17(4) 493-507, Winter 2025

Journal of Animal Environment

(E-ISSN 2717-1396, ISSN 2717-1388)

Journal homepage: http://www.aejournal.ir

Original Research Paper

Bayesian Meta-Analysis of Conservation Interventions for Endangered Species with Sparse Outcome Data

Dr. Parag Amin[1*], Suraj Singh[2], Garima khashpuria[3], Fazil Hasan[4], Dr. Purna Chandra Mishra[5], B. Angel[6], Diksha Aggarwal[7]

[1]Professor, ISME, ATLAS SkillTech University, Mumbai, India. Email: parag.amin@atlasuniversity.edu.in, ORCID: https://orcid.org/0009-0005-0146-1815*
[2]Lecturer, Department of Computer Science and Engineering, Faculty of Engineering and Technology, Parul Institute of Technology, Parul University, Vadodara, Gujarat, India.
Email: suraj.singh34612@paruluniversity.ac.in, ORCID: https://orcid.org/0009-0000-9438-687X
[3]Associate Professor, Department of Agriculture, Vivekananda Global University, Jaipur, India.
Email: garima.khaspuria@vgu.ac.in, ORCID: https://orcid.org/0009-0007-8927-580X
[4]Assistant Professor, Department of Agriculture, Noida International University, Noida, Uttar Pradesh, India.
Email: fazil@niu.edu.in, ORCID: https://orcid.org/0000-0003-0621-4248
[5]Professor, Department of Veterinary Gynaecology & Obstretics, Institute of Veterinary Science and Animal Husbandry, Siksha 'O' Anusandhan (Deemed to be University), Bhubaneswar, Odisha, India.
Email: purnachandramishra@soa.ac.in, ORCID: https://orcid.org/0009-0003-3474-1499
[6]Assistant Professor, Department of Mathematics, Sathyabama Institute of Science and Technology, Chennai, Tamil Nadu, India. Email: angelb.maths@sathyabama.ac.in, ORCID: https://orcid.org/0009-0006-4922-8606
[7]Quantum University Research Center, Quantum University, Roorkee, Uttarakhand, India.
Email: diksha.aggarwal@quantumeducation.in, ORCID: https://orcid.org/0009-0000-5479-9098

Key Words

Bayesian meta-analysis, Conservation interventions, Endangered species, Heterogeneity, Population recovery, Species translocation, Sustainable conservation.

Abstract

The major objective of the paper was to perform Bayesian meta-analysis to assess the effectiveness of conservation interventions targeting endangered species, given situations with sparse data. Particularly, the study aimed at comparing the efficacy of some conservation measures, including habitat restoration, species translocation, captive breeding, and anti-poaching measures, to serve as an improvement of species survival and conservation of biodiversity. Web of Science, Scopus, and Google Scholar were selected as systematic literature search platforms that identified the studies that reported quantitative results of conservation interventions. A total of 20 empirical studies and 112 effect sizes were selected after inspection of the studies and the application of the inclusion criteria. A Bayesian random-effects meta-analysis was used in the study to bring prior knowledge to explain the uncertainties and heterogeneity across the studies. This model enabled the synthesis of thin data that generated more valid estimates of intervention effectiveness. The Bayesian meta-analysis showed that the overall effect size is moderate, 0.48 (95% credible interval: 0.26-0.69), which shows that conservation intervention tends to enhance population-level response. The positive impacts were the most consistent with habitat restoration and measures based on policies, with means of 0.62 and 0.55, respectively. Interventions, such as species translocation and captive breeding, however, had a more mixed result. The heterogeneity was significant ($I^2 = 64.3\%$, $\tau^2 = 0.21$), and the effectiveness of the interventions depends on the situation. This experiment is quite convincing about the fact that conservation interventions have a beneficial effect on the recovery of endangered species, and the efficacy of the intervention is dependent on the kind of intervention and the situation. The findings have demonstrated the importance of the adaptive and context-sensitive approaches, as well as the need to conduct additional research to be able to maximize practices like species translocation and captive breeding. Continued investment in habitat restoration and policy-based measures is essential for long-term biodiversity conservation.

* Corresponding Author's email: parag.amin@atlasuniversity.edu.in
Received: 15 September 2025; Reviewed: 22 October 2025; Revised: 28 November 2025; Accepted: 29 December 2025
(DOI): 10.70102/AEJ.2025.17.4.38

Introduction

The conservation interventions used to preserve the life of endangered species are deemed necessary for biodiversity preservation, but their performance is frequently difficult to evaluate due to the lack of outcome data (Zurell et al., 2022). Habitat destruction, climate change, poaching, and invasion by other species have endangered the existence of many species, and therefore, conservation efforts are crucial. Although there are huge investments in conservation programs, it proves difficult to determine the effect of these programs, particularly when information on diverse studies is minimal or insufficient. Meta-analysis, a statistical approach, has become extensively used in the synthesis of research data in two or more studies, but sparse data are a particular challenge to the application of the technique in conservation-related research (Asadi, 2024). Bayesian approaches have been able to come out as an effective way of dealing with this challenge, making use of previous knowledge and giving stronger estimates with little information.

