

FROM THE CAPTIVITY TO WILD: A CRITICAL REVIEW OF BREEDING PROGRAMMES FOR ENDANGERED MAMMAL SPECIES

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Abstract

Heavy deforestation leads to the threat of extinction of various mammals' species in near future due to the habitat loss, which imposes a great risk at survival of these species in a particular area. Another cause of mammal's extinction is the increasing demand of their body parts that leads to uncontrolled hunting and decrease in their number. Protection of sustainable population of endangered mammals is a great challenge. Therefore, in-situ and ex-situ conservation techniques of captive breeding are being practiced for many years to protect the endangered mammals. These techniques have been proved successful in many cases of mammals. The main problem that we face in ex-situ conservation is the reintroduction of mammals in their natural habitat because natural habit is different from captive environment. However, this problem has been solved to a greater extent by the in-situ conservation in which population of organisms are protected in their natural habitat. In this review we will highlight the history and types of captive breeding. We will also review the in-situ and ex-situ conservation techniques and compare the effectiveness of each of these techniques. It also contains the challenges faced in reintroduction of organisms in their habitat and policies to face these challenges

Introduction

The increasing rate of biodiversity loss on a global scale has put many species of mammals at a great risk of extinction. Habitat loss, climate change, poaching, invasive species, and the growth of human populations are some of the factors that continue to cause the decline of many species. According to the International Union for the Conservation of Nature a significant number of species of mammals that have been assessed are facing the threat of extinction. Therefore, there is a great need to develop effective conservation strategies (Snyder et al., 1996). Although the most preferred method of conservation, known as in situ conservation, involves the conservation of species within their ecosystem, there are situations when the number of species becomes

very small, and therefore, ex situ conservation, such as the use of captive breeding programs, has been introduced as an effective method of preventing the extinction of species. Captive breeding programs for endangered species involve the breeding of endangered species in controlled environments such as zoos, wildlife reserves, and breeding centres. The ultimate objective of all of these efforts is not necessarily permanent captivity, but rather the eventual release of individuals into appropriate natural habitats, where they can eventually establish their own populations (Seddon et al., 2007). In the past few decades, captive breeding efforts have been visibly involved in the conservation of a number of high-profile mammalian species. For example, coordinated breeding and habitat conservation efforts have been instrumental in

the conservation of the Giant Panda in China, as well as the reintroduction of the Arabian Oryx into various areas of the Middle East. Similarly, captive breeding efforts have been critical to the survival of the Black-footed Ferret in North America. While these efforts have been successful in preventing the extinction of various species, the transition from a captive to a wild environment is a complex and often controversial issue, as a captive environment, no matter how well it is designed, is quite different from a natural environment (Hogg et al., 2018). Animals that are raised under human care can show modified behavioural development, decreased awareness of predators, and modified foraging patterns. These changes can reduce survival rates after release if not addressed through training and acclimatization before release (Jule et al., 2008). In addition, small founder populations can result in a lack of genetic diversity, which can result in inbreeding depression and decreased adaptability to changing environments (Frankham et al., 2010). Another factor that makes the debate on the captive breeding programmes more complex is the issue of financial costs and resource allocation. There are significant financial costs associated with keeping the species in captivity, providing them with medical attention, conducting genetic tests, and releasing them back into the wild. There are arguments that the financial resources allocated to certain species, such as charismatic species, might not be allocated to the entire ecosystem. However,

there are counterarguments that the resources allocated to the charismatic species might benefit the entire ecosystem, despite the fact that the species are not the focal point.

In the recent past, there has been significant improvement in the reproductive techniques, molecular genetics, and wildlife health management, thereby improving the science behind the conservation breeding. Techniques such as artificial insemination, cryopreservation, and assisted reproductive techniques have become viable options for the conservation of genetic diversity. At the same time, conservationists increasingly appreciate the value of behavioural enrichment and naturalistic enclosures in preparing animals for a wild lifestyle. Such developments clearly reflect the changing perspective on how captive breeding programs can be improved for the betterment of animal reintroduction. It is quite evident that captive breeding programs embody the hope and challenge facing modern conservation (Seddon et al., 2007).

Clearly, captive breeding programs serve as a safety net for endangered species on the brink of extinction (Fig. 01). However, the success of captive breeding programs is a product of effective planning and cooperation with habitat conservation. A critical review of breeding programs for endangered mammal species is a necessity to evaluate the success and failure of the programs and develop strategies for the betterment of animal transition from captivity to the wild (Ceballos et al., 2015).

