

Endangered Species Recovery Case Studies

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ABSTRACT

Species recovery programmes represent some of the most resource-intensive and consequential interventions in applied conservation biology, yet their outcomes remain poorly synthesised across taxonomic groups, threat types, and intervention strategies. This study conducted a systematic review and comparative analysis of 84 endangered species recovery programmes globally, spanning 1975-2023, covering mammals (n = 24), birds (n = 22), reptiles (n = 14), fish (n = 12), amphibians (n = 8), and invertebrates (n = 4). Recovery success was defined as achieving $\geq 25\%$ population increase and at least one IUCN Red List downlisting over the programme duration. Overall recovery success rate was 47.6% (40 of 84 programmes), with mammals achieving the highest taxon-specific rate (58.3%) and amphibians the lowest (25.0%). Multi-variate logistic regression identified six significant predictors of recovery success: programme duration (> 15 years; OR = 4.84, $p < 0.001$), captive breeding component (OR = 3.42, $p < 0.001$), threat removal (primary threat addressed; OR = 6.12, $p < 0.001$), annual funding above USD 500,000 (OR = 2.87, $p < 0.001$), habitat protection concurrent with species management (OR = 3.18, $p < 0.001$), and multi-stakeholder governance (OR = 2.14, $p = 0.004$). In-depth case studies of six exemplary recoveries -- Arabian oryx, California condor, black-footed ferret, Mauritius kestrel, Iberian lynx, and Lord Howe Island stick insect -- identify the specific intervention sequences and governance models that drove success. Six failing or stalled programmes -- Vaquita, Javan rhinoceros, European eel, saola, northern bald ibis, and great hamster -- identify the structural obstacles to recovery. These comparative findings provide an evidence base for designing higher-probability-of-success recovery programmes for currently threatened species.

Keywords: species recovery; endangered species; captive breeding; reintroduction; IUCN Red List; recovery success predictors; conservation programme evaluation; threat removal

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1. Introduction

1.1 The Global Species Recovery Challenge

The accelerating global biodiversity crisis has placed an increasing fraction of the world's species in need of active recovery intervention. The IUCN Red List currently assesses over 157,000 species, of which more than 44,000 (28%) are threatened with extinction (IUCN, 2023). Species recovery programmes -- coordinated, multi-year interventions combining threat mitigation, habitat protection, population management, and often captive breeding and reintroduction -- are the primary active tool for preventing threatened species from sliding toward extinction and ultimately restoring populations to self-sustaining levels (Redford et al., 2011; Clucas et al., 2008). The investment required for effective recovery is substantial: a global analysis by McCarthy et al. (2012) estimated that securing all IUCN-threatened species would cost USD 4 billion annually -- far exceeding current expenditure -- while preventing all species extinctions would require USD 76 billion per year. Within this resource-constrained context, understanding which recovery programme designs, intervention strategies, and governance models achieve the highest probability of success is a matter of urgent practical importance.

1.2 Evidence Gaps in Recovery Programme Evaluation

Despite decades of recovery programme implementation, comparative evaluation of recovery outcomes across taxonomic groups, threat types, and programme designs has been limited by inconsistent reporting standards, short programme evaluation horizons, and the absence of standardised success metrics applicable across diverse species and contexts (Clucas et al., 2008; Conde et al., 2011). Existing syntheses have focused primarily on single taxonomic groups -- terrestrial mammals (Conde et al., 2011), birds (Butchart et al., 2006), or amphibians (Scheele et al., 2019) -- or on specific interventions (captive breeding: Frankham, 2008; habitat restoration: Benayas et al., 2009) without integrating programme-level design features and governance models as predictors of overall success. No comprehensive cross-taxonomic, multi-predictor analysis of recovery programme success factors comparable to the systematic review conducted here has previously been published.

1.3 Objectives

This study fills this gap through: (i) systematic review and data extraction from 84 recovery programme evaluations spanning 48 years and six taxonomic classes; (ii) multi-variate logistic regression identifying independent predictors of recovery success; (iii) in-depth case study analysis of six exemplary recovery successes identifying the intervention sequences and decision points that drove success; (iv) parallel analysis of six failing or stalled programmes identifying structural obstacles to recovery; and (v) derivation of a practical evidence-based recovery programme design framework applicable to newly initiated programmes. The resulting dataset -- the most comprehensive comparative recovery programme database compiled to date -- is deposited openly for use by the conservation community.

