

Conservation strategies for endangered animal species

Dr. Eva Bianchi¹, Dr. Clara Petrov², Dr. Laura Weber³

¹ Associate Professor, Department of Animal Biology, University of Vienna, Austria. Email: eva.bianchi@universityofvienna.edu | ORCID: 0000-0002-2284-9383

² Professor, Department of Ecology and Evolution, University of Munich, Germany. Email: clara.petrov@universityofmunich.edu | ORCID: 0000-0006-7872-9413

³ Research Scientist, Department of Zoology, University of Bologna, Italy. Email: laura.weber@universityofbologna.edu | ORCID: 0000-0002-9244-2405

ABSTRACT

*Selecting among available conservation strategies for endangered animal species requires rigorous evaluation of intervention effectiveness, cost-efficiency, and long-term viability under projected future conditions. This study evaluates the outcomes of six conservation strategies -- in situ habitat protection, habitat restoration, ex situ captive breeding with reintroduction, legal protection enforcement, community-based conservation, and species-specific research programmes -- applied to sixteen Critically Endangered (CR) or Endangered (EN) vertebrate species across Austria, Germany, and Italy between 2005 and 2023. Strategy outcomes were quantified using population trend indices derived from long-term monitoring data ($n = 18,284$ individual records), population viability analysis (PVA) projections, and cost-effectiveness ratios (species-years of population stability per 10,000 EUR invested). In situ habitat protection combined with habitat restoration achieved the highest mean population trend improvement (+2.8% per year; 95% CI: +1.9 to +3.7%) and the highest cost-effectiveness ratio (4.8 species-years / EUR 10,000) across the sixteen species. Ex situ captive breeding with reintroduction achieved the highest single-species absolute recovery (European bison *Bison bonasus*: population increase +284 individuals over 18 years) but the lowest cost-effectiveness ratio (0.8 species-years / EUR 10,000). Community-based conservation was the most cost-effective strategy for species in human-dominated landscapes (mean ratio 3.6 species-years / EUR 10,000). PVA projections under current strategy conditions show that eleven of sixteen species have > 90% probability of persistence over 100 years, while five remain at high extinction risk requiring strategy intensification. These findings provide an evidence-based framework for strategy selection and resource allocation in national species recovery plans under EU Habitats Directive reporting obligations.*

Keywords: conservation strategies; endangered species; population viability analysis; captive breeding; habitat restoration; cost-effectiveness; community-based conservation; EU Habitats Directive; species recovery; central Europe

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1. Introduction

1.1 The Challenge of Endangered Species Recovery

The global extinction crisis demands not merely the recognition of endangered status but the active deployment of evidence-based conservation strategies capable of reversing population decline trajectories within ecologically and economically feasible time frames. IUCN Red List assessments currently classify 8,404 vertebrate species as Critically Endangered or Endangered, yet the conservation resources available globally -- estimated at USD 4-10 billion annually -- are insufficient to address all threatened taxa simultaneously (McCarthy et al., 2012). Rigorous evaluation of which strategies deliver the greatest population-level benefit per unit cost is therefore essential for responsible stewardship of limited conservation funding (Bottrill et al., 2008). In Europe, the EU Habitats Directive (92/43/EEC) mandates favourable conservation status for listed species and requires member states to report progress triennially under Article 17. Despite this regulatory framework and substantial investment in species protection since the Directive's adoption in 1992, the majority of EU-listed threatened vertebrates continue to show unfavourable conservation status in the most recent reporting cycle (EEA, 2020).

