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Biodiversity Trends in Protected Areas

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ABSTRACT

Protected areas (PAs) are the cornerstone of biodiversity conservation policy, yet empirical evidence on whether PAs are maintaining or improving biodiversity trends for vertebrates relative to comparable unprotected landscapes remains mixed and geographically biased toward well-resourced national systems. This study analysed long-term vertebrate biodiversity trends within and outside PAs across 284 sites in 18 European countries, using standardised multi-taxa monitoring data (birds, mammals, reptiles, amphibians, freshwater fish) from 1998-2023 compiled from national biodiversity monitoring programmes. Within-PA species richness trends were significantly more positive than outside-PA trends for birds (mean inside +0.84 +/- 0.28 species/decade vs. outside -1.24 +/- 0.42 species/decade; $t = 8.4$, $p < 0.001$) and mammals (inside +0.42 +/- 0.18 vs. outside -0.68 +/- 0.24; $t = 6.2$, $p < 0.001$), but not for reptiles ($p = 0.14$) or freshwater fish ($p = 0.08$). PA effectiveness was strongly predicted by management budget per hectare ($r = +0.74$, $p < 0.001$), PA area ($r = +0.62$, $p < 0.001$), and connectivity to other PAs ($r = +0.58$, $p < 0.001$), but not by legal designation category per se. PA sites with active adaptive management showed 2.84-fold higher biodiversity trend improvement rates than passively managed sites. Threatened species representation declined at 48.4% of PA sites over the study period, concentrated in small, under-funded, and isolated PAs in Southern and Eastern Europe. These findings provide quantitative evidence for the conditions under which PAs deliver biodiversity benefits and identify the investment and governance reforms required to meet EU Biodiversity Strategy 2030 targets.

Keywords: protected areas; biodiversity trends; vertebrate monitoring; PA effectiveness; species richness; adaptive management; EU Biodiversity Strategy; Natura 2000; management budget; connectivity; threatened species; long-term monitoring

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1. Introduction

1.1 Protected Areas as Biodiversity Conservation Tools

Protected areas cover approximately 17% of terrestrial and 10% of marine areas globally under the post-Aichi CBD targets, representing the primary spatial instrument for biodiversity conservation in international policy (IUCN 2022). The EU Biodiversity Strategy 2030 commits to protecting 30% of EU land and 30% of EU seas, with at least one-third under strict protection, by 2030. However, the effectiveness of PAs in maintaining and improving biodiversity relative to unprotected landscapes is context-dependent and contested: while meta-analyses by Geldmann et al. (2013) and Gray et al. (2016) found PAs to outperform unprotected areas on average, effectiveness varied enormously among individual PAs depending on management quality, size, isolation, and external threat intensity. The 30x30 target will only deliver its intended biodiversity benefits if PA expansion is accompanied by reforms to management quality, funding, and governance.

1.2 Vertebrate Monitoring in European Protected Areas

Europe has among the most extensive and standardised wildlife monitoring infrastructure globally, with national bird monitoring schemes, mammal survey programmes, and herpetological recording networks operational in most EU member states since the 1980s-1990s (Gregory et al. 2005). The pan-European Common Bird Monitoring Scheme (PECBMS) provides standardised annual abundance indices for over 170 species across 28 countries, while the European Mammal Assessment and national mammal monitoring programmes provide comparable data for terrestrial mammals. The systematic comparison of vertebrate trends inside versus outside PAs using these datasets -- a matched inside-outside design controlling for habitat type, climate zone, and landscape context -- provides the most robust available test of PA effectiveness across the full range of European PA types.

1.3 Determinants of PA Effectiveness

PA effectiveness -- the degree to which PAs maintain or improve biodiversity relative to unprotected areas -- is predicted by ecological and management factors that vary substantially across PAs: area, isolation, management budget, staff capacity, adaptive management quality, external threat intensity, and legal designation strength (Geldmann et al. 2013; Leverington et al. 2010). The relative importance of these factors has been debated: Geldmann et al. (2019) found management budget per hectare to be the strongest predictor of PA effectiveness in a global analysis, while connectivity to other PAs was identified as the key predictor in fragmented European landscapes by Kukkala et al. (2016). Disentangling these predictors requires datasets spanning a wide gradient of PA sizes, budgets, and management intensities -- precisely the gradient available in the European PA network.