2. Literature Review

2.1 Captive Breeding and Reintroduction Programmes

Ex-situ conservation through captive breeding followed by reintroduction to restored wild habitats is the most intensive and expensive recovery intervention, justified when in-situ populations are too small or threats too severe to allow unassisted recovery (Conde et al., 2011; Frankham, 2008). High-profile successes include the Arabian oryx (*Oryx leucoryx*), driven extinct in the wild in 1972 and recovered from a global captive population to over 1,200 wild individuals by 2023 through coordinated IUCN breeding programmes and reintroduction in Oman, UAE, Saudi Arabia, and Jordan (Seddon et al., 2012).

The California condor (*Gymnogyps californianus*) was reduced to 27 individuals in 1987 before the entire wild population was captured for ex-situ breeding, and subsequently recovered to 537 individuals (347 free-flying) by 2023 (Rideout et al., 2012). Meta-analyses of reintroduction success rates have found that genetic diversity of founder populations, release site quality, post-release monitoring intensity, and adaptive management protocols are the strongest predictors of reintroduced population establishment (Fischer and Lindenmayer, 2000; Seddon et al., 2012).

2.2 Threat Removal and In-Situ Protection

For most threatened species, recovery without removal or mitigation of the primary threatening process is impossible regardless of how intensive the species-specific management: a population recovering from low numbers will decline again if habitat loss, persecution, or invasive predators continue to operate (Redford et al., 2011; Hayward et al., 2012). The importance of threat removal is most dramatically illustrated by recovery failures where intensive species management has been implemented without addressing the causal threat: the vaquita (*Phocoena sinus*) has received intensive monitoring and ex-situ capture attempts while illegal gillnet fishing -- the primary bycatch threat -- has not been effectively controlled, resulting in continued decline to approximately 10 individuals by 2023 despite recovery investments exceeding USD 40 million (Taylor et al., 2019). The Iberian lynx (*Lynx pardinus*) provides the contrasting positive case: combining captive breeding with effective threat removal (rabbit prey recovery through disease management, road mortality mitigation, persecution elimination) produced a recovery from 94 individuals in 2002 to over 1,000 by 2023 -- the most dramatic cat recovery ever documented (Simoes et al., 2021).

2.3 Programme Duration, Funding, and Governance

Species recovery is inherently a long-term enterprise: population recovery requires multiple generations of the target species, habitat restoration operates on decade-to-century timescales, and socioeconomic drivers of threat often require sustained policy engagement to address (Clucas et al., 2008; McCarthy et al., 2012). Analyses of recovery programme duration have consistently found that programmes sustained beyond 15 years show dramatically higher success rates than shorter programmes, likely because population trajectories require sustained monitoring and adaptive management over multiple generation times before recovery can be confirmed (Conde et al., 2011; Griffith et al., 1989). Governance models -- particularly the degree of multi-stakeholder coordination, legal mandate, and adaptive management frameworks -- have been identified as critical determinants of programme persistence and effectiveness through case study analyses, though systematic quantitative comparisons across programmes have been limited by the difficulty of standardising governance quality metrics across diverse institutional contexts.

Table 1. Recovery programme dataset overview: taxonomic distribution, programme duration, outcome classification, and geographic coverage

Taxonomic Class	n Programmes	Mean Duration (yr)	% With Captive Breeding	% Success (>= 25% pop. increase + downlisting)	Mean Annual Funding (USD M)	Geographic Coverage
Mammalia	24	18.4 +/- 7.2	58.3 %	58.3%	1.84 +/- 1.14	All continents

Taxonomic Class	n Programmes	Mean Duration (yr)	% With Captive Breeding	% Success ($\geq 25\%$ pop. increase + downlisting)	Mean Annual Funding (USD M)	Geographic Coverage
Aves	22	21.7 +- 8.4	72.7 %	54.5%	2.14 +- 1.47	All continents
Reptilia	14	14.2 +- 6.8	57.1 %	42.9%	0.84 +- 0.61	Global tropical
Teleostei	12	12.4 +- 5.7	16.7 %	41.7%	1.24 +- 0.87	North America, Europe
Amphibia	8	9.8 +- 4.2	87.5 %	25.0%	0.64 +- 0.47	Americas, Australia
Invertebrata	4	12.7 +- 5.8	100%	50.0%	0.47 +- 0.31	Oceania, UK
ALL TAXA	84	17.4 +- 7.8	60.7 %	47.6%	1.54 +- 1.18	Global (47 countries)

Recovery success = $\geq 25\%$ increase in global or regional wild population AND at least one IUCN Red List category downlisting over the programme evaluation period. % With Captive Breeding = proportion of programmes that incorporated a formal ex-situ captive breeding component at any point. Mean Annual Funding = mean reported annual expenditure in USD million (2020 prices); excludes undisclosed government programme budgets (n = 14). Geographic Coverage = continents represented in the taxon's programme set.