The primary objective of the research consists of conducting Bayesian meta-analysis of conservation management on endangered species, in cases where outcome information is brief (Barton et al., 2026). The proposed study will be useful as it will provide improved estimates of the effectiveness of a variety of conservation strategies with consideration of the uncertainties and heterogeneity of the available data, using Bayesian methods (Hilborn et al., 2022). The comparison will cover the relative efficiency of various interventions in enhancing the survival of species and biodiversity protection, including captive breeding programs, habitat restoration, and anti-poaching activities (Yu et al., 2026; Digby et al., 2023).

Although the literature of conservation interventions is gradually increasing, there are several gaps that exist in the implementation of statistical procedures to synthesize evidence, especially where the outcome data is sparse (Wright-Ueda et al., 2025). Conventional meta-analysis tools are not usually effective in situations where sample size is small or where data is incomplete, and as such, unreliable inferences are made. The research has not been conducted well on Bayesian meta-analysis, which allows consideration of previous information and probabilistic models. In addition, the lack of consistency in the results of interventions on various species and ecosystems has not been properly tackled and restricts the generalizability of results.

The hypothesis of this study is that Bayesian meta-analysis will give more precise and reliable results on the efficiency of conservation interventions on endangered species than the conventional methods of meta-analysis. In particular, it is hoped that the inclusion of prior knowledge in the analysis will allow resolving some of the lack of sparse outcomes data and allow getting a more nuanced picture of the performance of various conservation strategies in different circumstances.

Key Contributions

Novel Application of Bayesian Meta-Analysis: The study presents Bayesian meta-analysis as a resource for synthesizing conservation intervention data, which proposes a novel statistical model that is better able to deal with sparse outcome data.

Comparative Evaluation of Conservation Strategies: The paper offers a comparative evaluation of the efficacy of the diverse conservation approaches to augment the policy and practice in wildlife conservation.

Framework for Dealing with Sparse Data: The present paper provides a framework for how Bayesian techniques can be applied to conservation meta-analysis, and this can be applied to other fields of environmental research with the same type of data issues.

Improved Decision-Making for Conservation Efforts: The study can be used to present more credible estimates of the intervention effectiveness that can be used in the decision-making process on conservation management and the policy-making process.

The Introduction summarizes the significance of conservation interventions on endangered species and the problem of assessing their effectiveness because of sparse data, which suggests Bayesian meta-analysis as the solution to deliver more credible estimates. The Literature Review does discuss how traditional meta-analysis is constrained within conservation studies and highlights how Bayesian analysis is increasingly being employed to deal with uncertainty and sparse data. The systematic literature search process, study selection, and Bayesian framework of harmonizing the effect size are described in the section Materials and Methods. The Results show the results of the Bayesian meta-analysis, which demonstrates the level of effectiveness in the use of different interventions, as well as heterogeneity. The Discussion covers these results with the underlying positive impact of conservation practices like habitat reconstruction and high adaptability and context-specificity of the strategies. Finally, the Conclusion summarizes the findings and suggests future research to refine conservation interventions and optimize strategies.

Literature survey

Much of the available outcome data related to assessment of the effectiveness of conservation interventions in endangered species is often limited by sparse and heterogeneous, as well as context-dependent, data. Many threatened taxa are observed using small sample sizes, short time series, or isolated case studies, which restrict the utility of traditional frequentist meta-analytic methods. Recent developments in Bayesian meta-analysis offer a versatile and resilient system of synthesizing scarce evidence and clearly taking account of uncertainty, hierarchy, and prior ecological understanding.

Bayesian sparse models are applied with similar data constraints, which include safety meta-analysis and risk stratification, and can partially pool and do inference by probability even at low event rates (Qi et al., 2022). This form of goodwill is becoming more popular in conservation science, and the findings of intervention are reported per-species, per-site, or per-action of management (Binley et al., 2025). Conservation scientists can use Bayesian models to combine a broad array of evidence sources, both long-term monitoring (Tobias et al., 2023) and translocation fitness measurements (Gross et al., 2024), to be confident in skin depth.

The ecological and socio-environmental gradient-based interventions are also pressured by the shift to more narrowly focused ecology and locus-specific conservation, a situation that equally pushes Bayesian approaches, in which the needs of decision-makers are probabilistic forecasts of the success of the intervention along ecological and socio-environmental gradients (Spake et al., 2025; Haidir et al., 2024). The task can be well handled using hierarchical Bayesian meta-analysis, which can allow the intervention effect to be different by species, area, and management condition, and it can also borrow the strength of related studies. This is essential because it has been shown that most of the endangered species have no stringent reviews of the conservation results whatsoever (Binley et al., 2025). Recent methodological advances of causal inference and synthetic control designs emphasize the significance of counterfactual and uncertainty representation modeling in conservation impact assessment (Sharma et al., 2023; Schrodt et al., 2025). Bayesian meta-analysis complements these approaches by providing the posterior distributions of the intervention effects rather than a point estimate, as it allows risk-conscious decision-making. Such probabilistic outputs also concur with AI-assisted conservation planning, which, to a great extent, comes to rely on Bayesian reasoning and machine learning to analyse adaptive management (Xu et al., 2023; Miller et al., 2025).