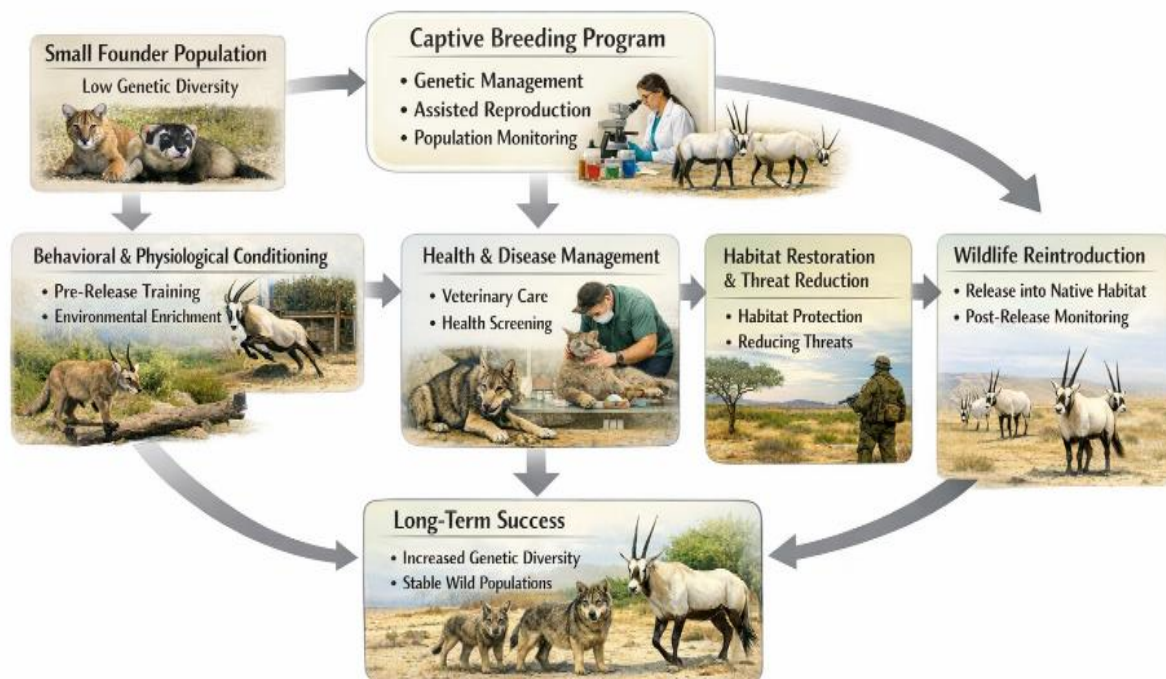


Fig. 01: Captive breeding and reintroduction of Mammal species

Principles of captive breeding programmes

Captive breeding is a type of ex-situ conservation that involves the controlled reproduction of species outside their natural habitats, typically in zoos, wildlife breeding farms, botanical gardens, or conservation centres. The primary goal of captive breeding is to prevent species from going extinct and to maintain sufficient population numbers for future reintroduction programs (Conde et al., 2011). This approach is grounded in the principles of conservation genetics, population biology, and animal science. A key objective is the preservation of genetic diversity, since small populations are vulnerable to inbreeding depression, genetic drift, and reduced adaptive fitness (Frankham et al., 2017). However, equally relevant in this context is the question of the relationship between these programs and other conservation activities. In this regard, the IUCN Guidelines for Ex Situ Conservation of Animal Species state captive breeding programs should be seen as a way of supporting the conservation of the natural habitats of the species concerned rather than replacing it. Without addressing the fundamental causes of decline, captive breeding programs on their own cannot ensure the ultimate survival of the species. For example, the

offspring of a captive breeding program may not acquire some of the vital survival skills required for the wild. Such vital survival skills may include predator avoidance, foraging behavior, etc. In a sense, captive breeding may be said to be at the crossroads of genetics, ecology, demography, and behavioral science with the ultimate goal not only of increasing the population size of a given species but also of producing a species which is capable of contributing to the self-sustaining wild populations (Snyder et al., 1996).

Historical development of captive breeding programmes

The 1970s and 1980s marked a critical period with the establishment of Species Survival Plans by the Association of Zoos and Aquariums which allowed for systematic management of genetic and demographic data. Advances in conservation genetics during the 1990s further enhanced breeding program management, including the use of studbooks and molecular tools for genetic monitoring (Frankham et al., 2017). In the 21st century, captive breeding has incorporated advanced reproductive technologies such as artificial insemination, embryo transfer, cryopreservation, and genomic management. These innovations are particularly

valuable for critically endangered species with very few breeding individuals. Despite these technological developments, debates continue over the cost effectiveness, potential genetic adaptation to captivity, and the ecological viability of reintroduced populations (Conde et al., 2011).

Captive breeding programs can be divided on the base of their primary aims (Synder et al., 1996). Conservation breeding aims to maintain viable populations of endangered species as a safeguard against extinction. These programs focus on preserving genetic diversity, ensuring demographic stability, and effectively managing populations. Conservation breeding is particularly applied to species with critically small or fragmented wild populations, serving as an insurance measure to protect against catastrophic losses (Synder et al., 1996).

Some captive breeding programs are established to support scientific research in areas such as reproductive biology, genetics, physiology, disease management, and behavioural ecology. These programs create knowledge that can be used to better manage species, both in captivity and in the wild. For example, research carried out on the reproductive patterns of animals in captivity has offered insightful information about the patterns of reproduction, assisted reproductive techniques and infant mortality rates of endangered mammals (Synder et al., 1996).