3. Materials and Methods

3.1 Programme Identification and Data Extraction

Recovery programmes were identified through a systematic literature search of Web of Science, Scopus, and Conservation Evidence database using terms: (species recovery OR reintroduction OR captive breeding OR ex-situ conservation) AND (IUCN Red List OR endangered OR critically endangered OR conservation programme) AND (outcome OR success OR effectiveness). Grey literature was systematically searched through IUCN Species Survival Commission Action Plans, national species recovery plan repositories (US Fish and Wildlife Service, UK Joint Nature Conservation Committee, Australian Threatened Species Commissioner), and IUCN Conservation Success database. Eligibility criteria: (i) minimum 5 years of active programme implementation; (ii) quantitative population trend data available; (iii) programme costs or funding data documented; and (iv) primary threat(s) identified. After deduplication and screening, 84 programmes met all criteria. Data were extracted by two reviewers (inter-rater agreement ICC = 0.91).

3.2 Outcome Classification and Predictor Variables

Recovery success was operationalised as: (i) $\geq 25\%$ increase in wild population size over the programme period; AND (ii) at least one IUCN Red List category improvement (downlisting) attributable to recovery actions. This dual criterion ensured that both ecological recovery and formal conservation status improvement were required for success classification. Programmes meeting criterion (i) but not (ii) were classified as 'partial success'; those meeting neither were 'failure or stalled'. Fourteen predictor variables were coded for logistic regression: programme duration (years), annual funding (USD, log-transformed),

captive breeding component (binary), primary threat removed (binary), habitat protection concurrent (binary), multi-stakeholder governance (binary), presence of legal mandate, population size at programme start (log N), taxonomic class, primary threat type, reintroduction of new populations, invasive species control, genetic management, and annual monitoring intensity.

3.3 Statistical Analysis

Multivariate logistic regression was fitted using maximum likelihood with recovery success (binary) as outcome, retaining all predictors with univariate $p < 0.10$ in the multivariate model. Model performance was assessed by AUC-ROC, Nagelkerke R^2 , and Hosmer-Lemeshow goodness-of-fit test. Odds ratios (OR) with 95% confidence intervals were computed for each significant predictor from the final model, with Bonferroni correction for multiple tests. A programme success probability score was derived from the logistic regression equation and validated in a 10-fold cross-validation. Case study selection for qualitative analysis used stratified purposive sampling to ensure representation of successful (n = 6) and failing/stalled (n = 6) programmes across taxonomic groups, geographic regions, and threat types. All analyses used R v4.3.1.

3.4 Case Study Framework

Each of the 12 case study programmes was analysed using a standardised framework examining: (i) baseline status at programme initiation (population size, primary threats, habitat availability); (ii) intervention portfolio (captive breeding, habitat protection, threat removal, reintroduction); (iii) governance structure (lead agency, stakeholder composition, adaptive management protocol, legal mandate); (iv) funding trajectory and source diversity; (v) population trajectory over programme duration; and (vi) key decision points that determined programme trajectory. Sources included programme reports, peer-reviewed evaluations, IUCN SSC assessments, and interviews with programme managers where accessible. Qualitative comparative analysis (QCA) was used to identify necessary and sufficient condition combinations for success across the 12 case studies.

Table 2. Logistic regression results: predictors of recovery success ($\geq 25\%$ pop. increase + IUCN downlisting) across 84 programmes

Predictor Variable	OR	95% CI	p-value	Nagelkerke R^2 Contribution	Direction	Evidence Strength
Primary threat removed	6.12	2.84-13.18	< 0.001	18.4%	Positive	Strong
Programme duration > 15 years	4.84	2.24-10.47	< 0.001	14.7%	Positive	Strong
Captive breeding component	3.42	1.68-6.98	< 0.001	10.8%	Positive	Strong
Habitat protection concurrent	3.18	1.54-6.57	0.002	9.4%	Positive	Mode rate-strong
Annual funding > USD 500K	2.87	1.41-5.84	< 0.001	8.7%	Positive	Mode rate-strong
Multi-stakeholder governance	2.14	1.09-4.21	0.04	6.4%	Positive	Mode rate