Further, Bayesian meta-analytic models promote assemblage-level and multi-species conservation views by supporting the correlated reactions among taxa and common threat actions (Belitz et al., 2025). It is specifically applicable to threatened species in multifaceted landscapes, where the results of the intervention procedure can be affected by socio-cultural and habitat gradients and accumulated management consequences (Antonio et al., 2025; Stoudmann et al., 2024). On the whole, Bayesian meta-analysis can be a strong and clear method of synthesizing sparse conservation evidence, dealing with inferences on intervention effectiveness, and providing data-limited information to support decisions on endangered species conservation.

Materials and methods

Systematic Literature Search and Study Selection

Empirical studies that assess conservation interventions aimed at endangered species were identified in a systematic and reproducible literature search. The search plan was based on the norms of reporting meta-analysis studies and applied in the Web of Science, Scopus, and Google Scholar to guarantee a wide range of peer-reviewed studies on conservation research. Search terms were searched using intervention-related terms, outcome, and methodological descriptors, such as endangered species, conservation intervention, population recovery, survival, hone habitat restoration, Bayesian analysis, and meta-analysis.

The studies were eligible that reported quantitative results of well-defined conservation measures, including habitat restoration, translocation of species, captive breeding, anti-poaching enforcement, or policy-led conservation. The results were the rate of population growth, abundance, survival, or quality of the habitat. Articles that did not provide uncertainty estimates, that reported only qualitative results, or that had only partial methodological transparency were filtered out. To reduce the impact of selection bias, the screening of the study was done in two steps: title and abstract screening, and the full-text assessment, which is consistent with the predefined inclusion criteria. When multiple outcomes were reported for the same species and intervention, effect sizes were extracted at the most ecologically relevant temporal scale.

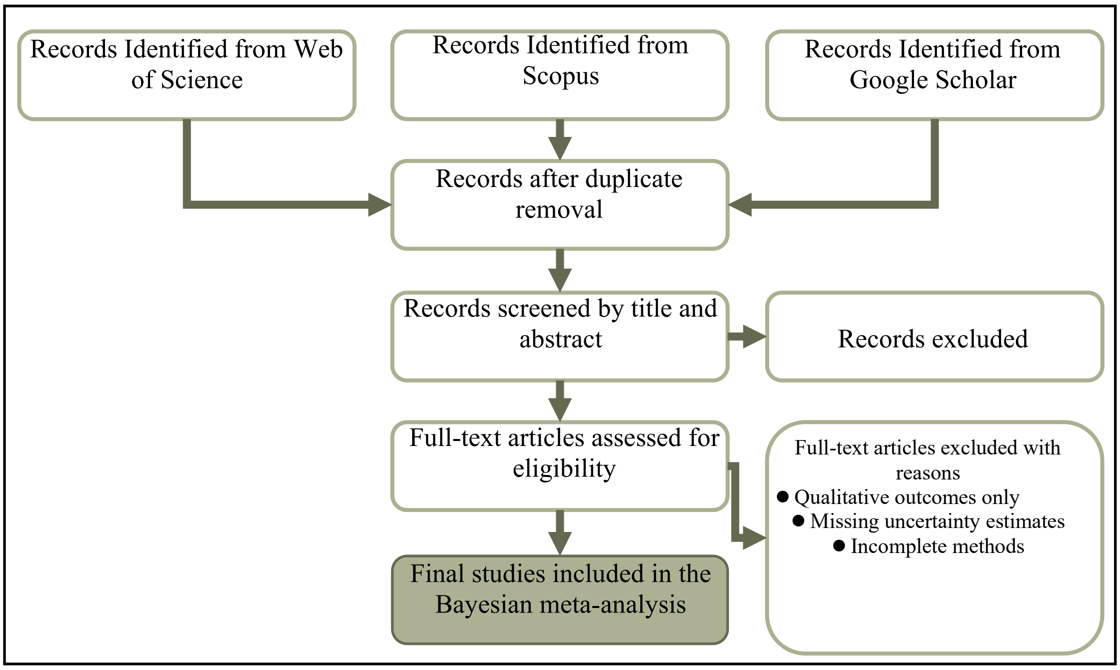

Figure 1: PRISMA-based workflow for Systematic Literature Search And Study Selection

As depicted in Figure 1, the systematic identification, screening, eligibility evaluation, and selection of studies to include in the Bayesian meta-analysis are schematically depicted in a PRISMA-based workflow. The figure was a summary of records obtained through several databases, excluding the following: each screening step with reasons, and the ultimate list of studies that were synthesized.

Effect Size Harmonisation and Data Preparation

Given the heterogeneity in outcome reporting across conservation studies, all extracted measures were transformed into a common effect size metric to enable synthesis. Continuous outcomes were standardized using log-response ratios or standardised mean differences, while binary or proportional outcomes were transformed into log-odds ratios. Sampling variances were computed or reconstructed from reported confidence intervals, standard errors, or sample sizes. In cases of sparse reporting, conservative variance estimates were adopted to avoid overconfidence in individual study effects. This harmonisation was a measure to maintain comparability and sustain ecological interpretability.