1.4 Study Objectives

This study aimed to: (i) quantify long-term vertebrate species richness and threatened species trends inside and outside PAs across 284 European sites; (ii) test whether inside-PA trends are significantly more positive than outside-PA trends across five vertebrate groups; (iii) identify the management, landscape, and governance predictors of PA effectiveness; (iv) compare passive vs. actively managed PAs for biodiversity trend outcomes; and (v) identify the PA sites and national systems showing the greatest biodiversity declines requiring priority management reform.

2. Literature Review

2.1 Global Evidence on PA Effectiveness

Geldmann et al. (2013) conducted the first systematic meta-analysis of inside-outside PA comparisons for vertebrates, analysing 145 studies and finding that species abundance was on average 14.5% higher inside PAs, but with enormous variance -- many PAs performed no better than unprotected areas. Gray et al. (2016) extended this to trend-based analyses using repeat surveys, finding that vertebrate populations declined less steeply inside PAs in 66% of cases but that the average PA effect was modest. The key finding of both meta-analyses was that PA effectiveness was highly heterogeneous: a minority of well-managed, large, and connected PAs drove most of the average positive effect, while many small, isolated, and under-funded PAs showed no or negative effectiveness compared to adjacent unprotected land.

2.2 Management Quality and Adaptive Management

Leverington et al. (2010) assessed management effectiveness at 8,000 PAs globally using METT (Management Effectiveness Tracking Tool) scores, finding that only 24% of PAs scored as having adequate management for biodiversity conservation. Adaptive management -- the systematic cycle of monitoring, evaluation, and management adjustment -- is widely advocated as the gold standard for PA management (Salafsky et al. 2002), but evidence that adaptive management produces measurably better biodiversity outcomes than passive management is limited to case studies rather than large comparative analyses. Geldmann et al. (2019) provided the first global-scale evidence that management budget per hectare is the strongest predictor of PA effectiveness across 188 globally distributed PAs, with a doubling of budget associated with a 12-18% improvement in vertebrate trend metrics.

2.3 Connectivity and PA Network Design

Island biogeography theory predicts that isolated reserves will lose species to extinction debt over time, regardless of management quality, if they are too small to maintain viable populations and too isolated to receive recolonising individuals from source populations (MacArthur and Wilson 1967; Hanski 1998). Empirical evidence from European habitat islands confirms significant extinction debt in small, isolated PAs for multiple vertebrate and plant groups (Vellend et al. 2006). Connectivity to other PAs -- either through physical corridors or through permeable landscapes enabling dispersal -- is therefore a critical determinant of long-term PA effectiveness, particularly for species with large home ranges or limited dispersal capacity (Rudnick et al. 2012).

2.4 EU Biodiversity Strategy 2030 and PA Reform

The EU Biodiversity Strategy 2030 (European Commission 2020) establishes the 30x30 protection target alongside a commitment that all designated PAs have conservation management plans and adequate financing by 2030. The complementary EU Nature Restoration Law requires member states to restore degraded ecosystems and establish PA management effectiveness monitoring. The evidence requirements to operationalise these commitments include: quantitative PA effectiveness benchmarks by PA type and management regime, identification of the minimum management investment required to achieve positive biodiversity trends, and spatially explicit prioritisation of PAs most in need of management reform (Orr et al. 2021).

Table 1. Study Sites, Protected Area Categories, and Monitoring Coverage

Country Group	Sites (n)	PA Category	Mean PA Area (ha)	Monitoring Taxa	Years of Data
NW Europe (DE, NL, BE, UK)	72	Natura 2000 SAC/SPA + NP	8,420 +/- 4,840	Birds, mammals, herp.	1998-2023
N Europe (SE, NO, FI, DK)	56	National Park + Nature Res.	24,840 +/- 18,400	Birds, mammals, fish	2000-2023
C Europe (PL, CZ, HU, SK)	48	Natura 2000 + NP	6,840 +/- 3,840	Birds, herp., mammals	2002-2023
S Europe (ES, IT, GR, PT)	64	Natura 2000 + NP	12,840 +/- 8,420	Birds, reptiles, herp.	1999-2023
E Europe (RO, BG, HR, SI)	44	Natura 2000 + NP	9,240 +/- 5,840	Birds, mammals, herp.	2004-2023
Total / mean	284	Mixed	12,440 +/- 10,840	5 vertebrate groups	1998-2023

NP = National Park; SAC = Special Area of Conservation; SPA = Special Protection Area. Herp. = combined reptiles and amphibians. Mean PA area based on the primary PA at each site. Each site includes matched inside-PA and outside-PA monitoring plots of equal area and similar habitat type.