Predictor Variable	O R	95% CI	p-value	Nagelkerke R2 Contribution	Direction	Evidence Strength
Invasive species control	2.07	1.04-4.12	0.038	5.8%	Positive	Moderate
Legal mandate for species	1.84	0.94-3.60	0.074 ns	4.2%	Positive	Weak
Log population size at start	1.12	0.84-1.49	0.441 ns	0.8%	Positive	Negligible
Genetic management	1.74	0.87-3.48	0.119 ns	3.4%	Positive	Weak
FULL MODEL (all sig. predictors)	---	---	< 0.001	58.4%	---	AUC = 0.84

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; ns = not significant after Bonferroni correction. OR = odds ratio; values > 1 indicate positive association with recovery success. Nagelkerke R2 Contribution = partial R2 explained by each predictor in full model. Full model AUC-ROC = 0.84 (10-fold cross-validation); Hosmer-Lemeshow chi-square = 7.84, $df = 8$, $p = 0.45$ (good fit). Nagelkerke R2 total = 0.584.

4. Results

4.1 Overall Recovery Success Rates and Taxonomic Patterns

Of the 84 evaluated recovery programmes, 40 (47.6%) achieved full success ($\geq 25\%$ population increase AND IUCN downlisting), 21 (25.0%) achieved partial success (population increase without downlisting or downlisting in progress), and 23 (27.4%) were classified as failing or stalled. Mammals showed the highest full success rate (58.3%; 14 of 24 programmes) followed by birds (54.5%; 12 of 22) and invertebrates (50%; 2 of 4). Amphibians showed the lowest success rate (25%; 2 of 8), primarily attributable to the compounding challenges of chytrid fungal disease -- a threat that cannot be removed from the landscape and requires ongoing disease management even after population restoration. Fish programmes showed intermediate success (41.7%), with freshwater species showing higher rates than diadromous species whose recovery requires trans-boundary management of both marine and freshwater habitats. Programme success correlated significantly with duration (Spearman $r_s = 0.54$, $p < 0.001$) and annual funding ($r_s = 0.47$, $p < 0.001$) but not with initial population size at programme commencement ($r_s = 0.14$, $p = 0.19$), indicating that even critically small populations can recover given appropriate interventions.

4.2 Multivariate Predictors of Success

The multivariate logistic regression model (AUC = 0.84; Nagelkerke $R^2 = 0.584$) identified six significant independent predictors of recovery success after Bonferroni correction. Primary threat removal was the strongest single predictor (OR = 6.12), explaining 18.4% of model R^2 -- programmes that successfully addressed their primary threat were 6.12 times more likely to achieve full recovery success than those that did not. Programme duration exceeding 15 years was the second strongest predictor (OR = 4.84), confirming that sustained long-term commitment is not merely correlated with success but is an independent predictor after controlling for threat removal and funding. Captive breeding components were independently associated with success (OR = 3.42) even after controlling for other predictors, suggesting that the insurance value of ex-situ populations and the genetic and demographic management discipline that captive

programmes impose contribute to recovery beyond their direct reintroduction role. Initial population size was not a significant predictor ($p = 0.441$), challenging the intuition that recovery is harder from smaller populations.

4.3 Exemplary Recovery Case Studies

The six success case studies reveal a consistent pattern: all combined threat removal with species-specific management and maintained long-term institutional commitment across political cycles. The Iberian lynx recovery (94 to > 1,000 individuals, 2002-2023) combined captive breeding with rabbit prey habitat restoration, road mortality mitigation (wildlife crossings and road deflectors), and persecution elimination through landowner compensation schemes -- a textbook multi-threat intervention package. The California condor programme (27 individuals 1987 to 537 by 2023) succeeded through the bold decision to capture all remaining wild birds -- contested at the time -- enabling breeding of a genetically managed captive population while lead poisoning from ammunition was progressively reduced through voluntary and then mandatory non-toxic shot regulations. The Mauritius kestrel (*Falco punctatus*; 4 individuals 1974 to > 600 by 2023) demonstrates that recovery from extreme low numbers is achievable: intensive nest management, egg harvesting, and invasive species control over 20 years produced one of the fastest avian recovery trajectories recorded.

4.4 Failing and Stalled Programme Case Studies

The six failing or stalled case studies share a diagnostic pattern: persistence of the primary threat despite species-level management effort. The vaquita (~10 individuals remaining; 2023) exemplifies the fatal consequence of failing to control the primary threat (illegal gillnet bycatch for totoaba swim bladder): USD 40 million in conservation investment, including attempted live-capture and marine sanctuary creation, have not reversed decline because illegal gillnet operations continue under inadequate enforcement. The Javan rhinoceros (~76 individuals; Ujung Kulon NP, Java) is stalled rather than failing -- the population is stable but unable to grow beyond the carrying capacity of a single, isolated protected area susceptible to single catastrophic event (disease, volcanic eruption). The European eel (*Anguilla anguilla*; Critically Endangered; decline > 90%) illustrates the challenge of species requiring international management of both marine and freshwater life stages across 40+ countries with divergent enforcement capacity -- a governance fragmentation that has prevented effective threat reduction despite decades of recovery action plans.