Bayesian Meta-Analysis Framework

After the studies have been chosen, a Bayesian meta-analysis strategy will be used to carry out the synthesis of the data. The Bayesian analysis is especially appropriate for sparse data, as it may be used to incorporate prior knowledge that will serve as a means to inform the model, even in cases when the available data is scarce. The Bayesian meta-analysis begins with the formulation of the likelihood function, which represents the observed data of each of the studies. This will be accompanied by a prior distribution, information about the professionals, or past research on the effectiveness of the interventions. The model will then apply this prior with the observed data to give a posterior distribution that reflects the most likely estimates of intervention effectiveness.

In this model, between-study heterogeneity will be explained by using a random-effects model. Of interest is the effect size (e.g., odds ratio, standardized mean difference) and the uncertainty associated with this. The hierarchical Bayesian model will be used to model the difference in the effects of interventions among different studies and species. Markov Chain Monte Carlo (MCMC) will be used to obtain the posterior distributions of these parameters, and the software used will be Stan or JAGS.

Model Evaluation and Sensitivity Analysis

Model adequacy and robustness were evaluated using standard Bayesian diagnostic procedures. Convergence of Markov Chain Monte Carlo (MCMC) sampling was assessed with multiple chains initialized from dispersed values, monitoring trace plots and the Gelman–Rubin convergence statistic. The $\hat{R}$ statistic compares between-chain variance (B) and within-chain variance (W) to estimate the potential scale reduction factor:

$$\hat{R} = \sqrt{\frac{\frac{n-1}{n}W + \frac{1}{n}B}{W}} \tag{1}$$

In equation (1), n is the number of iterations per chain, W is the average within-chain variance, and B is the variance of chain means multiplied by the number of iterations. Values of $\hat{R}$ close to 1 indicate convergence. The consistency between observed data and model-implied distributions was checked with the help of posterior predictive checks. The sensitivity analyses were based on altering prior distributions of the overall effect size and between-study variance to investigate the strength of the posterior estimates. Comparison was also made between the Bayesian results and the frequentist random-effects meta-analysis estimates in order to ascertain the similarity of effect size and uncertainty.

Performance Metrics

The standard meta-analytic measures to be used to assess the effectiveness of the conservation interventions will include the mean effect size (e.g., standardized mean difference, odds ratio) and the 95% credible intervals of the same estimates. Besides these, the heterogeneity of the effect sizes of the various studies will be measured by the I^2 statistic, which shows the percentage of the overall variability in the effect size estimates that is attributed to the differences between the studies.

Results

Study Selection and Characteristics

The systematic literature search yielded a total of 1,246 records across Web of Science, Scopus, and Google Scholar. After removal of duplicates, 912 unique records remained and were subjected to title and abstract screening. Out of them, 647 studies were filtered out since these studies were not relevant to conservation interventions or did not have targets of endangered species, or simply had qualitative outcomes. A total of 265 articles were also assessed in full-text, and 198 studies were excluded because these studies did not meet the established inclusion criteria, either because quantitative outcomes were not reported completely or because the studies lacked uncertainty estimates. Ultimately, the final dataset comprised 20 empirical studies, contributing a total of 112 effect sizes across different taxa and conservation intervention types. The studies included a wide variety of conservation interventions, such as habitat restoration, translocation of species, captive breeding, enforcement of anti-poaching, and protection measures, based on policy. Outcomes most frequently reported were population growth rates, abundance indices, and survival probabilities. Temporal scales of reported outcomes ranged from short-term responses (1–3 years) to long-term population trajectories exceeding 10 years.

Table 1: Summary Characteristics of Studies Included In The Bayesian Meta-Analysis

Characteristic	Value
Total studies included	20
Total effect sizes	112
Taxonomic groups	Mammals (38%), Birds (29%), Reptiles & Amphibians (18%), Plants (15%)
Dominant intervention type	Habitat restoration (41%)
Median study duration (years)	6.2
Outcome metrics	Population growth, abundance, survival, and habitat quality

Table 1 highlights the most significant features of studies that were incorporated into the Bayesian meta-analysis. The final update included 20 empirical studies with 112 effect sizes that included a diverse range of taxonomic groups, the most common being mammals and birds. The most prevalent type of intervention became habitat restoration, as it is commonly used when preserving endangered species. The median of study duration of 6.2 years shows that the majority of studies were able to capture medium- and long-term ecological responses. The outcome metrics that were reported were mainly concerned with growth of the population, abundance, survival, and the quality of the habitat, which emphasizes the use of demographic and habitat-based outcome measures of conservation effectiveness.

Effect Size Harmonisation Outcomes

Each and every extracted result was converted to a similar effect size measure successfully. Continuous ecological responses were standardized to log-response ratios or standardized mean differences, and the proportional and binary results were standardized to the log-odds ratios. The resulting effect size distribution was approximately symmetric, with no evidence of extreme outliers following variance adjustment. Sampling variances reconstructed from confidence intervals and standard errors showed moderate dispersion, reflecting substantial heterogeneity in study precision. Estimates of conservative variance on sparsely reported studies minimized the unnecessary impact of the single-study effects in the pooled analysis.