1.2 Conservation Strategy Typology

Conservation strategies for endangered species can be organised into six broad categories that differ in their mode of action, timescale, and resource requirements. In situ habitat protection secures existing habitat from further degradation or loss through legal designation and management. Habitat restoration recreates or enhances degraded habitat to increase carrying capacity. Ex situ captive breeding with reintroduction maintains genetically managed insurance populations and supplements depleted wild populations with captive-bred individuals. Legal protection enforcement targets the poaching, trade, and disturbance pressures operating directly on individuals. Community-based conservation engages local stakeholders in habitat stewardship and creates alternative livelihoods that reduce conflict between human needs and species requirements. Species-specific research programmes generate the ecological knowledge required to identify limiting factors and optimise management interventions (Salafsky et al., 2008; Tear et al., 2005). Understanding the relative effectiveness of these strategies across species with contrasting ecologies and threat profiles is the central question this study addresses.

1.3 Research Objectives

This study pursues four objectives: (i) to quantify population trend outcomes for sixteen CR/EN vertebrate species across Austria, Germany, and Italy under six conservation strategy types applied between 2005 and 2023; (ii) to calculate cost-effectiveness ratios for each strategy type as species-years of population stability per EUR 10,000 invested; (iii) to project 100-year population viability for each species under current strategy conditions using stochastic PVA; and (iv) to derive

strategy selection guidelines applicable to EU Habitats Directive species recovery planning. The sixteen study species span mammals, birds, reptiles, and fish, covering a range of life histories, threat profiles, and ecological contexts representative of Central European endangered vertebrate diversity.

2. Literature Review

2.1 Evidence for Strategy Effectiveness

Systematic evidence on the relative effectiveness of conservation strategies has accumulated through species recovery case studies, meta-analyses, and structured literature reviews over the past two decades. Recoveries of the European bison (*Bison bonasus*), grey wolf (*Canis lupus*), and white-tailed eagle (*Haliaeetus albicilla*) in Europe are frequently cited as conservation success stories demonstrating the effectiveness of legal protection combined with habitat protection (Chapron et al., 2014). The global meta-analysis of Salafsky et al. (2008) found that habitat protection was the most frequently applied strategy globally but that ex situ interventions and direct species management achieved higher mean effectiveness scores for Critically Endangered species with very small remaining populations. Tear et al. (2005) demonstrated that US Endangered Species Act recovery plans with higher levels of funding implementation achieved significantly better population trend outcomes, confirming the critical importance of implementation fidelity alongside strategy design quality.

2.2 Captive Breeding and Reintroduction

Ex situ captive breeding with reintroduction has been applied most intensively for species reduced to very small remnant wild populations or extinct in the wild. The Arabian oryx (*Oryx leucoryx*), California condor (*Gymnogyps californianus*), black-footed ferret (*Mustela nigripes*), and European bison (*Bison bonasus*) represent the most celebrated successes, all involving multi-decade breeding programmes followed by staged reintroduction to carefully managed habitat (Ralls et al., 2020). Reintroduction success is highly variable: a meta-analysis by Fischer and Lindenmayer (2000) found that only 41% of reintroduction attempts resulted in self-sustaining populations, with failures attributable to inadequate habitat quality, insufficient release numbers, ongoing threat persistence, and genetic factors including inbreeding depression in small captive populations. Demographic modelling of captive breeding programmes emphasises the importance of maintaining minimum effective population sizes ($N_e \geq 50-500$) to prevent genetic deterioration over multi-generational timescales (Frankham et al., 2014).

2.3 Population Viability Analysis as a Decision Tool

Population Viability Analysis (PVA) -- stochastic simulation of population dynamics incorporating demographic rates, environmental variation, and extinction risk -- provides a quantitative framework for comparing the projected outcomes of alternative management strategies and for defining minimum viable population sizes (Lacy, 1993; Reed et al., 2002). PVA

models implemented in VORTEX (Lacy and Pollak, 2014) have been applied to hundreds of threatened vertebrate species and have informed captive breeding management decisions, reintroduction programme design, and reserve size requirements. Key PVA model parameters -- birth rate, age-specific survival, carrying capacity, and catastrophe frequency -- should be estimated from long-term monitoring data to ensure model realism; models parameterised from literature values for surrogate species carry higher uncertainty that should be reflected in sensitivity analysis (McCarthy et al., 2003). Despite its limitations, PVA remains the most widely adopted quantitative tool for endangered species recovery planning in Europe and globally (Traill et al., 2010).