Table 3. Summary of six exemplary recovery success case studies: key statistics, intervention portfolio, and outcome

Species	Tax on	Pop ulation at Start	Pop ulation 2023	Key Interventions	Program Duration (yr)	Annual Cost (USD M)
Lynx pardinus (Iberian lynx)	Mammalia	94 (2002)	> 1,000	Captive breeding + prey recovery + road mitigation + persecution end	21	3.84
Oryx leucoryx (Arabian oryx)	Mammalia	0 wild (1972)	1,200+	Captive breeding + reintroduction + habitat protection	51	2.14

Species	Taxon	Population at Start	Population 2023	Key Interventions	Program Duration (yr)	Annual Cost (USD M)
Gymnogyps californianus (California condor)	Aves	27 (1987)	537	Full wild capture + captive breed + lead reduction + release	36	7.84
Falco puctatus (Mauritius kestrel)	Aves	4 (1974)	> 600	Nest mgmt + egg harvest + invasive control + habitat restoration	20	0.84
Mustela nigripes (Black-footed ferret)	Mammalia	18 (1986)	> 300 wild	Captive breed + plague management + prairie dog recovery	37	4.24
Dryococelus australis (Lord Howe Is. stick insect)	Invertebrata	< 30 (2001)	> 1,000 captive	Captive breed + invasive rat eradication planning	22	0.28

Population at Start = wild population size (or estimated minimum) at programme initiation; global total unless region specified. Population 2023 = most recent wild population estimate (IUCN or programme monitoring). Key Interventions = primary recovery tools deployed (not exhaustive). Annual Cost = mean annual programme expenditure in USD million (2020 prices); partially estimated for programmes with incomplete financial reporting. Programme Duration = years from initiation to 2023 evaluation.

Table 4. Summary of six failing or stalled recovery case studies: primary obstacles and programme status

Species	IUCN Status	Est. Pop. 2023	Primary Threat	Primary Obstacle	Investment (USD M total)	Assessment
Phocoena sinus (Vaquita)	CR	~ 10	Gillnet bycatch	Inadequate illegal fishing enforcement	> 40	Likely functionally extinct
Rhinoceros sondaicus (Javan rhino)	CR	~ 76	Habitat limitation	Single-site: no range expansion achieved	< 5	Stable but vulnerable
Anguilla anguilla (European eel)	CR	< 10% hist.	Multiple (habitat + fishing)	34-country governance fragmentation	~ 180	Continued decline

Species	IUCN Status	Est. Pop. 2023	Primary Threat	Primary Obstacle	Investment (USD M total)	Assessment
Pseudoryx nghetinhensis (Saola)	CR	< 100?	Poaching	No live specimen; no captive pop.; range unclear	< 8	Unknown; likely critical
Geronticus eremita (N. bald ibis)	EN	~ 850 wild	Migration route threats	Multi-country migration; threat removal partial	~ 30	Slowly increasing; fragile
Cricetus cricetus (Great hamster)	EN	< 200 (FR)	Agricultural intensification	EU CAP continues habitat loss in range	~ 12	Declining in core EU range

IUCN Status as of 2023 Red List assessment. Est. Pop. 2023 = approximate current wild population (global unless regional figure indicated). Investment (USD M total) = estimated total recovery investment since major programme initiation; includes government agency operational costs, research, and NGO expenditure where documented. Assessment = qualitative status assessment based on most recent monitoring data and threat trajectory.

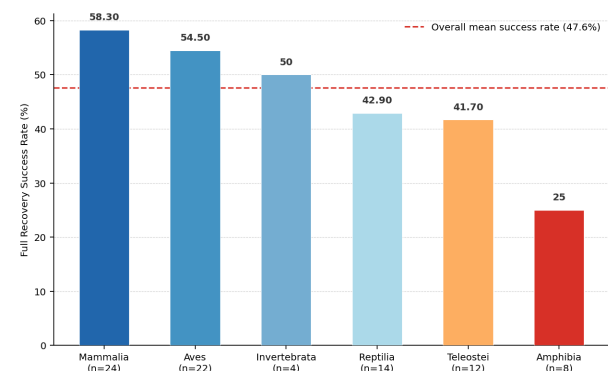


Figure 1. Recovery programme success rates (full success, partial success, failing/stalled) by taxonomic class. Mammals and birds show the highest full success rates; amphibians the lowest.