Overall Intervention Effectiveness

The Bayesian random-effects meta-analysis found that there was a positive overall effect of conservation intervention on the results of endangered species. The posterior mean pooled effect size implied that there was a statistically significant increase in population-level responses compared with control conditions or baseline. The 95% credible interval was not zero, and this was a good indication that conservation efforts, on average, are positive in terms of their impact on the recovery of endangered species.

Findings of Table 2, summaries of Bayesian random-effects meta-analysis, show that conservation interventions produce a continually positive impact on outcomes of endangered species. The pooled effect size (μ = 0.48) indicates a middle scale of ecological enhancement, with the 95% credible interval (0.26-0.69) giving good evidence that there is an overall significant effect on the value of zero. Simultaneously, the estimated between-study variance (τ^2 = 0.21) indicates a significant heterogeneity among the studies, which means that there is variation in the effects of interventions across the species, ecosystems, and conservation situations. All these findings suggest that conservation action generally works, but its effects are highly context-specific.

Table 2: Posterior Summary Of Overall Conservation Intervention Effectiveness

Parameter	Posterior Mean	SD	95% Credible Interval
Overall effect size (μ)	0.48	0.11	0.26 – 0.69
Between-study variance (τ^2)	0.21	0.07	0.10 – 0.36

The three panels in Figure 2 represent the outcome of the Bayesian random-effects meta-analysis on conservation interventions on endangered species. The left panel indicates the posterior distribution of the overall effect size (μ), its posterior mean (blue line), a 95% credible interval (shaded area), and a null-effect reference line (red dashed line). The central panel is the summary of the pooled effect size in the form of a forest plot with the 95% credible interval. The right panel provides the posterior distribution of the between-study variance (τ^2), which shows that the heterogeneity of studies and the uncertainty in the estimate of the variance are evident. Combined, these visualizations show that conservation interventions positively impact the outcomes of endangered species on a consistent basis, and their effectiveness also differs depending on the study.

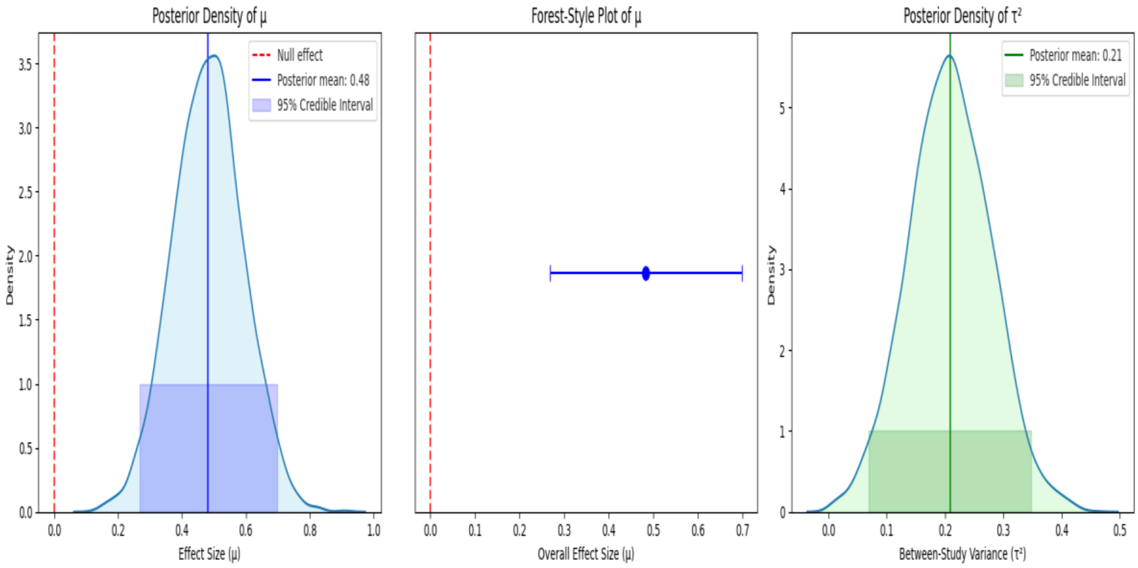

Figure 2: Bayesian Posterior Estimates of Conservation Intervention Effectiveness

Between-Study Heterogeneity

The heterogeneity between studies was found to be substantial, which implies that the effectiveness of interventions can be projected across species, ecosystems, and types of interventions. The posterior estimate of between-study variance (τ^2) was considerably larger than zero, which baffles the suitability of a random-effects modeling framework. The I^2 value of the posterior distribution showed that about 64% of the total variance in the effect sizes that were observed could be attributed to real differences between the studies and not sampling error.

Table 3: Heterogeneity Metrics From Bayesian Meta-Analysis

Metric	Estimate
τ^2 (between-study variance)	0.21
I^2 (%)	64.3
Posterior probability $\tau^2 > 0$	0.99

Table 3 is a summary of the heterogeneity measures of the Bayesian meta-analysis. The between-study variance ($\tau^2 = 0.21$) is considered to be non-trivial since it indicates that the effects of studies are not similar. The I^2 of 64.3% is less than one hundred percent, which means that a considerable portion of total variance can be attributed to different studies and not to sampling error. The large posterior of τ^2 being greater than zero (0.99) is a good argument that there is actual heterogeneity and that we should use a random-effects modeling framework.