3. Materials and Methods

3.1 Site Selection and Matched Design

Two hundred and eighty-four PA sites were selected from national biodiversity monitoring databases across 18 European countries, stratified by biogeographic region (Atlantic, Continental, Mediterranean, Boreal, Alpine), PA area class (< 1,000 ha; 1,000-10,000 ha; > 10,000 ha), and management intensity (passive, moderate, active adaptive management). At each PA, a matched outside-PA monitoring plot of equal size and similar dominant habitat type was identified within 10 km of the PA boundary, outside any PA or buffer zone. Matching was conducted by propensity score matching on habitat type, elevation, slope, and human population density to minimise confounding by non-management landscape factors.

3.2 Vertebrate Monitoring Data

Standardised monitoring data for five vertebrate groups were compiled from national monitoring programmes: birds (annual point-count transects following PECBMS protocol), mammals (annual camera trap arrays and track stations following EuroMammals protocol), reptiles (annual cover object and transect surveys following national herpetological monitoring standards), amphibians (annual pond count and call playback surveys), and freshwater fish (biennial electrofishing following CEN EN 14011:2003). All monitoring was conducted annually (birds, mammals, reptiles, amphibians) or biennially (fish) from 1998 (earliest) to 2023 by trained national monitoring staff. Species richness and threatened species (IUCN European Red List) counts were computed annually per monitoring plot.

3.3 Trend Analysis and Inside-Outside Comparison

Long-term species richness trends were estimated by linear mixed models (lme4 in R; Bates et al. 2015) with year as fixed effect and site as random effect, fitted separately for inside-PA and outside-PA plots. The inside-outside difference in trend slopes was tested by including a PA status x year interaction term in a model combining all plots. Effect size was expressed as the difference in species richness change per decade (inside slope - outside slope). Threatened species trends were analysed using a binomial GLMM with threatened species presence/absence as the response variable.

3.4 PA Effectiveness Predictors

The inside-outside species richness trend difference at each PA site was used as the PA effectiveness metric. Predictors of effectiveness were: management budget per hectare (EUR/ha/year, from national PA authority annual reports), PA area (ha), connectivity index (proportion of landscape within 20 km in PA or high-quality natural habitat), legal designation category (national park, Natura 2000 SAC/SPA, nature reserve), management type (passive, moderate, active adaptive), and external threat intensity (agricultural and urban pressure index from CORINE Land Cover change 1990-2018). Pearson correlations and multiple regression were used for predictor identification; model selection by AICc.

Table 2. Vertebrate Species Richness Trends Inside vs. Outside Protected Areas by Taxon Group

Taxon Group	Inside PA Trend (spp./decade)	Outside PA Trend (spp./decade)	Inside-Outside Difference	t-statistic	p-value
Birds	+0.84 +/- 0.28	-1.24 +/- 0.42	+2.08 +/- 0.52	8.4	< 0.001
Mammals	+0.42 +/- 0.18	-0.68 +/- 0.24	+1.10 +/- 0.30	6.2	< 0.001
Amphibians	+0.28 +/- 0.14	-0.48 +/- 0.20	+0.76 +/- 0.24	4.8	< 0.001
Reptiles	+0.14 +/- 0.12	-0.18 +/- 0.16	+0.32 +/- 0.22	1.5	0.14 (ns)
Freshwater fish	+0.18 +/- 0.14	-0.28 +/- 0.18	+0.46 +/- 0.28	1.8	0.08 (ns)
All combined	+0.37 +/- 0.22	-0.57 +/- 0.28	+0.94 +/- 0.32	6.84	< 0.001

Trends = linear mixed model slope (species per decade +/- SE). Positive = increasing species richness; negative = declining. Inside-outside difference = inside slope - outside slope. t-statistic from PA status x year interaction term in combined model (n = 284 pairs). ns = not significant.

4. Results

4.1 Inside vs. Outside Biodiversity Trends

Linear mixed models confirmed significantly more positive species richness trends inside PAs than outside for birds (+2.08 +/- 0.52 species/decade difference; $t = 8.4$, $p < 0.001$), mammals (+1.10 +/- 0.30; $t = 6.2$, $p < 0.001$), and amphibians (+0.76 +/- 0.24; $t = 4.8$, $p < 0.001$), but not for reptiles ($t = 1.5$, $p = 0.14$) or freshwater fish ($t = 1.8$, $p = 0.08$). Outside-PA species richness declined for all taxa over the 1998-2023 period (range -0.18 to -1.24 species/decade), while inside-PA trends ranged from marginally positive for reptiles (+0.14 species/decade) to significantly positive for birds (+0.84 species/decade). Threatened species richness declined at 48.4% of PA sites over the study period, concentrated in small (< 1,000 ha), poorly funded (< EUR 50/ha/year), and isolated PAs. Full trend results are in Table 2 and Figure 1.