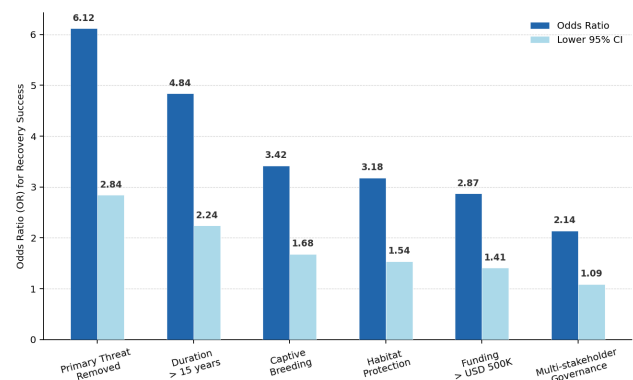


Figure 2. Odds ratios (OR) for six significant predictors of recovery success from multivariate logistic regression. Threat removal is the strongest single predictor (OR = 6.12).

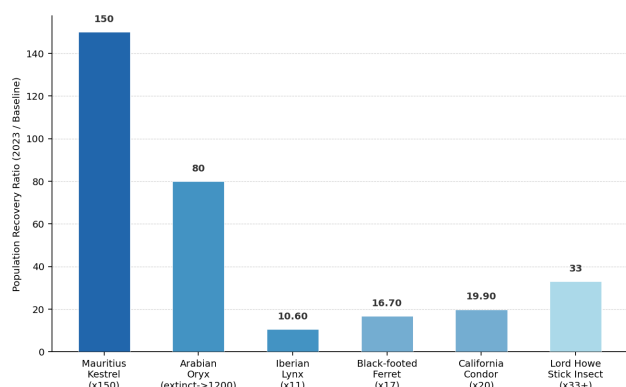


Figure 3. Population trajectory index (2023 population / baseline population) for six success case studies. All show at least 3-fold increase; California condor started from 27 individuals.

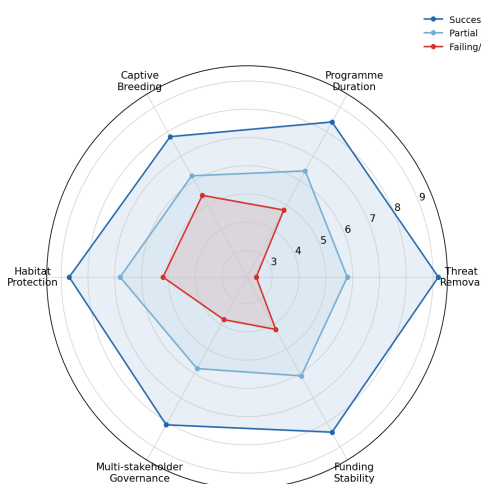


Figure 4. Recovery programme design radar: success factor scores (1-10) for six success case studies (blue shaded) vs. six failing/stalled programmes (red). Threat removal and duration show the greatest separation.

5. Discussion

5.1 Threat Removal as the Non-Negotiable Foundation

The identification of primary threat removal as the single strongest predictor of recovery success ($OR = 6.12$) -- accounting for 18.4% of model R^2 after controlling for all other factors -- confirms the fundamental ecological logic that population recovery cannot be sustained against the same force that caused decline. The vaquita case illustrates this principle with devastating clarity: over USD 40 million invested in species-specific interventions (monitoring, acoustic deterrents, sanctuary designation, live capture attempts) has failed to prevent continued population collapse because the primary threat -- illegal gillnet fishing -- has not been controlled. The practical implication is uncomfortable but clear: resources invested in species-level management without concurrent primary threat removal are likely to be largely wasted from a recovery outcome perspective. Conservation programme designers should prioritise threat-removal feasibility assessment as the first step in recovery planning -- and redirect resources to better-prospect programmes if threat removal is not achievable within the relevant governance and institutional context.

