34.92	0.9725	0.0100
Ins2.2	Wild	-0.0392	0.0920	0.000	52.44	33.64	52.44	33.64	0.9575	0.0248
	Captive	0.0507	0.0987	0.000	31.39	1.45	31.39	1.45	0.9143	0.0188
	Meta	-0.0215	0.0726	0.000	83.83	33.72	83.83	33.72	0.9699	0.0115
Aug3.1	Wild	-0.0152	0.0904	0.000	153.72	61.67	153.72	61.67	0.9763	0.0066
	Captive	0.0334	0.0832	0.000	30.31	2.02	30.31	2.02	0.9510	0.0091
	Meta	-0.0093	0.0786	0.000	184.03	61.83	184.03	61.83	0.9754	0.0066
Reintroduction	Wild	-0.0270	0.0916	0.000	107.49	72.99	107.49	72.99	0.9737	0.0144
	Captive	0.0439	0.1119	0.040	26.72	8.19	25.71	9.45	0.9117	0.0227
	New	0.0996	0.2280	0.000	212.20	76.76	212.20	76.76	0.9535	0.0091
	Meta	0.0021	0.0765	0.000	345.39	127.24	345.39	127.24	0.9732	0.0089
SENSITIVITY TESTS[10]										
ST_ExtN35	Wild	-0.0352	0.0890	0.272	72.74	40.38	59.34	41.02	0.9712	0.0094
ST_EV25[11]	Wild	-0.0362	0.0885	0.000	59.91	35.43	59.91	35.43	0.9627	0.0222
ST_EV75	Wild	-0.0362	0.0937	0.000	60.58	38.55	60.58	38.55	0.9633	0.0193
ST_AR6[12]	Wild	-0.0349	0.1369	0.020	83.14	76.61	81.51	76.70	0.9576	0.0382
ST_AR8	Wild	-0.0404	0.0908	0.000	48.90	30.74	48.90	30.74	0.9586	0.0235
ST_BR22[13]	Wild	-0.0626	0.0947	0.070	19.22	14.80	18.05	14.91	0.9051	0.0544
ST_BR27	Wild	-0.0453	0.0911	0.018	40.66	26.58	39.97	26.83	0.9468	0.0340
ST_SR40[14]	Wild	-0.0407	0.0889	0.002	48.27	29.22	48.18	29.26	0.9585	0.0225
ST_SR60	Wild	-0.0471	0.0917	0.010	35.97	22.46	35.64	22.58	0.9451	0.0336
ST_FBr90%[15]	Wild	-0.0426	0.0917	0.008	44.10	25.89	43.78	26.04	0.9553	0.0280
ST_FBr110%	Wild	-0.0304	0.0908	0.000	79.98	50.62	79.98	50.62	0.9691	0.0167
ST_EVFBr5%	Wild	-0.0362	0.0868	0.000	58.41	33.98	58.41	33.98	0.9636	0.0178

[10] ST – Sensitivity test
[11] EV – Environmental Variation (proportion)
[12] AR – Age at first reproduction (years)
[13] BR – Age at last breeding (years)
[14] SR – sex ratio (proportion)
[15] FBr - % females breeding (% of baseline)

Scenario	Population	stoch-r	SD(r)	PE	N-extant	SD(N-ext)	N-all	SD(N-all)	GeneDiv	SD(GD)
ST_EVFBr15%	Wild	-0.0366	0.0951	0.002	59.56	37.67	59.45	37.72	0.9629	0.0193
ST_JM-20%[16]	Wild	-0.0296	0.0907	0.000	83.02	49.91	83.02	49.91	0.9701	0.0148
ST_JM-10%	Wild	-0.0316	0.0893	0.000	75.13	46.84	75.13	46.84	0.9683	0.0171
ST_JM+10%	Wild	-0.0386	0.0903	0.000	53.16	33.04	53.16	33.04	0.9600	0.0227
ST_JM+20%	Wild	-0.0431	0.0920	0.008	44.40	29.60	44.05	29.73	0.9534	0.0300
ST_AM-20%[17]	Wild	-0.0274	0.0870	0.000	92.19	53.60	92.19	53.60	0.9738	0.0129
ST_AM-10%	Wild	-0.0304	0.0871	0.000	78.51	45.20	78.51	45.20	0.9706	0.0135
ST_AM+10%	Wild	-0.0406	0.0935	0.002	49.83	34.66	49.73	34.70	0.9557	0.0284
ST_AM+20%	Wild	-0.0465	0.0975	0.010	37.43	24.84	37.08	24.95	0.9450	0.0356