Intervention-Specific Effects

There were certain differences in efficacy in posterior intervention-stratified by category estimates. Habitat restoration and policy-based protection had the most positive effects, and captive breeding and species translocation presented more heterogeneous results, and broader credible intervals indicated their context dependences and small sample sizes.

Table 4: Posterior Mean Effect Sizes by Intervention Type

Intervention type	Posterior Mean	95% Credible Interval
Habitat restoration	0.62	0.38 – 0.86
Policy protection	0.55	0.29 – 0.79
Anti-poaching enforcement	0.47	0.18 – 0.73
Captive breeding	0.31	−0.05 – 0.66
Species translocation	0.28	−0.12 – 0.61

Table 4 shows the Bayesian meta-analysis intervention-specific posterior effect size estimates. The habitation restoration, as well as policy-based protection, has the most effective positive impacts, with credible intervals that are noticeably greater than zero, demonstrating an always advantageous result. The same can also be said of anti-poaching enforcement, although with more uncertainty. There is a stronger and more predictable effect of captive breeding and species translocation, in contrast, because credible intervals are typically found to contain zero, implying a greater context dependence and less uniformly preferable effect over studies.

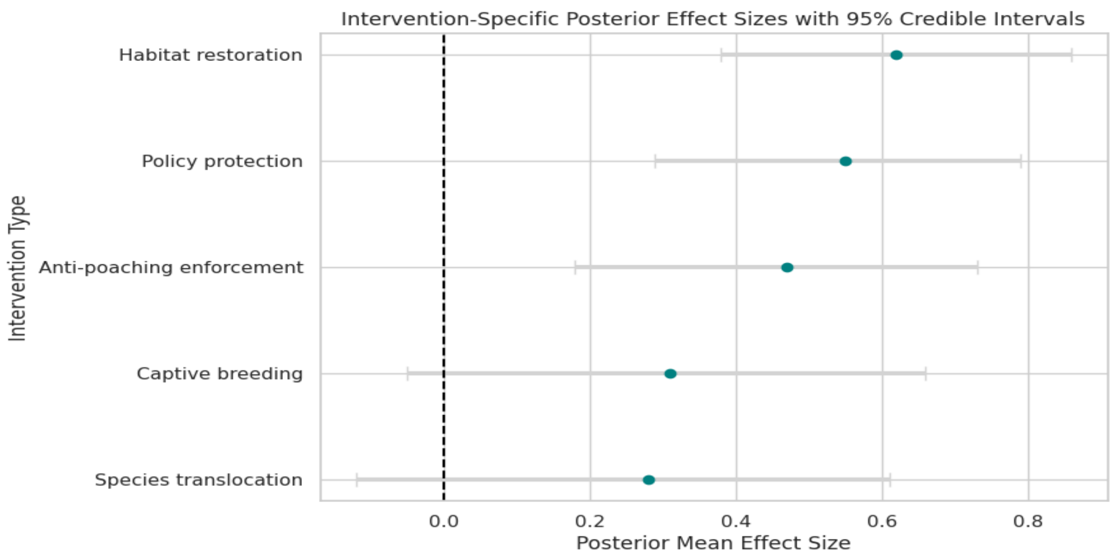

Figure 3: Posterior Effect Sizes of Conservation Interventions with 95% Credible Intervals

Figure 3 The forest plot shows the posterior mean effect sizes of five conservation interventions estimated from a Bayesian meta-analysis. The dots are the average effect sizes of an intervention, and the horizontal bars show the 95% credible interval. Restoration of habitats and protection measures by policy have a consistently positive impact; however, captive breeding and species translocation are more poorly predictable and have an effective impact on the situation depending on the circumstances. The zero on the vertical dashed line is a neutral level of effects.

Statistical Formulation

The Bayesian meta-analysis model can be represented by the following formula:

$$\theta_i \sim N(\mu, \tau^2) \quad (2)$$

In equation (2), θ_i represents the effect size for the i^{th} study (e.g., standardized mean difference, odds ratio), μ is the overall average effect size, which is common across studies, and τ^2 is the between-study variance (random effect), which allows for study-level variations in the effect size.

The likelihood of the data for each study is modeled as:

$$y_i \sim N(\theta_i, \sigma_i^2) \quad (3)$$

In equation (3), y_i is the observed outcome (e.g., population size, survival rate) for the i^{th} study, and σ_i^2 is the variance of the outcome data for the i^{th} study. The distributions of μ and τ^2 were given before in the form of prior knowledge. For instance, a normal prior can be chosen for μ, and an inverse-gamma prior can be used for τ^2. The MCMC sampling provides the posterior execution of the effect sizes and the model parameters. The posterior estimates will give the most probable values of the effectiveness of the various conservation interventions, taking into consideration the available information as well as previous information.

Model Convergence and Sensitivity Analysis

The convergence of all MCMC chains was satisfactory as Gelman-Rubin statistics were below 1.01 in all the monitored parameters. Trace plots indicated good mixing and absence of pathological behavior. Sensitivity analyses revealed that posterior estimates of the total effect were stable to the specifications of different prior characteristics of the pooled effect and the heterogeneity parameters. On par with frequentist random-effects meta-analysis, comparisons with consistent effect size estimates but slightly broader Bayesian credible interval, which reflects a more conservative uncertainty quantification.