Conservation breeding programs that have the objective of reintroduction concentrate on breeding animals with the objective of releasing them back to their former habitats after the threats have been addressed. Successful examples include the Arabian oryx and the black-footed ferret *Mustela nigripes* which prove that this method is a useful tool in species recovery. Another example is the California condor, which was on the brink of extinction in the 1980s but was saved through a breeding program (Synder et al., 1996).

Captive breeding programmes are primarily based on the principles of evolutionary biology, conservation genetics, behavioural ecology, and reproductive physiology. Though the increase in numbers is a visible outcome of captive breeding programmes, the overall conservation significance of the programmes lies in the

conservation of genetic integrity, the conservation of adaptive potential, and the avoidance of any form of maladaptive change. The knowledge of these biological principles is vital for determining the viability of captive populations' reintegration into the wild (Johnson et al., 2010).

Small founder populations are prone to loss of heterozygosity, inbreeding depression, and genetic drift (Frankham, 2008). For instance, the Florida panther population exhibited traits such as kinked tails, heart defects, and reduced fertility until genetic rescue through the introduction of Texas cougars increased heterozygosity and improved overall survival (Johnson et al., 2010).

Inbreeding occurs when closely related individuals reproduce, leading to increased homozygosity and the expression of harmful recessive alleles. This can result in reduced fitness, lower reproductive success, and higher juvenile mortality due to impaired immune function and increased susceptibility to disease a phenomenon known as inbreeding depression (Frankham et al., 2017). In captive populations founded by only a few individuals, the risk of inbreeding is particularly high unless actively managed. Genetic drift, the random fluctuation of allele frequencies in small populations, further diminishes genetic variation by causing the loss of rare alleles and reducing the population's ability to adapt once reintroduced into the wild (Allendorf et al., 2013).

Changes, effects and challenges in captivity programmes

Captive environments can significantly influence animal behaviour and physiology. Animals may exhibit reduced predator awareness, inappropriate social behaviours, and altered feeding patterns, all of which can lower post-release survival (Araki et al., 2007). To mitigate these effects, pre-release training, environmental enrichment, and simulated natural challenges are often employed (Christie et al., 2012). Such behavioural changes resemble those seen during early domestication and can significantly reduce post release survival (Christie et al., 2010).

It may also lead to physiological stress and reproductive problems. Changes in diet, light

patterns, space, and stress have been known to affect the external or internal endocrine system and reproductive hormones. Increased levels of glucocorticoids, which are often a result of stress, have been associated with wildlife reproductive problems and immunosuppression of captive breeding programmes (Dickens et al., 2013). Furthermore, disruption of the natural social structure may also inhibit reproduction further. Assisted reproductive technologies such as artificial insemination, in vitro fertilization, and cryopreservation have emerged as key strategies for addressing the problems. ART is a key tool for improving demographic performance, it does not address the behavioural and ecological competency needed for a species reintroduction (Holt et al., 2014).

Captive breeding and species recovery outcomes

Captive breeding strategy plays a significant role in the prevention of mammals whose species are under the risk of extinction due to the destruction of habitat, overuse and invasion of other species to their area of living. Sudden outbreak of diseases also causes in the loss of population of organisms and if the number of organisms is small in the population it can lead to threat of that particular species in that area. In such small populations ex situ conservation programs are the best way to conserve their genetic diversity and prevent inbreeding. (Pérez-Epson et al., 2025).

Modern captive breeding programs use various aspects from different fields including genetics, pedigree analysis and behavioural sciences to improve the recovery outcomes. Conservation of once endangered black-footed ferret is a well-known example of the organism who once considered endangered is now restored by critically managing its reproduction and environmental influence on it (Ali et al., 2024). In 20th century the Przewalski's horse survived only in controlled captive environment but in recent times it has been set free in the Mongolia and parts of China. Because of international cooperation, careful management and protection of their natural habitat we can conserve the endangered mammals although continued management is needed to ensure the persistent genetic diversity (Torgan et al., 2022).

Captive breeding of many organisms proves to be successful but the reintroduction of these captive organisms has varied results. The captive breeding assessment suggests that if we want to reintroduce these captive organisms successfully, we have to carefully look after their habit, predator, and diseases and mitigate these threats (Harding et al., 2025). Captive breeding is a revolutionary technique for the conservation of endangered mammals but we can only achieve sustainable results if we add in situ conservation techniques in it. (Harding et al., 2025).