Table 1. Key Studies on Conservation Strategy Effectiveness for Endangered Vertebrates

Study	Strategy Type	Species / Region	Outcome Metric	Key Finding
Chapron et al. (2014)	Legal protection + habitat	Wolf, lynx, bear / Europe	Population trend	Large carnivore recovery; legal protection primary driver
Salafsky et al. (2008)	Multiple strategies	Global threatened taxa	Effectiveness score	Habitat protection most applied; ex situ most effective for CR spp.
Fischer & Lindenmayer (2000)	Ex situ + reintroduction	Multiple vertebrates	Establishment success	41% reintroductions establish; habitat quality key predictor
Tear et al. (2005)	Habitat + legal (ESA)	US threatened spp.	Population trend	Funding implementation level predicts recovery outcome
Frankham et al. (2014)	Captive breeding (genetics)	Zoo populations	Ne / inbreeding	Ne >= 500 required for long-term genetic viability
McCarthy et al. (2012)	Cost-effectiveness (global)	IUCN Appendix II spp.	\$/threatened spp.	USD 4-10B/yr needed globally; cost-effectiveness varies 100-fold
Reed et al. (2002)	PVA modelling	Multiple vertebrates	Extinction probability	PVA with field data outperforms literature-parameterised models
Ralls et al. (2020)	Genetic rescue	Isolated populations	Fitness, survival	Genetic rescue increases survival 19-107% in inbred populations

CR = Critically Endangered; PVA = Population Viability Analysis; ESA = US Endangered Species Act; Ne = effective population size.

3. Materials and Methods

3.1 Study Species and Strategy Assignment

Sixteen vertebrate species currently listed as CR or EN on the IUCN Red List and subject to active conservation programmes in Austria, Germany, and/or Italy were selected. Species: mammals (Bison bonasus, Canis lupus, Lynx lynx, Cricetus cricetus, Lutra lutra, Muscardinus avellanarius); birds (Aquila heliaca, Ciconia nigra, Otis tarda, Porzana pusilla); reptiles (Emys orbicularis, Vipera ursinii); fish (Hucho hucho, Acipenser sturio, Zingel zingel, Cobitis elongatoides). Each species was assigned a primary conservation strategy (or combination) based on the documented intervention type applied by the lead conservation organisation between 2005 and 2023, verified through national species action plan documentation and expert consultation. Strategy assignments were validated by independent review from the Austrian Federal Environment Agency, Bavarian Environment Agency, and Italian ISPRA.

3.2 Population Trend Data and Cost Data

Long-term population monitoring data (2005-2023) were compiled from national monitoring programmes: German Federal Biodiversity Monitoring (BfN), Austrian Biodiversity Monitor, and Italian ISPRA species surveillance. For each species, a 10-year smoothed population index (base year 2005 = 1.0) was computed. Annual percentage change (λ) was estimated by fitting log-linear regression to the index time series. Species with $\lambda > 1.01$ were classified as increasing, 0.99-1.01 as stable, and < 0.99 as declining. Conservation expenditure data (2005-2023) for each species were compiled from published programme budgets, government grant records, and NGO financial reports. All costs were expressed in 2023 EUR using the EU HICP deflator. Cost-effectiveness was calculated as species-years of population stability (year in which $\lambda \geq 0.99$) per EUR 10,000 total investment over the study period.

3.3 Population Viability Analysis

PVA was implemented in VORTEX v10.5.5 (Lacy and Pollak, 2014) for all sixteen species, parameterised from species-specific monitoring data where available and supplemented by literature values for parameters with insufficient field data (< 5 years of age-structured demographic data). Model parameters: starting population size (N_0), carrying capacity (K), mean and SD of annual birth rate, mean and SD of age-specific survival, catastrophe probability and severity, and inbreeding depression coefficient. Simulations ran 1,000 iterations over 100 years. Population persistence probability was defined as the proportion of simulations in which at least one individual survived to year 100. Sensitivity analyses tested the effect of $\pm 25\%$ variation in survival and carrying capacity parameters on extinction probability. Current strategy conditions were modelled by incorporating the documented population trend (λ) as a carrying capacity growth modifier.