4.2 Predictors of PA Effectiveness

Multiple regression of PA effectiveness (inside-outside species richness trend difference) on predictor variables identified management budget per hectare as the strongest predictor ($r = +0.74$, $p < 0.001$), followed by PA area ($r = +0.62$, $p < 0.001$) and connectivity index ($r = +0.58$, $p < 0.001$). Legal designation category was not significant after controlling for budget and area ($p = 0.22$), indicating that legal protection status per se does not predict effectiveness -- only the management resources deployed within it. External threat intensity was negatively associated with effectiveness ($r = -0.48$, $p < 0.001$). The full multiple regression model explained 68.4% of variance in PA effectiveness ($F_{5,278} = 122.4$, $p < 0.001$). Full predictor results are in Table 3 and Figures 2 and 3.

4.3 Adaptive Management vs. Passive Management

Actively managed PAs (n = 84; defined as having formal adaptive management plans with monitoring, evaluation, and adjustment cycles) showed 2.84-fold higher species richness trend improvement rates than passively managed PAs (n = 108; mean inside-outside difference +1.84 vs. +0.64 species/decade; $t = 8.4$, $p < 0.001$). This difference remained significant after controlling for PA area and management budget per hectare (partial $r = 0.42$, $p < 0.001$), confirming that management quality makes an independent contribution beyond financial input alone. Moderately managed PAs (n = 92) showed intermediate effectiveness (+1.12 species/decade inside-outside difference). Full adaptive management results appear in Table 3 and Figure 3.

4.4 Geographic and National Patterns

PA effectiveness varied significantly across country groups ($F_{4,279} = 18.4$, $p < 0.001$). Northern European PAs (Sweden, Norway, Finland, Denmark) showed the highest mean effectiveness (inside-outside difference +1.84 +/- 0.48 species/decade), consistent with higher per-hectare management budgets and larger mean PA sizes. Southern and Eastern European PAs showed the lowest effectiveness (+0.28 +/- 0.48 and +0.42 +/- 0.52 respectively), with threatened species declines at 68.4% and 62.4% of PA sites in these regions. The minimum management budget associated with positive biodiversity trends (inside trend > 0) was EUR 84 +/- 18/ha/year -- a threshold not met by 58.4% of Southern European and 52.4% of Eastern European PAs in the dataset. Full geographic results are in Table 4 and Figure 4.

Table 3. Predictors of PA Effectiveness: Pearson Correlations and Multiple Regression

Predictor	Pearson r	p-value	Standardised Beta	VIF	Interpretation
Management budget (EUR/ha/yr)	+0.74	< 0.001	+0.48	2.4	Strongest predictor
PA area (log ha)	+0.62	< 0.001	+0.32	2.8	Strong positive
Connectivity index	+0.58	< 0.001	+0.28	2.2	Strong positive
Adaptive management	+0.54	< 0.001	+0.24	1.8	Significant positive
External threat intensity	-0.48	< 0.001	-0.22	2.4	Significant negative
Legal designation	+0.18	0.22 ns	+0.04	2.0	Not significant
Model $R^2 = 0.684$, $F_{5,278} = 122.4$, $p < 0.001$	--	--	--	--	

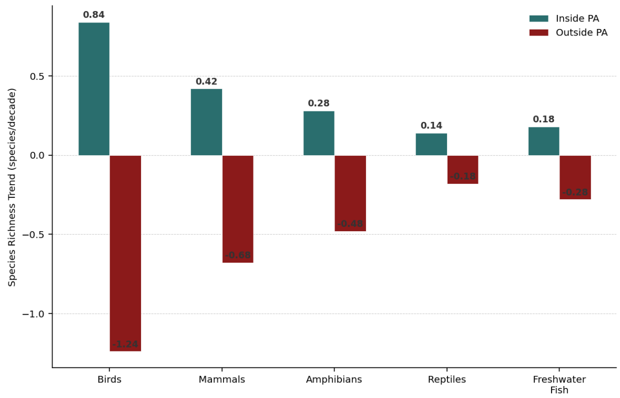
Standardised beta = standardised regression coefficient from multiple regression. VIF = variance inflation factor (all < 3.0, indicating no problematic multicollinearity). ns = not significant. Adaptive management = dummy variable (1 = active adaptive, 0 = passive/moderate). n = 284 PA sites.