Reintroduction and post release performance

The reintroduction of captive breeding mammals is a major step in the conservation of those mammals that have been threatened with extinction because of anthropogenic activities. Studies conducted on threatened species, for example, *Pseudemys novaehollandiae*, have shown that knowledge gained from captive breeding, reproductive output, health, and behavioural measures has shown that it can be applied directly for the improvement of reintroduction and performance. (Smith et al., 2023). If we lack the authentic data of the cases of organisms that were bred in captivity, we can release these mammals in to wild successfully. The survival of these organisms depends upon their intrinsic factors like genetics and behaviour as well as extrinsic factors like resource competition and predator's number. For instance, research synthesizing multiple reintroduction trials demonstrated that effective predator control and habitat preparation were associated with higher survival and reproduction of released populations whereas unmanaged sites often showed rapid declines post release. This shows that post-release performance is not only a reflection of captive breeding success but also of how well are external threats handled. Species-specific examples of captive-bred mammal reintroductions show these general findings. The Black-footed ferret once extinct in the wild, has been slowly reintroduced across its historical range in North America following captive breeding, with population growth at some sites linked to adequate prey availability and habitat management, although not all sites have achieved self-sustaining populations (Jackowski et al., 2011).

In-depth studies of reintroduction trials highlight, for example, the importance of prey population size and quality, in this study the prairie dogs, in relation to the survival and reproductive success of released ferrets, thus illustrating the need for mammals, even those of high breeding quality, to have support to survive in the wild after being released from captivity. Though there have been successes, there are still challenges in terms of the success of mammals bred in captivity to perform in the wild after being released. One of the main reasons is the fact that captivity is very different from the natural environment, and this has been found to alter the survival probability of mammals released into the wild. For example, a study of other carnivores, including the endangered Iberian lynx, *Lynx pardons*, has found that there is a higher probability of death of mammals bred in captivity compared to those in the wild, because of changes in their behaviour or metabolic programming in captivity (Reeves et al., 2020).

Captive breeding (ex situ conservation) of endangered mammals

Captive breeding is a conservation strategy in which endangered mammals are maintained and reproduced in controlled environments such as zoos, wildlife parks and specialized breeding centres. This strategy is used when the population of a particular organisms is at the risk of extinction because of some unfortunate reasons that may be genetic or environmental. A well-documented example is the Black-footed ferret, which was declared extinct in the wild in 1987. A small group of 18 individuals formed the foundation of a captive breeding program in the United States. Through intensive genetic management and coordinated reintroduction efforts, thousands of ferrets have since been bred and reintroduced into grassland ecosystems, although the species remains conservation-dependent (Jackowski et al., 2011). Nevertheless, the program is not cost-effective, and it requires sophisticated biological instruments. Studies on comparison of cost between ex situ and in situ conservation strategies shows that ex situ conservation require more financial investment ac compared to the in-situ conservation technique (Steak et al., 2023). Because of small

founder size, inbreeding and acclimatization the total gene pool of that population in affected badly and these things cause reduction in their survival rate (Ralls & Ballou, 2004).

In-situ conservation habitat protection and long-term sustainability

The main focus of in situ conservation is to protect the endangered species of organisms with in their natural habitat by maintaining their ecological and evolutionary aspects. For the mammals that are at the risk of extinction in near future the in-situ conservation strategy is the establishment of protected areas and formation of laws for their protection. In situ conservation not only aims to conserve the species but also their habitat. From the perspective of cost effectiveness the in-situ technique is more effect because here the ecosystem is also protected that ensure the conservation of many species at a time. It also promotes natural selection, genetic recombination and adaptability to environment for long-term. (Soulé et al., 1985).

Comparison cost effectiveness and long-term viability

Several key differences arise when we compare the captive breeding and in situ conservation. Captive breeding requires advanced infrastructure, more veterinary care and long-term management of organisms while the cost applied for in situ conservation protect habitat for different species at a time that's why captive breeding is more expensive as compared to in situ conservation. When comparing captive breeding and in situ conservation several key differences arise. Biologically in situ conservation provide support to factors like natural behaviour, predator prey interaction and the ecosystem dynamics all of them are critical for long term sustainability. In captive population the reintroduction success may fluctuate because these populations face artificial selection pressure that reduces their survival skills (Ballou et al., 2004). Nevertheless, captive breeding is an excellent technique to conserve the endangered species on immediate bases. For example, the Arabian oryx and many other threatened mammals have been conserved by it. But only captive breeding is not effective proper

management of the habitat in which these organisms are living pre or post release is the

major factor to decide their fate, Table 01 (Ballou et al., 2004).