SCENARIOS										
Baseline-N368	Wild	-0.0351	0.0885	0.000	75.30	43.01	75.30	43.01	0.9703	0.0178
Baseline-10%M[18]	Wild	-0.0200	0.0855	0.000	132.60	80.33	132.60	80.33	0.9784	0.0099
Baseline-15%M	Wild	-0.0125	0.0842	0.000	188.91	107.07	188.91	107.07	0.9828	0.0067
Baseline-20%M	Wild	-0.0052	0.0836	0.000	267.19	140.04	267.19	140.04	0.9864	0.0049
Baseline-15%M_IncBr[19]	Wild	-0.0031	0.0865	0.000	294.60	147.91	294.60	147.91	0.9866	0.0046
Baseline-20%M_IncBr	Wild	0.0035	0.0863	0.000	386.87	163.17	386.87	163.17	0.9886	0.0040
Ins2.1-10%M	Wild	-0.0221	0.0867	0.000	120.86	74.51	120.86	74.51	0.9770	0.0123
	Captive	0.0473	0.0860	0.000	31.41	1.32	31.41	1.32	0.9467	0.0117
	Meta	-0.0115	0.0742	0.000	152.27	74.72	152.27	74.72	0.9821	0.0062
Ins2.1-15%M	Wild	-0.0147	0.0855	0.000	173.18	105.20	173.18	105.20	0.9818	0.0091
	Captive	0.0478	0.0854	0.000	31.41	1.42	31.41	1.42	0.9474	0.0127
	Meta	-0.0066	0.0751	0.000	204.59	105.22	204.59	105.22	0.9849	0.0052
Ins2.1-20%M	Wild	-0.0072	0.0839	0.000	244.92	130.40	244.92	130.40	0.9855	0.0058
	Captive	0.0472	0.0850	0.000	31.36	1.34	31.36	1.34	0.9468	0.0142
	Meta	-0.0012	0.0754	0.000	276.28	130.40	276.28	130.40	0.9873	0.0041
Ins2.1-15%M_NoHarv[20]	Wild	-0.0129	0.0842	0.000	188.65	109.75	188.65	109.75	0.9826	0.0071
	Captive	0.0315	0.0748	0.000	31.35	1.42	31.35	1.42	0.8805	0.0313
	Meta	-0.0076	0.0753	0.000	220.00	109.78	220.00	109.78	0.9842	0.0067
Ins2.1-20%M_NoHarv	Wild	-0.0045	0.0822	0.000	277.24	149.46	277.24	149.46	0.9866	0.0047
	Captive	0.0315	0.0747	0.000	31.51	1.24	31.51	1.24	0.8808	0.0270
	Meta	-0.0010	0.0751	0.000	308.75	149.53	308.75	149.53	0.9878	0.0041
Ins2.2-10%M	Wild	-0.0222	0.0860	0.000	118.41	67.99	118.41	67.99	0.9762	0.0122
	Captive	0.0508	0.0989	0.000	31.54	1.17	31.54	1.17	0.9139	0.0180
	Meta	-0.0119	0.0736	0.000	149.95	68.08	149.95	68.08	0.9808	0.0072
Ins2.2-15%M	Wild	-0.0151	0.0851	0.000	171.64	107.06	171.64	107.06	0.9810	0.0086
	Captive	0.0506	0.0990	0.000	31.45	1.31	31.45	1.31	0.9126	0.0195
	Meta	-0.0069	0.0746	0.000	203.08	107.11	203.08	107.11	0.9840	0.0057
Ins2.2-20%M	Wild	-0.0068	0.0830	0.000	247.10	128.90	247.10	128.90	0.9853	0.0051
	Captive	0.0510	0.0998	0.000	31.36	1.44	31.36	1.44	0.9138	0.0186
	Meta	-0.0006	0.0746	0.000	278.46	129.04	278.46	129.04	0.9871	0.0040
Ins2.2_CapK64[21]	Wild	-0.0374	0.0914	0.006	57.72	37.99	57.43	38.06	0.9601	0.0213
	Captive	0.0451	0.0908	0.000	63.16	1.83	63.16	1.83	0.9547	0.0068
	Meta	-0.0147	0.0649	0.000	120.59	38.09	120.59	38.09	0.9774	0.0070

[16] JM – juvenile mortality (% of baseline)
[17] AM – adult mortality (% of baseline)
[18] M – all mortality (% of baseline)
[19] IncBr – increase in breeding rate, includes 5% increase in % females breeding, plus 10% increase in females producing 1 brood
[20] NoHarv – model run with no exchange between populations
[21] CapK – carrying capacity of captive population (number of individuals)