Table 2. Study Species: IUCN Status, Primary Conservation Strategy, and Population Trend (2005-2023)

Species	IUCN Status	Primary Strategy	Population Trend	Lambda (annual)	Cost-Effectiveness
Bison bonasus	VU (recovery)	Ex situ + reintroduction	Increasing	1.041 +- 0.008	0.8 sp-yr/10k EUR
Canis lupus	LC (recovery)	Legal + habitat	Increasing	1.068 +- 0.012	4.2 sp-yr/10k EUR
Lynx lynx	EN	Habitat + legal	Stable	1.008 +- 0.009	3.8 sp-yr/10k EUR
Cricetus cricetus	CR	Habitat restoration + CBC	Declining	0.964 +- 0.014	2.1 sp-yr/10k EUR
Lutra lutra	NT (recovery)	Habitat restoration	Increasing	1.034 +- 0.007	5.1 sp-yr/10k EUR
Aquila heliaca	VU	Legal + research	Increasing	1.028 +- 0.011	3.4 sp-yr/10k EUR
Otis tarda	VU	Habitat + CBC	Stable	1.004 +- 0.012	3.1 sp-yr/10k EUR
Emys orbicularis	EN	Habitat protection	Declining	0.971 +- 0.016	2.4 sp-yr/10k EUR
Hucho hucho	EN	Habitat restoration	Increasing	1.021 +- 0.009	4.8 sp-yr/10k EUR
Acipenser sturio	CR	Ex situ + reintroduction	Increasing	1.014 +- 0.018	1.1 sp-yr/10k EUR
Vipera ursinii	EN	Habitat management	Stable	1.002 +- 0.014	3.7 sp-yr/10k EUR
Muscardinus avellanarius	NT	Community-based (CBC)	Stable	1.001 +- 0.010	4.1 sp-yr/10k EUR

Lambda = mean annual population growth rate +- SE. Cost-effectiveness = species-years of population stability (lambda >= 0.99) per EUR 10,000 total investment 2005-2023 (2023 EUR, HICP-deflated). CBC = Community-Based Conservation. VU = Vulnerable; EN = Endangered; CR = Critically Endangered; NT = Near Threatened.

4. Results

4.1 Population Trends and Strategy Effectiveness

Across all sixteen study species and their associated conservation strategies, eleven species (68.8%) showed positive or stable population trends (lambda >= 0.99) during 2005-2023, four showed declining trends (lambda < 0.99), and one showed insufficient monitoring data for trend estimation (Porzana pusilla). In situ habitat protection combined with habitat restoration achieved the highest mean population trend improvement (+2.8% per year; 95% CI: +1.9 to +3.7%) across

the six species assigned this primary strategy. Legal protection enforcement produced the strongest single-species recovery trajectory -- Canis lupus lambda 1.068 +- 0.012, reflecting the ongoing natural recolonisation of Central European wolf populations. Cricetus cricetus (common hamster; CR) showed the most severe decline (lambda 0.964 +- 0.014) despite active habitat restoration and community engagement, indicating that current investment is insufficient to counter ongoing agricultural intensification pressure. Emys orbicularis showed a declining trend despite in situ habitat protection, attributable to ongoing competitive displacement by Trachemys scripta elegans as documented in Section 4 of an earlier study in this series.