Table 01: Captive breed mammals and their success

Common Name	Scientific Name	IUCN Status	Description	References
Addax	<i>Addax nasomaculatus</i>	Critically Endangered	>1,000 in global ex-situ population; reintroductions in Tunisia & Chad; wild supplementation from captive stock	IUCN, 2016
Saiga antelope	<i>Saiga tatarica</i>	Critically Endangered	Captive insurance herds established; limited reproductive success; conservation breeding ongoing	Milner et al., 2003
Banteng	<i>Bos javanicus</i>	Endangered	Captive herd management (Australia & SE Asia); breeding stable in managed populations	Bradshaw et al., 2006
Malayan tapir	<i>Tapirus indicus</i>	Endangered	International studbook; consistent zoo reproduction under genetic pairing programs	Lees & Wilcken, 2009
Lowland anoa	<i>Bubalus depressicornis</i>	Endangered	Small but stable captive population; coordinated breeding in Indonesian & global zoos	Burton et al., 2005
Visayan warty pig	<i>Sus cebifrons</i>	Critically Endangered	Captive breeding since 1990s; successful reintroductions to Negros & Panay Islands	Oliver & Heaney, 1996
Bawean deer	<i>Axis kuhlii</i>	Endangered	Managed breeding in Indonesia; supplementation of wild population documented	Semiadi et al., 2015
Chinese giant salamander	<i>Andrias davidianus</i>	Critically Endangered	Large-scale captive production (>100,000 bred annually); reintroduction trials ongoing	Turvey et al., 2019
Hispaniolan solenodon	<i>Solenodon paradoxus</i>	Endangered	Early-stage conservation breeding research; limited ex-situ population	Kennerley et al., 2018
African forest elephant	<i>Loxodonta cyclotis</i>	Critically Endangered	Small managed ex-situ population; limited but documented zoo reproduction	AZA Elephant TAG, 2022
Sumatran rhinoceros	<i>Dicerorhinus sumatrensis</i>	Critically Endangered	Assisted reproduction success; calves born 2012–2023 in managed facilities	Roth et al., 2016
Greater bamboo lemur	<i>Prolemur simus</i>	Critically Endangered	Coordinated European breeding; successful captive births recorded	Wright et al., 2008
Black lion tamarin	<i>Leontopithecus chrysopygus</i>	Endangered	Captive breeding increased population; individuals reintroduced to Brazil reserves	Kierulff & Rylands, 2003
Cotton top tamarin	<i>Saguinus oedipus</i>	Critically Endangered	>500 managed globally; stable breeding success in SSP programs	Savage et al., 2010
Snow leopard	<i>Panthera uncia</i>	Vulnerable	>600 in global managed population; strong zoo breeding coordination	McCarthy et al., 2017

Captive breeding (ex-situ conservative) of endangered species

Captive breeding is usually implemented as a last resort when endangered species of mammals are on the brink of extinction. When faced with threats such as the loss of habitat, disease, and poaching, conservationists capture the remaining members of the species and place them in protected environments such as zoos. In such controlled conditions, experts manage the breeding process to increase the numbers of the species while maintaining genetic diversity. In the long run, the goal of captive breeding is to produce a healthy population that can return to the wild. Among the most successful examples of captive breeding is the Black footed ferret. In the late 1980s, the species was declared extinct, primarily due to the loss of habitat and the decline of prairie dogs, the main source of food for the ferret. In 1987, wildlife officials found the remaining members of the species, and 18 ferrets were captured for the breeding program (Jackowski et al., 2011).

While captive breeding programs may prevent species from becoming extinct, they are expensive and scientifically intensive. Developing and maintaining a conservation breeding program requires substantial investment in facilities, animal management, and expert staff. These programs are longtermly, and this fact alone can increase costs. Studies done to evaluate spending in the European Union for conservation found that ex situ breeding programs may cost substantially more in financial resources per species compared to habitat based conservation. In fact, if long-term maintenance and management costs are factored in, hundreds of millions of euros may be spent (Steak et al., 2023). Apart from the financial risks associated with the breeding program, there are also biological risks associated with the program. For example, the breeding program usually begins with a few animals, and this could lead to inbreeding in the future. Also, animals that are bred in captivity could adapt to the controlled environment and change their natural behaviours such as hunting or avoiding predators. This could lead to a reduction in their survival rate in the wild after they have been released from captivity wild (Ballou et al., 2004).

In-situ conservation habitat protection and long-term sustainability

In situ conservation involves the preservation of species in their natural habitats. Unlike ex situ conservation, which involves the removal of species from their natural habitats for the purpose of preservation, in situ conservation involves the preservation of species in their habitats. This form of conservation involves the preservation of habitats and ecosystems in their natural state. For endangered mammals, in situ conservation involves the development of protected areas such as national parks and wildlife reserves, stepping up antipoaching activities, restoration of damaged ecosystems, and the development of wildlife corridors that connect isolated habitats. These corridors are vital in that they ensure the free flow of genes among species. Unlike ex situ conservation, in situ conservation involves the preservation of whole ecosystems and the species that depend on these ecosystems.

According to the International Union for Conservation of Nature, about 17% of the total land surface is now protected in the form of protected areas. These areas have played a vital role in maintaining biodiversity (Ballou et al., 2004). From an economic perspective, conserving habitats can prove to be cost-effective in the long run since it involves the conservation of multiple species at once. As long as mammals are in their natural habitats, natural selection will continue to influence their genetic makeup to improve their ability to cope with changes in the environment. This ensures genetic diversity and strength, which are critical for longtermly survival (Soulé et al., 1985).