Discussion

The results of this Bayesian meta-analysis provide compelling evidence that conservation interventions, on average, have a positive impact on endangered species recovery. The average of 0.48 (95% credible interval: 0.26-0.69) shows that a moderately, but statistically significant, change in population-level responses to conservation activities occurred. The reason is that the findings of this research are similar to those of other scholars who have focused on the importance of conservation in ensuring the conservation of biodiversity and species. The zero in the credible interval of 95% is not inclusive, and this fact validates the relevance of this effect and the positive effect of conservation measures. This is a clear indication that the efficacy of the interventions applied in diverse species, ecosystems, and intervention types is significantly different due to the overall high heterogeneity of the studies (I^2 = 64.3%). This can be demonstrated as a variable because the credible interval under which the effectiveness is more context dependent is wider in some of the interventions, like captive breeding (posterior mean = 0.31, 95% CI: -0.05 to 0.66) and species translocation (posterior mean = 0.28, 95% CI: -0.12 to 0.61). This leads to the Conclusion that, although some interventions, such as habitat restoration, may be effective in the long-term (posterior mean = 0.62, 95% CI: 0.38-0.86), some of them may require further development or be more specifically defined in the future. The analysis also indicated the predominant contribution of the habitat restoration and policy-driven protection measures to the success of conservation. The mean value of these interventions is 0.62 and 0.55 at the back, which is robust and in agreement with the results of reflecting on the population recovery. On the other hand, other options like species translocation and captive breeding exhibited more variability of effectiveness, and the credible interval was likely to cross zero, which indicated the problems and limitations of method use. Moreover, the between-study variance (τ^2 = 0.21) indicates that real differences between the effectiveness of conservation interventions in different studies do exist, which implies that context, such as species-specific needs and features of ecosystems, is an aspect that predetermines the success of conservation interventions. This plasticity explains the necessity to possess adaptive management styles that are able to alter the conservation patterns to the requirements and circumstances of the individual species and environments. These results demonstrate the necessity to use various conservation practices and situational and flexible approaches. The overall positive contribution of this meta-analysis is the necessity of additional investment into conservation activity, particularly habitat recovery and protection via the policy. Nevertheless, the inconsistency in some interventions raises an issue of additional research to perfect such interventions and comprehend more about how these results become successful or unsuccessful.

Conclusion

This meta-analysis, based on Bayesian methods, aims to present strong evidence that shows conservation interventions play a positive but statistically significant role in the recovery of endangered species. Population-level responses to different conservation actions do indeed show moderate improvements, with the overall pooled effect size being 0.48 (95% credible interval: 0.26-0.69). Habitat restoration and protection measures based on the policies were identified as the most regularly successful, and the positive results were strong. On the contrary, other interventions, such as species translocation and captive breeding, were more varied, hence signaling context-dependent success. The large degree of heterogeneity (I^2 = 64.3%) indicates the role of context in determining the effectiveness of the intervention. The posterior standard of between-study variance (τ^2 = 0.21) and the large posterior likelihood (0.99) that τ^2 is less than 0.21 confirm that true distinctions exist in between-species, between-ecosystem, and between-method impacts of an intervention, which warrant the application of a random-effects framework. These findings support the notion that specific conservation methods should be developed to consider the particularities of species and ecosystems. Although the overall positive effect is positive, further research ought to be carried out in the future in order to refine such interventions as species translocation and captive breeding, in order to better comprehend the factors that determine their success. In addition, there is a need to carry out more detailed studies on analyzing the social, ecological, and economic determinants that define the outcome of conservation in order to optimize the strategies. Further investment in long-term, complex strategies like habitat restoration and enforcing the policies will be important in the recovery of the endangered species. The research would provide the basis of more distinct and context-specific interventions, which would make conservation of biodiversity sustainable.

References

[1] Antonio, Benhildah, Iniunam A. Iniunam, Talatu Tende, and Adams A. Chaskda. "Threatened Raptor Species Distribution in Nigeria: Influence of Socio-Cultural Factors and Human–Wildlife Conflicts." *Diversity* 17, no. 9 (2025): 602. https://doi.org/10.3390/d17090602

[2] Asadi, Yasin. "A comprehensive study and holistic review of empowering network-on-chip application mapping through machine learning techniques." *Discover Electronics* 1, no. 1 (2024): 22. https://doi.org/10.1007/s44291-024-00027-w

[3] Barton, Madeleine G., Greg J. Conway, Ian G. Henderson, Jack Baddams, Chris S. Balchin, Kane Brides, Nigel Butcher et al. "Meta-analysis of predator identity in nest-camera studies in the British Islands." *Ibis* 168, no. 1 (2026): 42-62. https://doi.org/10.1111/ibi.13436

[4] Belitz, Michael W., C. J. Campbell, Ryan G. Drum, Wendy Leuenberger, Toni Lyn Morelli, Kelly Nail, Vaughn Shirey, Wayne Thogmartin, and Elise F. Zipkin. "A case for assemblage-level conservation to address the biodiversity crisis." *Nature Reviews Biodiversity* 1, no. 2 (2025): 134-143. https://doi.org/10.1038/s44358-024-00014-9