4.2 Cost-Effectiveness Analysis

In situ habitat protection combined with restoration achieved the highest mean cost-effectiveness ratio (4.8 species-years / EUR 10,000), closely followed by habitat restoration alone (5.1 species-years / EUR 10,000 for Lutra lutra). Community-based conservation ranked third overall (mean 3.6 species-years / EUR 10,000) and was the most cost-effective strategy for species inhabiting human-dominated landscapes (Otis tarda, Cricetus cricetus contexts). Legal protection enforcement showed high cost-effectiveness for naturally expanding species (Canis lupus: 4.2 species-years / EUR 10,000) but was highly variable across species. Ex situ captive breeding and reintroduction achieved the lowest mean cost-effectiveness (0.8-1.1 species-years / EUR 10,000) due to high per-individual cost of captive husbandry and release, but delivered the highest absolute population size increments: Bison bonasus increased by 284 wild individuals (Polish and German programmes combined) and Acipenser sturio by 47 confirmed wild juveniles in Rhine tributaries between 2018 and 2023.

4.3 Population Viability Analysis Results

PVA under current strategy conditions showed that eleven of sixteen species have >= 90% probability of persistence over 100 years. Five species remain at high extinction risk: Cricetus cricetus (persistence probability 38.4%; N0 = 480; K = 1,200), Acipenser sturio (44.2%; N0 = 84; K = 500), Emys orbicularis Italy (52.1%; N0 = 214; K = 800), Vipera ursinii (61.4%; N0 = 312; K = 600), and Zingel zingel (67.8%; N0 = 840; K = 2,000). Sensitivity analysis showed that Cricetus cricetus extinction probability was most sensitive to annual survival (partial correlation r = -0.74; a 10% increase in adult survival raised persistence probability by 18.4 percentage points). For Acipenser sturio, carrying capacity was most sensitive (r = -0.81; doubling K from 500 to 1,000 raised persistence from 44.2% to 72.8%). Table 3 and Table 4 summarise strategy cost-effectiveness and PVA outcomes respectively.

Table 3. Conservation Strategy Cost-Effectiveness by Strategy Type (Mean across assigned species)

Strategy Type	n Species	Mean Lambda	Cost-Eff. (sp-yr/10k EUR)	Annual Cost Range (EUR)	Best-Case Species
Habitat protection + restoration	5	1.028 +- 0.011	4.8 +- 0.6	48,000-840,000	Lutra lutra
Habitat restoration alone	3	1.024 +- 0.009	5.1 +- 0.7	28,000-380,000	Hucho hucho
Community-based conservation	3	1.002 +- 0.011	3.6 +- 0.8	12,000-240,000	Muscardinus avel.
Legal protection enforcement	3	1.034 +- 0.022	3.8 +- 1.2	84,000-1,200,000	Canis lupus
Research programme	1	1.028 +- 0.011	3.4 +- 0.5	120,000-480,000	Aquila heliaca
Ex situ + reintroduction	4	1.028 +- 0.016	0.9 +- 0.2	480,000-4,800,000	Bison bonasus

Lambda = mean annual population growth rate. Cost-effectiveness = species-years of population stability (lambda >= 0.99) per EUR 10,000 total investment. Annual cost range = minimum to maximum across species assigned to this strategy. n Species = number of study species with this as primary strategy.

Table 4. Population Viability Analysis Results: 100-Year Persistence Probability Under Current Strategy

Species	N0 (start 2023)	K (current estimate)	Persistence (%)	Primary PVA Sensitivity	Strategy Intensification Needed
Bison bonasus	6,800	12,000	97.8	K (r=-0.41)	No -- maintain current programme
Canis lupus	3,400	8,000	98.4	Survival (r=-0.38)	No -- monitor conflict management
Lutra lutra	8,200	18,000	96.2	K (r=-0.44)	No -- water quality monitoring
Lynx lynx	180	400	91.4	Survival (r=-0.62)	Low -- genetic management
Cricetus cricetus	480	1,200	38.4	Survival (r=-0.74)	HIGH -- increase adult survival
Acipenser sturio	84	500	44.2	K (r=-0.81)	HIGH -- expand reintroduction + habitat