Comparison or cost effectiveness and long term viability

Comparing captive breeding and in situ conservation, the following differences have been noted: captive breeding tends to be more costly per individual species or population being conserved, compared to habitat protection, where the cost is diluted among all species and functions. From a biological point of view, in situ conservation allows for natural behaviour, predator prey relationships, and ecosystem functioning, all of which are critical for sustainability. In captivity, artificial selective

pressures and diminished survival skills of the captive population can be problematic (Ballou et al., 2004).

Integration of ex situ and in situ conservation

Recently the conservationists have realized that the protection of endangered species can no longer depend on the implementation of a single approach. Therefore, many experts nowadays support the implementation of a combination of ex situ techniques, such as captive breeding, and in situ techniques, such as the protection of species in their natural habitats. In fact, the International Union for Conservation of Nature advocates for the use of the one plan approach which encourages the joint management of species found in the wild and those found in captivity through a single approach to conservation. In fact, the use of captive breeding techniques, within the context of the integrated approach to conservation, is not implemented independently. Instead, the implementation of such techniques is closely integrated with the restoration of the species habitats, the minimization of threats such as poaching, and ecological monitoring. In fact, the use of captive breeding techniques, within the context of the integrated approach to conservation, ensures that species found in captivity can, at a later stage, survive in the wild (Ballou et al., 2004).

Ethical debates on long term confinement

The endangered species of mammals for long periods of time also raises questions of a moral and philosophical nature. For example, certain theorists have questioned the ethics of holding species such as elephants or large predators in confined spaces, suggesting that such actions restrict the freedom of the species and reduce the value of the species as wild animals (Jamieson et al., 1985). Even if the holding of the species has the ultimate objective of preventing the species from becoming extinct, the species will not be released into the wild but will instead spend the rest of its life in a confined environment, effectively becoming part of a captive population rather than a wild mammal species. On the other hand, other conservation theorists have defended the use of captivity from a utilitarian perspective, suggesting that if holding the species prevents it from becoming

extinct, then it is arguably justified (Collins et al., 2005).

Ecological risk to releasing captive bred mammal's species

The risk associated with the reintroduction of mammals born or raised in captivity. One of the main risks is the genetic wellbeing of the animals. Most breeding programs start with a small founder group, which leads to a higher possibility of inbreeding. This leads to a loss of fitness over a period of time due to a lack of genetic variation and random genetic effects. Another factor is the lack of natural survival pressures on animals held in captivity. This leads to the possibility that some animals may not be fit for the wild, which lowers the chances of survival and reproduction (Frankham et al., 2008).

Climate change as driver for captive breeding in endangered mammals

Climate change has been posing a great threat to the existence of many mammal species. This is mainly due to changes in their habitats and climatic conditions. Global warming has been on the rise, and this has increased the chances of extinction for many mammal species. This has been affecting their behaviours such as reproduction and migration. This has been posing a threat to the existence of many mammal species. For many mammal species, the changing environmental conditions make their existence in their habitats a challenge (Sattar et al., 2021). For species whose current habitats are becoming unsuitable due to climate change, captive breeding has become an important tool to buy time. By maintaining small populations in controlled environments, conservationists can preserve both genetic diversity and population numbers while long-term strategies such as habitat restoration or climate adaptation are developed. In this way, captive breeding acts as an insurance measure, providing a safety net against imminent extinction when environmental pressures exceed a species ability to survive in the wild species (Hedrick et al., 2011). Recognizing that captive breeding alone may not be enough under rapid climate change, conservationists have increasingly turned to complementary strategies such as assisted

colonization and genetic rescue. Assisted colonization, also called assisted migration, involves relocating animals to areas with more suitable climate conditions when their original habitats become uninhabitable. Genetic rescue, on the other hand, refers to the introduction of fresh genetic material to small, isolated populations for the sake of increasing the diversity, minimizing the effects of inbreeding, and improving the population's adaptability to environmental changes. (Hedrick et al., 2010).

Conservation and policy management

Most people who work in conservation policy agree that captive breeding should only be used as a last resort when efforts to protect animals in their natural habitat are not enough to keep them from going extinct. The International Union for Conservation of Nature has made international recommendations that say *ex situ* conservation should not take the place of protecting habitats and removing hazards. Instead, they should work together in a planned way. To ascertain the appropriate timing for the initiation of captive breeding, conservation governance increasingly relies on transparent and systematic decision making frameworks that consider extinction risk, reintroduction feasibility, biological uncertainty, and resource availability (Frankham et al., 2017).

The literature consistently indicates that the efficacy of conservation is contingent upon the robustness of the interface between scientific knowledge and policy execution (Snyder et al., 1996). Recovery programs often stress demographic goals that aims to grow the population but also include these goals in long term management plans enforced by laws (Snyder et al., 1996). Environmental policies frequently isolate from land-use planning, agriculture policy and infra-structure development in regulatory inconsistencies that destroy the efficiencies of biodiversity conservation. The literature also explains the integrated policy framework that incorporates biodiversity conservation into vast socio-economic planning system (Purvis et al., 2008). Conservation strategies that disregard genetic diversity may facilitate short term demographic recovery while jeopardizing longtermly adaptive capacity (Frankham et al., 2007). To govern well,

you need to turn molecular and population genetic data into management rules, such as guidelines for captive breeding, translocation protocols, and the design of protected areas (Luikart et al., 2007).