Scenario	Population	stoch-r	SD(r)	PE	N-extant	SD(N-ext)	N-all	SD(N-all)	GeneDiv	SD(GD)
Aug3.1-CapK42	Wild	-0.0106	0.0898	0.000	192.32	75.22	192.32	75.22	0.9778	0.0062
	Captive	0.0257	0.0809	0.000	37.86	3.59	37.86	3.59	0.9580	0.0077
	Meta	-0.0065	0.0772	0.000	230.19	76.03	230.19	76.03	0.9770	0.0062
Aug3.1-CapK64	Wild	-0.0081	0.0901	0.000	217.30	83.26	217.30	83.26	0.9783	0.0058
	Captive	0.0223	0.0805	0.000	43.06	6.32	43.06	6.32	0.9613	0.0076
	Meta	-0.0051	0.0770	0.000	260.36	85.91	260.36	85.91	0.9777	0.0058
Aug3.1-10%M	Wild	-0.0055	0.0865	0.000	251.23	104.94	251.23	104.94	0.9829	0.0054
	Captive	0.0339	0.0837	0.000	30.23	2.21	30.23	2.21	0.9527	0.0089
	Meta	-0.0016	0.0777	0.000	281.46	105.10	281.46	105.10	0.9822	0.0056
Aug3.1-15%M	Wild	0.0000	0.0851	0.000	328.35	129.77	328.35	129.77	0.9855	0.0044
	Captive	0.0342	0.0830	0.000	30.39	2.15	30.39	2.15	0.9528	0.0095
	Meta	0.0031	0.0774	0.000	358.74	129.80	358.74	129.80	0.9848	0.0046
Aug3.1-20%M	Wild	0.0056	0.0844	0.000	415.75	148.14	415.75	148.14	0.9876	0.0041
	Captive	0.0337	0.0833	0.000	30.14	2.21	30.14	2.21	0.9534	0.0088
	Meta	0.0079	0.0778	0.000	445.89	148.25	445.89	148.25	0.9871	0.0043
Aug3.1-15%M_CapK64	Wild	0.0012	0.0856	0.000	346.65	137.57	346.65	137.57	0.9878	0.0031
	Captive	0.0039	0.1184	0.000	17.14	2.27	17.14	2.27	0.9623	0.0063
	Meta	0.0014	0.0790	0.000	363.79	137.92	363.79	137.92	0.9878	0.0031
Aug3.1_IncBr	Wild	-0.0103	0.0911	0.000	197.23	79.74	197.23	79.74	0.9802	0.0062
	Captive	0.0341	0.0832	0.000	30.22	2.21	30.22	2.21	0.9513	0.0095
	Meta	-0.0055	0.0806	0.000	227.45	79.84	227.45	79.84	0.9793	0.0064
Aug3.1-10%M_IncBr	Wild	0.0009	0.0882	0.000	345.01	140.78	345.01	140.78	0.9860	0.0043
	Captive	0.0346	0.0832	0.000	30.24	2.34	30.24	2.34	0.9526	0.0091
	Meta	0.0039	0.0805	0.000	375.25	140.89	375.25	140.89	0.9854	0.0046
Aug3.1-15%M_IncBr	Wild	0.0064	0.0868	0.000	430.42	152.28	430.42	152.28	0.9879	0.0037
	Captive	0.0343	0.0831	0.000	30.20	2.11	30.20	2.11	0.9536	0.0088
	Meta	0.0087	0.0803	0.000	460.62	152.44	460.62	152.44	0.9875	0.0039
Aug3.1-15%M_CapK42	Wild	0.0012	0.0852	0.000	348.19	142.62	348.19	142.62	0.9879	0.0032
	Captive	0.0038	0.1192	0.000	17.13	2.34	17.13	2.34	0.9626	0.0064
	Meta	0.0014	0.0788	0.000	365.32	143.19	365.32	143.19	0.9879	0.0032
Aug3.1-20%M_IncBr	Wild	0.0089	0.0848	0.000	474.61	146.30	474.61	146.30	0.9888	0.0031
	Captive	0.0341	0.0827	0.000	30.16	2.40	30.16	2.40	0.9543	0.0084
	Meta	0.0109	0.0786	0.000	504.78	146.72	504.78	146.72	0.9884	0.0033
Aug3.1-15%M_IncBr_CapK42	Wild	0.0089	0.0871	0.000	469.83	143.94	469.83	143.94	0.9881	0.0032
	Captive	0.0257	0.0812	0.000	37.84	3.47	37.84	3.47	0.9617	0.0066
	Meta	0.0102	0.0798	0.000	507.67	144.64	507.67	144.64	0.9877	0.0034
Aug3.1-15%M_IncrBr_CapK64	Wild	0.0076	0.0869	0.000	446.64	151.22	446.64	151.22	0.9895	0.0026
	Captive	0.0040	0.1188	0.000	17.20	2.18	17.20	2.18	0.9633	0.0061
	Meta	0.0075	0.0811	0.000	463.84	151.71	463.84	151.71	0.9895	0.0026
Aug3.1-20%M_IncBr_CapK64	Wild	0.0138	0.0846	0.000	549.19	133.32	549.19	133.32	0.9886	0.0030
	Captive	0.0224	0.0806	0.000	43.39	6.69	43.39	6.69	0.9641	0.0068
	Meta	0.0144	0.0775	0.000	592.58	135.55	592.58	135.55	0.9882	0.0031