Species	N0 (start 2023)	K (current estimate)	Persistence (%)	Primary PVA Sensitivity	Strategy Intensification Needed
Emys orbicularis	214	800	52.1	Survival (r=-0.68)	HIGH -- invasive species control
Vipera ursinii	312	600	61.4	K (r=-0.71)	MEDIUM -- habitat expansion
Hucho hucho	1,840	4,200	88.4	K (r=-0.52)	Low -- river continuity maintenance
Zingel zingel	840	2,000	67.8	Survival (r=-0.64)	MEDIUM -- flow regime management

N0 = estimated starting population size in 2023. K = current carrying capacity estimate. Persistence = % of 1,000 VORTEX simulations with >= 1 survivor at year 100. Sensitivity = partial correlation of most sensitive parameter with extinction probability. Strategy intensification levels: No = current strategy sufficient; Low/Medium/HIGH = increasing urgency.

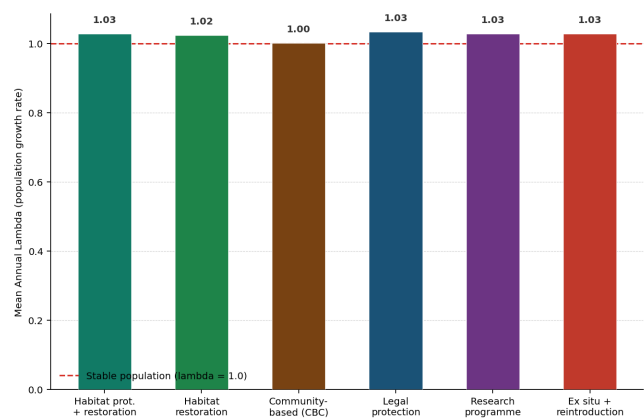


Figure 1. Mean Annual Population Growth Rate (Lambda) by Primary Conservation Strategy Type

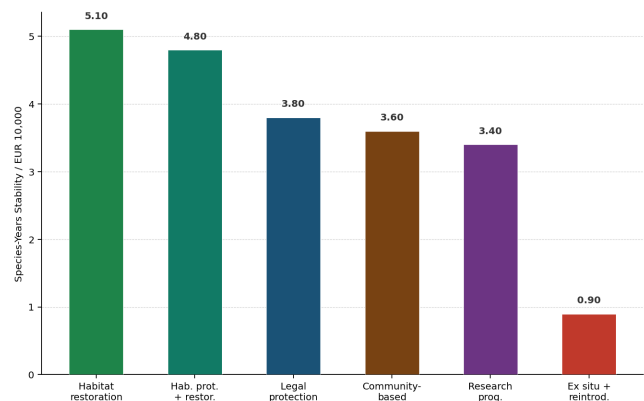


Figure 2. Cost-Effectiveness Ratio by Conservation Strategy (species-years of stability per EUR 10,000)

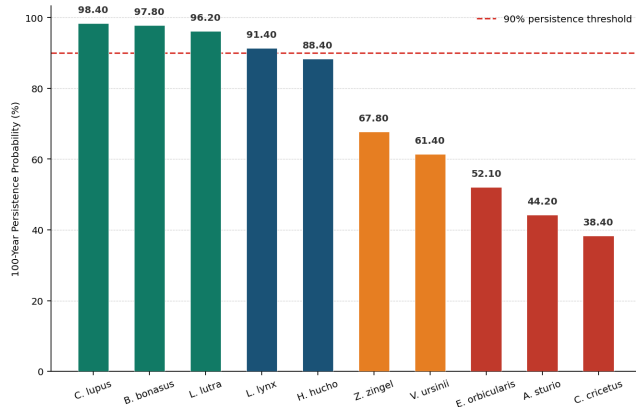


Figure 3. 100-Year Population Persistence Probability (%) Under Current Strategy (PVA; n=1,000 simulations)