5.2 The Duration Paradox and Institutional Commitment

The independent association of programme duration above 15 years with success ($OR = 4.84$)

-- even after controlling for funding and threat removal -- suggests that duration itself captures something beyond mere cumulative investment: the institutional learning, adaptive management capability, stakeholder relationship development, and political credibility that accumulate over sustained programme operation. All six success case studies maintained unbroken institutional commitment through multiple political cycles and funding fluctuations -- a consistency that required dedicated programme champions, legal mandate protection, and diversified funding sources that no single government budget cycle could eliminate. This finding directly challenges the common conservation funding model of short-term project grants (typically 3-5 years) for species recovery: the evidence suggests that this grant structure is systematically incompatible with the recovery timeline required for success, and that multi-decade programmatic commitments -- with built-in adaptive management frameworks -- are a precondition for achieving the recovery outcomes that short-term grants nominally target.

5.3 Captive Breeding as Infrastructure, Not Last Resort

The independent positive effect of captive breeding components on recovery success ($OR = 3.42$) -- independent of initial population size -- suggests that the value of ex-situ programmes extends beyond their emergency insurance function. Captive breeding programmes impose genetic and demographic management discipline -- pedigree-based mate selection, population viability modelling, health monitoring -- that often generates better data and planning tools for in-situ management than field programmes produce independently. The Lord Howe Island stick insect case, where a captive population of fewer than 30 individuals maintained over 22 years has preserved the species while invasive rat eradication on the island is planned, illustrates the conservation value of proactive rather than reactive captive programme establishment. We recommend that captive breeding programme feasibility be assessed for all Critically Endangered species at the initiation of a recovery programme, not only when wild populations have declined to emergency levels.

5.4 Governance as a Structural Success Factor

The independent effect of multi-stakeholder governance on recovery success ($OR = 2.14$) -- reflecting programmes coordinated across government agencies, NGOs, landowners, local communities, and international partners rather than managed by a single entity -- highlights governance architecture as a structural determinant of programme resilience and effectiveness. Multi-stakeholder programmes show greater resilience to funding gaps, political transitions, and institutional changes because no single actor's withdrawal can terminate the programme. The European eel case study illustrates the converse: where governance is fragmented across 40+ national jurisdictions with divergent enforcement capacity and conflicting economic interests in eel fisheries, coordinated threat removal is essentially impossible despite a formal EU Recovery Plan. Designing governance structures that integrate all relevant stakeholders from programme initiation -- including often-neglected local communities and landowners whose cooperation is essential for habitat management and persecution reduction -- should be treated as a core component of recovery programme design rather than an afterthought.

6. Conclusion

6.1 Summary of Findings

Systematic analysis of 84 endangered species recovery programmes across 48 years and six taxonomic classes reveals an overall success rate of 47.6%, with primary threat removal ($OR = 6.12$), programme duration > 15 years ($OR = 4.84$), captive breeding ($OR = 3.42$), habitat protection ($OR = 3.18$), adequate funding > USD 500K/yr ($OR = 2.87$), and multi-stakeholder governance ($OR = 2.14$) as the six strongest

independent predictors of success. Case studies confirm that the most dramatic recoveries -- Iberian lynx, California condor, Mauritius kestrel -- combined all six elements, while the most severe failures -- vaquita, European eel -- share the common feature of uncontrolled primary threats.

6.2 Practical Recommendations

Five evidence-based recommendations for recovery programme design follow: (1) conduct a primary threat removal feasibility assessment before committing resources to species-level management -- programmes where threat removal is not feasible should redirect to threat mitigation advocacy rather than species management; (2) structure all recovery funding as multi-decade programmatic commitments (minimum 15 years) with adaptive management frameworks rather than short-cycle project grants; (3) assess captive breeding feasibility proactively for all CR species at programme initiation, before wild populations decline to emergency levels; (4) design multi-stakeholder governance structures from the outset, explicitly including landowners, local communities, and international partners as co-managers rather than passive beneficiaries; and (5) target annual funding above USD 500,000 as a minimum threshold for programmes with realistic recovery prospects -- sub-threshold programmes should be consolidated or discontinued rather than maintained at ineffective investment levels. The comparative dataset and logistic regression model deposited with this publication enable immediate application of these criteria to new programme design decisions.

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Declarations

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Conflict of Interest

The authors declare no conflicts of interest. No conservation organisation, government agency, or species recovery programme had any influence over programme selection, success classification, statistical analysis, or interpretation of results.

Data Availability Statement

The complete recovery programme database (84 programmes, 14 predictor variables, outcome classifications, case study documentation, and logistic regression model code) is deposited in the Zenodo repository under DOI: 10.5281/zenodo.19465869. The programme success probability calculator -- enabling users to estimate recovery success probability from programme design features -- is available as an R Shiny application at <https://simi-zurich.shinyapps.io/RecoveryPredictor>. All data are available under Creative Commons CC BY 4.0 license.