For conservation governance to work, there needs to be institutional stability and legal processes that can be enforced (Snyder et al., 1996). The practical execution of recovery programs may be hindered by the lack of legally enforceable commitments and assurances of long-term funding (Snyder et al., 1996). Without laws to enforce them, conservation goals are still just dreams and not actions. It is also important for institutions to stay the same. Conservation programs that depend on unreliable funding sources face problems that threaten long-term monitoring and adaptive management. The literature emphasizes that interagency collaboration, sustained financial stability, and clearly delineated accountability mechanisms are essential for enduring governance frameworks (Purvis et al., 2008).

Management

Advancements in molecular biology have transformed conservation science due to the critical role of genetic diversity in population sustainability (Allendorf et al., 2007). Even in populations that appear demographically stable, losses of adaptive potential and diminished heterozygosity due to inbreeding depression significantly increase the risk of extinction (Frankham et al., 2007). Governance systems often view genetic issues as secondary rather than fundamental to conservation policy (Allendorf et al., 2007). Literature indicates incorporating specifically effective population size such as allelic richness, and connectivity indices long term species conservation and for avoiding extinction vortex (Purvis et al., 2008). Without this combination, demographic glance may hide the degradation that is already happening (Frankham et al., 2007). Genetic governance includes assisted migration and translocation policies as well. In the case of moving people between groups, the benefits of genetic rescue have to be balanced against the risks of outbreeding depression and maladaptation (Mace et al., 2008). The major gap in genetic management policy is the lack of

standardized regulatory frameworks (Luikart et al., 2007).

Conservation policy has been gradually shifted from a species are fully based approach to an ecosystem are based approach in biological conservation 2009. Research has highlighted the importance of habitat corridor metapopulation dynamics and landscape permeability to ensure healthy populations for biological conservation 2009. A fragmented landscape can impede gene flow and resilience to environmental change (Luikart et al., 2007). Landscape scale governance demands that government, borders are crossed to use conservation planning as a part of regional development biological conservation 2009. This type of ecosystem is based governance improves the resilience to both stochastic disruptions, and climate change (Purvis et al., 2008).

The use of ex situ strategies can be illustrated by the involvement of zoological institutions in conservation governance and its potential and limitations (Ballou et al., 1986). Recommendations on genetic matching as well as demographic modelling of studbook have enhanced the management of captive population (Ballou et al., 1986). Therefore, captive breeding rarely results in a long term recovery in the absence of ecological restoration and habitat protection (Snyder et al., 1996). Based on the recent studies, that artificial environments can facilitate the expression of male adaptive traits in the wild, due to the rapid evolution of systems to the captivity, which in turn demonstrate that captive programs can become sources of conservation terminals rather than transitional recovery aid unless fully integrated (Snyder et al., 1996).

Restrictions and deficiencies

One of the main pieces of criticism that emerge in the literature is that species recovery initiatives are based on the short term demographic benefits (Snyder et al., 1996). Recovery programs have been found to focus on the short term gains in populations as a measure of success, overlooking on the long term ecological and evolutionary sustainability (Snyder et al., 1996). These population statistics can be a masked weakness such as habitat insecurity and low genetic variety (Frankham et al., 2007). Once

reintroduced, it is not necessarily enough to monitor to determine whether a species will be able to sustain itself in the long run (Snyder et al., 1996). The sustainability would not be reflected accurately without assessing the survival, reproduction and ecological integration in the other generations (Purvis et al., 2008).

The field of conservation genetics has greatly developed through its applications in management and the policy system is inadequate (Allendorf et al., 2007). Genetic factors are not necessarily essential in the process of conservation planning but rather supplemental (Allendorf et al., 2007). The molecular ecological studies and evolutionary uses (Allendorf et al., 2007) indicate that a reduced effective population, inbreeding depression and loss of adaptive potential, all contribute to increased extinction. In addition, the policymakers might not have a knowledge on the genetic indicators, and therefore they fail to use the available molecular tools (Luikart et al., 2007).

Organisational fracturing in different levels of administration is a major setback to the effectiveness of the biodiversity protection. There might be a lack of consistency between national biodiversity strategies and regional implementations plans, as well as conflicting mandates between the conservation authorities and the development sectors resulting in policy inconsistencies biodiversity and conservation. According to literature, there is often the lack of appropriate conditioning among the agencies dealing with land use planning, the development of agricultural infrastructure, and the protection of the environment biodiversity and conservation. Captive breeding fragmentation that makes it more difficult to hold people responsible and enforcement less effective (Snyder et al., 1996). Also, international conservation agree is not very effective in addressing the cross-boundary ecological processes since they do not have binding provisions (Purvis et al., 2008).