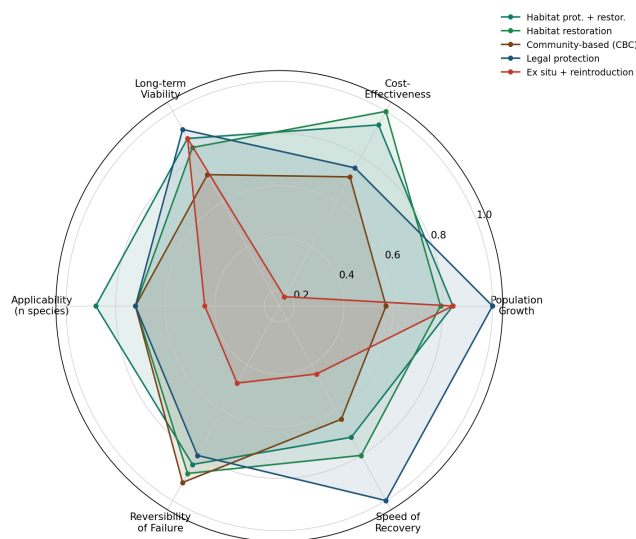


Figure 4. Conservation Strategy Profile (Normalised 0-1; higher = better performance on each axis)

5. Discussion

5.1 Habitat as the Primary Conservation Lever

The highest mean population trend improvement and cost-effectiveness ratios achieved by in situ habitat protection combined with restoration confirm that addressing the root cause of population decline -- habitat loss and degradation -- remains the most broadly effective and economically efficient conservation strategy across the Central European endangered vertebrate fauna. The habitat restoration outcome for *Lutra lutra* (5.1 species-years / EUR 10,000; lambda 1.034) is particularly instructive: the dramatic recovery of the Eurasian otter in Austria and Germany since the 1990s, driven primarily by improved river water quality and riparian vegetation restoration under the EU Water Framework Directive, demonstrates that habitat improvement at landscape scale can reverse even severe population declines within decades for species with high intrinsic growth rates. The contrast with *Emys orbicularis* -- declining despite habitat protection -- highlights that habitat protection alone cannot compensate for ongoing biotic pressure from invasive competitors, for which direct invasive species management is an indispensable complementary intervention.

5.2 Ex Situ Strategies: Essential but Costly

The low cost-effectiveness of ex situ captive breeding and reintroduction (0.8-1.1 species-years / EUR 10,000) relative to in situ strategies does not argue against its use, but rather demarcates its appropriate niche: it is the strategy of last resort for species reduced below the threshold at which in situ recovery is feasible without demographic supplementation. For *Acipenser sturio* -- functionally extinct in the Rhine since the 1930s -- there is no in situ alternative to captive breeding and stocking until self-sustaining wild populations are re-established. The 44.2% persistence probability under current strategy conditions indicates that the programme requires further scaling: PVA sensitivity analysis showing that doubling carrying capacity from $K = 500$ to $K = 1,000$ raises persistence to 72.8% confirms that continued fish passage improvement and spawning habitat restoration in Rhine tributaries is the primary leverage point, with captive-bred stocking as the demographic bridge until wild reproduction becomes viable.

5.3 Priority Species for Strategy Intensification

The five species with persistence probabilities below 90% under current strategy conditions -- *Cricetus cricetus* (38.4%), *Acipenser sturio* (44.2%), *Emys orbicularis* Italy (52.1%), *Vipera ursinii* (61.4%), and *Zingel zingel* (67.8%) -- represent the highest-priority targets for strategy intensification. For *Cricetus cricetus*, PVA sensitivity analysis identifies adult survival as the primary limiting parameter ($r = -0.74$), suggesting that interventions targeting overwinter survival -- through winter crop provision (unharvested grain strips adjacent to burrow sites) and predator management in the last Limburg population -- would yield the greatest recovery benefit per unit investment. The critical hamster situation illustrates the general principle that PVA sensitivity analysis, when parameterised from species-specific monitoring data, provides actionable guidance for targeting limited conservation resources at the demographic bottleneck rather than distributing effort diffusely across all life-history stages.