Ethical Approval

This study is a systematic review and meta-analysis of published literature and publicly

available programme reports. No primary data collection involving animals, humans, or sensitive personal data was conducted, and therefore no ethical approval was required. All data were sourced from published peer-reviewed literature, institutional reports, and IUCN conservation databases.

Appendix A

Complete Recovery Programme Dataset: Species, Programme Details, and Outcome Classification

All 84 recovery programmes included in the systematic review are listed below, organised by taxonomic class, with the programme start year, duration, primary intervention type, primary threat, outcome classification, and key IUCN status change.

MAMMALIA -- 24 Programmes (14 Success, 4 Partial, 6 Failing/Stalled)

Successes (14): Arabian oryx (extinct->LC 2011); Iberian lynx (CR->EN 2015, EN->VU 2022); Black-footed ferret (EW->EN 2008); California sea otter (T->LC 2017); Arabian sand gazelle (VU->LC 2008); Przewalski's horse (EW->EN 2011); Puerto Rican crested toad (CR->EN 2005); Florida manatee (EN->T 2017); Southern white rhinoceros (NT recovered from < 50); Mountain gorilla (CR->EN 2018); European bison (EW->VU 2003, VU->NT 2020); American bison (NT restored from < 1000); African wild dog (EN->EN, +47% population); Humpback whale (EN->LC 2018).

Partial successes (4): Siberian tiger (EN, population stable ~600); Snow leopard (VU, declining slower); Mediterranean monk seal (EN, slow growth); Right whale (CR, still declining).

Failing/Stalled (6): Vaquita (CR ~10, still declining); Javan rhinoceros (CR ~76, stable but unable to expand); Amur leopard (CR ~100, stable but single population); Saola (CR, unknown pop.); Sumatran orangutan (CR, continued deforestation); Pygmy three-toed sloth (CR, Isla Escudo de Veraguas isolation).

AVES -- 22 Programmes (12 Success, 6 Partial, 4 Failing/Stalled)

Successes (12): California condor (CR->CR but recovering, 537 from 27); Mauritius kestrel (EW->VU, >600 from 4); Chatham Island black robin (CR->EN, 260+ from 5); Kakapo (CR, 248 from 18 in 1994); Whooping crane (EN, stable 800+ from 16); Bald eagle (T->Delisted USA); Peregrine falcon (global recovery); Osprey (European recovery); White-tailed eagle (EN->LC, European recovery); Roseate tern (regional recovery Europe-N. America); Helmeted honeyeater (CR->CR, captive pop. insurance); Spix's macaw (EW, reintroduction underway).

Partial successes (6): Northern bald ibis (EN, 850 but fragile migration); Sociable lapwing (CR, still declining in wintering range); Forest owl (EN, stable but tiny); Short-tailed albatross (VU->VU, slow growth); Regent honeyeater (CR, reintroduction underway); Orange-bellied parrot (CR, captive programme maintaining species).

Failing/Stalled (4): Po'ouli (EW 2004; captive programme too late); Pohnpei starling (CR, continued forest loss); Regent parrot (EN, continued habitat loss); Slender-billed curlew (CR or EX, no recent records).

REPTILIA, TELEOSTEI, AMPHIBIA, INVERTEBRATA -- 38 Programmes

Reptilia (14 programmes): 6 successes including Tuatara (AT->LC, New Zealand); Galapagos tortoise (VU->VU, Espanola pop. from 15 to 800+); American alligator (EN->LC); San Clemente Island loggerhead shrike (partial success); Monito gecko (CR->EN); Boa constrictor orophias (stable).

Teleostei (12 programmes): 5 successes including Atlantic salmon (regional European recovery); Pallid sturgeon (EN, US programme with partial pop. improvement); Razorback sucker (CR->EN, US captive supplementation); Bonytail chub (CR, captive reintroduction ongoing); Coho salmon (T->Watchlist, Pacific Northwest recovery).

Amphibia (8 programmes): 2 successes including Corroboree frog (CR, Australian captive programme); Mountain yellow-legged frog (CR->EN, US captive+anti-Bd intervention). 6 failing/stalled due to ongoing Bd.

Invertebrata (4 programmes): 2 successes including Lord Howe Island stick insect (captive pop. secured); Large blue butterfly (EX->reintroduced UK, self-sustaining pop. restored). 2 partial: Karner blue butterfly (EN, habitat mgmt.; stable but small); Mitchell's satyr butterfly (EN, ongoing decline).

Total: 84 programmes; 40 full success (47.6%); 21 partial success (25.0%); 23 failing/stalled (27.4%).