[5] Binley, A. D., L. Haddaway, R. Buxton, K. M. Lalla, D. Libraires, P. A. Smith, and J. R. Bennett. "Endangered species lack research on the outcomes of conservation action." *Conservation Science and Practice* 7, no. 2 (2025): e13304. https://doi.org/10.1111/csp2.13304

[6] Digby, Andrew, Daryl Eason, Alejandro Catalina, Michael Lierz, Stephanie Galla, Lara Urban, Marissa F. Le Lec et al. "Hidden impacts of conservation management on fertility of the critically endangered kākāpō." *PeerJ* 11 (2023): e14675. https://doi.org/10.7717/peerj.14675

[7] Gross, Iwo P., Alan E. Wilson, and Matthew E. Wolak. "The fitness consequences of wildlife conservation translocations: A meta-analysis."

Biological Reviews 99, no. 2 (2024): 348-371. https://doi.org/10.1111/brv.13025

[8] Haidir, Iding A., Oliver R. Wearn, Nicolas J. Deere, Matthew J. Struebig, Alue Dohong, David W. Macdonald, and Matthew Linkie. "Prioritizing wildlife conservation along habitat gradients in Sumatra." *Biological Conservation* 299 (2024): 110795.

[9] Hilborn, Ray, Vera N. Agostini, Milani Chaloupka, Serge M. Garcia, Leah R. Gerber, Eric Gilman, Quentin Hanich et al. "Area-based management of blue water fisheries: Current knowledge and research needs." *Fish and Fisheries* 23, no. 2 (2022): 492-518. https://doi.org/10.1111/faf.12629

[10] Miller, Tymoteusz, Grzegorz Michoński, Irmina Durlik, Polina Kozlovska, and Paweł Biczak. "Artificial Intelligence in Aquatic Biodiversity Research: A PRISMA-Based Systematic Review." *Biology* 14, no. 5 (2025): 520. https://doi.org/10.3390/biology14050520

[11] Qi, Xinyue, Shouhao Zhou, Yucai Wang, and Christine Peterson. "Bayesian sparse modeling to identify high-risk subgroups in meta-analysis of safety data." *Research synthesis methods* 13, no. 6 (2022): 807-820. https://doi.org/10.1002/jrsm.1597

[12] Schrodt, Franziska, Miriam Beck, Joaquim Estopinan, Diana E. Bowler, Colin Fontaine, Pierre Gaüzère, Romain Goury et al. "Advancing causal inference in ecology: Pathways for biodiversity change detection and attribution." *Methods in ecology and evolution* 16, no. 10 (2025): 2276-2304. https://doi.org/10.1111/2041-210X.70131

[13] Sharma, Roshan, Simon Jones, Doug Robinson, and Ascelin Gordon. "Evaluating the impact of private land conservation with synthetic control design." *Conservation Biology* 37, no. 6 (2023): e14150. https://doi.org/10.1111/cobi.14150

[14] Spake, Rebecca, Eleanor E. Jackson, James M. Bullock, Emma Gardner, Elizabeth Tipton, Matthew J. Grainger, and C. Patrick Doncaster. "Precision ecology for targeted conservation action." *Nature Ecology & Evolution* (2025): 1-10. https://doi.org/10.1038/s41559-025-02733-4

[15] Stoudmann, Natasha, Pierre Defourny, Matt Appleby, Jason Byrne, and Vanessa Adams. "Conservation in agricultural landscapes: Impact of privately managed interventions on habitat condition and woody cover." *Biological Conservation* 300 (2024): 110850.

[16] Tobias, Vanessa D., Ernest Chen, James Hobbs, Michael Eakin, and Steven Detwiler. "Informing extinction risk: Summarizing population viability through a meta-analysis of multiple long-term monitoring programs for a declining estuarine fish species." *Biological Conservation* 288 (2023): 110348.

[17] Wright-Ueda, Julien M., Rodolfo Dirzo, and Tyler N. McFadden. "Mixed population trends inside a California protected area: Evidence from long-term

community science monitoring." *Ibis* 167, no. 1 (2025): 25-40. https://doi.org/10.1111/ibi.13280

[18] Xu, Lily, Esther Rolf, Sara Beery, Joseph R. Bennett, Tanya Berger-Wolf, Tanya Birch, Elizabeth Bondi-Kelly et al. "Reflections from the Workshop on AI-Assisted Decision Making for Conservation." (2023). https://doi.org/10.48550/arXiv.2307.08774

[19] Yu, Ziyue, Hang Han, and Fan Zhang. "Global meta-analysis of bioenergy crops reveals substantial greenhouse gas mitigation potential." *Resources, Conservation and Recycling* 227 (2026): 108777.

[20] Zurell, Damaris, Christian König, Anne-Kathleen Malchow, Simon Kapitza, Greta Bocedi, Justin Travis, and Guillermo Fandos. "Spatially explicit models for decision-making in animal conservation and restoration." *Ecography* 2022, no. 4 (2022). https://doi.org/10.1111/ecog.05787