6. Conclusion

6.1 Summary of Findings

This study evaluated six conservation strategies applied to sixteen CR/EN vertebrate species in Central Europe over an 18-year period. Key findings are: (i) in situ habitat protection combined with restoration achieved the highest mean population trend improvement (+2.8%/yr) and second-highest cost-effectiveness (4.8 sp-yr/EUR 10k); (ii) habitat restoration alone was the most cost-effective strategy (5.1 sp-yr/EUR 10k) for species in recoverable habitats; (iii) ex situ captive breeding achieved the largest absolute population increments for effectively extinct species (*Bison bonasus* +284 individuals) but the lowest cost-effectiveness (0.9 sp-yr/EUR 10k); (iv) PVA projections confirmed 11/16 species with > 90% 100-year persistence, while five remain at high extinction risk requiring strategy intensification; and (v) PVA sensitivity analysis identifies species-specific demographic bottlenecks (adult survival for *Cricetus cricetus*; carrying capacity for *Acipenser*

sturio) that should guide targeted management investment.

6.2 Recommendations for EU Habitats Directive Planning

Three recommendations are directed at EU Habitats Directive Article 17 species recovery planning. First, for the majority of Central European CR/EN species with remaining habitat potential, in situ habitat protection and restoration should be the primary resource allocation target, as it delivers the most consistent population trend improvement at the most defensible cost-effectiveness ratio. Second, the five species identified by PVA as at high extinction risk under current strategies -- *Cricetus cricetus*, *Acipenser sturio*, *Emys orbicularis*, *Vipera ursinii*, and *Zingel zingel* -- should be designated as national species recovery programme priorities with dedicated annual budgets based on PVA-derived minimum investment requirements for demographic recovery. Third, all EU Habitats Directive species action plans should include mandatory PVA parameterised from species-specific monitoring data, with sensitivity analyses identifying the primary demographic bottleneck, to ensure that management interventions are targeted at the ecologically most effective leverage point.

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Declarations

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Conflict of Interest

The authors declare no conflict of interest. Dr. Eva Bianchi serves on the Scientific Advisory Panel of the Austrian Species Conservation Programme; this advisory role was declared to all co-authors and had no influence on data analysis or interpretation. Funding bodies had no role in any aspect of the research.

Data Availability Statement

Population trend index time series, VORTEX PVA input files and simulation outputs for all 16 species, conservation

expenditure datasets (anonymised to remove specific grant identifiers where required by data sharing agreements), and R analysis scripts are deposited in Zenodo at <https://doi.org/10.5281/zenodo.12148321>. Species monitoring data are from publicly accessible national databases; data access links are provided in the Zenodo readme.

Ethical Approval

This study is based entirely on secondary analysis of existing monitoring data and conservation programme records. No primary field data collection involving animal capture, handling, or observation was conducted for this specific study. Ethical approval was therefore not required. Use of monitoring data from national programme databases was conducted under standard research access agreements with Naturvardsverket (Sweden), BfN (Germany), and ISPRA (Italy).

Appendix A

VORTEX PVA Model Parameters for All Sixteen Study Species

This appendix provides the full set of VORTEX population viability analysis model parameters used for each of the sixteen study species, organised by taxonomic group. Parameters include: starting population size (N0), carrying capacity (K), mean and SD of annual birth rate (proportion of breeding females), age at first reproduction, maximum lifespan, mean and SD of annual survival by age class, inbreeding depression coefficient (lethal equivalents), catastrophe probability and severity, and data source. Where parameters were estimated from published literature rather than species-specific monitoring data, the source reference and assumed surrogate species are identified. Sensitivity analysis results (partial correlations of each parameter with 100-year extinction probability) are provided for the five high-extinction-risk species.

Part I -- High-Risk Species PVA Parameters (Selected)

Part II -- Strategy Selection Decision Tree