Gaps in climate change integration

Pervious conservation models that were used to plan species recovery have not considered climate change estimates fully (Mace et al., 2008). With the change in the species range

caused by global warming and change in the precipitation, fixed designs of the protected areas could find key themselves to be outdated in terms of ecological balance biological conservation. According to biological conservation, predictive ecological modelling is still not used in statutory conservation planning despite the acknowledgement that landscape connectivity is mitigation measure. One of the knowledge gaps in guaranteeing the sustainability of the biodiversity conservation is the lack of climate ingrained govern systems (Purvis et al., 2008).

Future directions

The literature reviewed (Snyder et al., 1996). says that conservation governance needs to move from fixed rules to flexible systems that can respond to changes in the environment (Snyder et al. 1996) assert that stringent rehabilitation strategies lacking long term monitoring and evaluation protocols frequently fail to yield sustainable outcomes. biodiversity and conservation 2011 say that institutional rigidity makes it hard to change policies quickly when new ecological data comes in or when the environment changes. To put adaptive governance into action, species recovery plans must have required review cycles that include ongoing ecological monitoring, demographic re-evaluation, and policy changes that happen again and again (Snyder et al., 1996). Biodiversity and conservation 2011 say that these frameworks should have legally required monitoring standards and clear ways for regulatory bodies and scientific advisory groups to give and get feedback from each other. Conservation planning is more reactive than proactive because there aren't any institutionalized adaptive processes (Snyder et al., 1996).

Conservation genetics advancements have significantly improved our comprehension of the factors that elevate extinction risk, particularly concerning inbreeding depression, reduced effective population size, and the loss of adaptive variation (Allendorf et al., 2007). Empirical research indicates that, even when demographic recovery appears successful, genetic degradation may threaten long-term population viability (Frankham et al., 2007).

Despite these advancements, genetic science has not yet been fully integrated into official policy frameworks (Luikart et al., 2007). Facilitated migration, genetic rescue and translocations are the management strategies that need continuous genomic risk assessment in order to avoid the maladaptation or outbreeding depression (Mace et al., 2008). This has resulted in the fact that genomic risk assessment systems should be used as part of the reintroduction strategies and genetic surveillance of endangered should be compulsory in future policy frameworks (Luikart et al., 2007).

Research indicates that when ecological interconnectedness is disrupted, isolated reserves fail to sustain viable populations biological conservation, 2009. Less connection makes the environment less stable and the population more random, which makes it harder for genes to move around and raises the risk of extinction (Luikart et al., 2007). In future governance, it is important to make biodiversity a top priority in regional planning tools and transboundary conservation agreements for ecological corridors biological conservation, 2009 (Mace et al., 2008).

Programs for captive breeding remain a valuable yet limited conservation strategy (Snyder et al., 1996). They assert that enduring recovery is infrequently realized when captive breeding is implemented without simultaneous habitat conservation (Ballou et al., 1986). This emphasizes the significance of genetic management in isolated populations to prevent the erosion of diversity and the occurrence of inbreeding. Recent studies indicate that post release fitness may be compromised by swift genetic adaptation to confinement (Frankham et al., 2007). Future governance should include genetic management procedures to reduce domestication selection (Ballou et al., 1986). Behavioural conditioning to improve reintroduction success (Snyder et al., 1996), and coordinated global studbook databases to unify zoo and wild population management (Snyder et al. 1996).

The importance of stakeholder engagement and participatory frameworks is increasingly highlighted in conservation governance literature biodiversity and conservation 2011. Policies that are enforced without community

involvement often encounter resistance, resulting in diminished compliance and long-term effectiveness biodiversity and conservation 2011. By incorporating local knowledge systems and aligning conservation incentives with community livelihoods, participatory governance enhances ecological stewardship (Mace et al., 2008). Adding benefit-sharing mechanisms and community are derived based conservation projects makes policies more legitimate and institutions more stable biodiversity and conservation 2011. These methods also improve the ability to adapt by using ecological data from the area in question to make management plans that are more complete biodiversity and conservation, 2011 (Mace et al., 2008).

Climate change makes planning for conservation more uncertain than ever, which means that governments need to think ahead (Purvis et al., 2008). Biological conservation says that landscape connectedness makes it easier for a species to change its range when the climate changes 2009. (Luikart et al., 2007) assert that maintaining genetic diversity enhances the capacity for adaptation to environmental stressors. Consequently, climate envelope modelling, genomic assessment informed assisted migration strategies, and dynamic protected area networks must be incorporated into forthcoming conservation planning. When climate projections are included in species recovery plans, static conservation methods are less likely to become ecologically obsolete (Purvis et al., 2008).

Conclusions

The literature examined indicates that conservation challenges are fundamentally governance challenges. Biological knowledge has grown a lot, especially in genetics and landscape ecology. But effectiveness is limited by institutions that don't work together, policies that only last for a short time, and laws that don't include enough science. For conservation to be successful in the future, we need participatory frameworks, cooperation across scales, and adaptive governance genetic integration. Without changes to institutions, scientific advances alone won't be enough to stop the loss of biodiversity

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