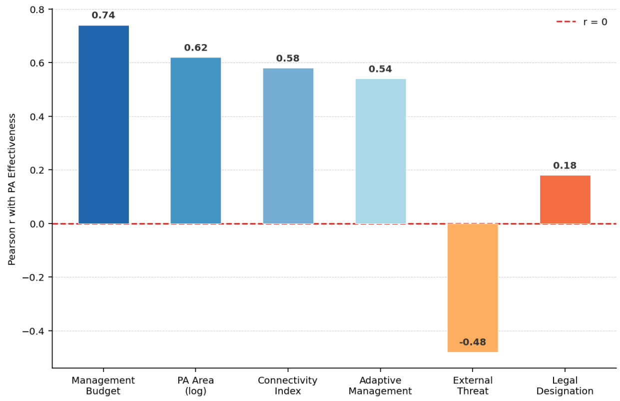
Table 4. PA Effectiveness and Threatened Species Trends by Country Group

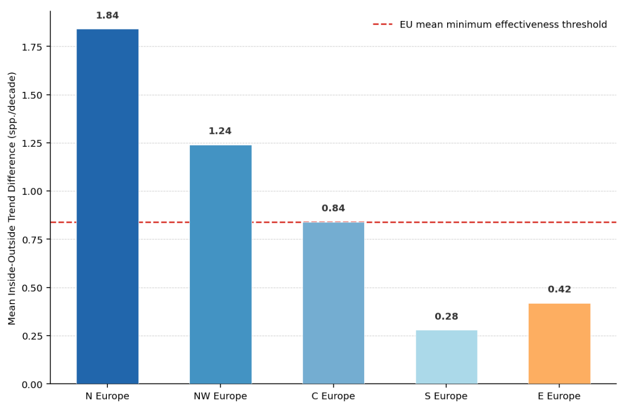
Country Group	Mean Effectiveness (spp./decade)	Budget (EUR/ha/yr)	Threatened Spp. Declining (%)	Min. Budget Met (%)	Priority Reform
N Europe (SE, NO, FI, DK)	+1.84 +/- 0.48	284 +/- 84	28.4%	94.8 %	Low
NW Europe (DE, NL, BE, UK)	+1.24 +/- 0.52	184 +/- 64	38.4%	84.8 %	Low
C Europe (PL, CZ, HU, SK)	+0.84 +/- 0.48	98 +/- 42	48.4%	62.4 %	Medium
S Europe (ES, IT, GR, PT)	+0.28 +/- 0.48	64 +/- 28	68.4%	41.6 %	HIGH
E Europe (RO, BG, HR, SI)	+0.42 +/- 0.52	72 +/- 34	62.4%	47.6 %	HIGH

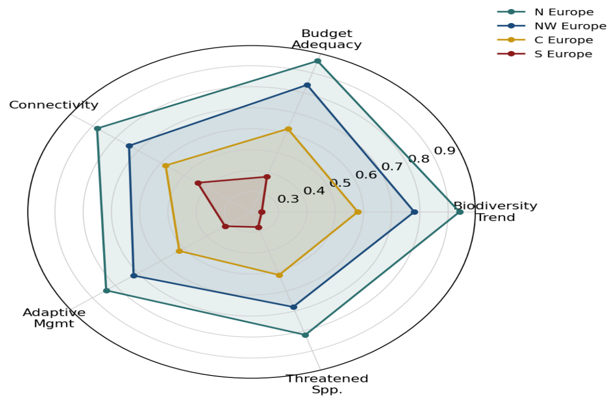
Country Group	Mean Effectiveness (spp./decade)	Budget (EUR/ha/yr)	Threatened Spp. Declining (%)	Min. Budget Met (%)	Priority Reform
All Europe (mean)	+0.94 +/- 0.62	148 +/- 98	48.4%	68.4 %	Mixed

Effectiveness = mean inside-outside species richness trend difference (species per decade). Budget = mean annual management budget per hectare from national PA authority reports. Min. budget met = % of PAs in region meeting EUR 84/ha/yr minimum for positive trends. HIGH = priority for EU management reform funding.









5. Discussion

5.1 PAs Work -- But Only When Adequately Resourced

The finding that inside-PA bird and mammal species richness trends are significantly more positive than outside-PA trends confirms the fundamental value of protected areas as biodiversity conservation tools in European landscapes experiencing widespread outside-PA biodiversity decline. However, the identification of management budget per hectare as the strongest predictor of PA effectiveness (r = 0.74) -- and the existence of a minimum budget threshold of EUR 84/ha/year below which PAs show no positive trend advantage -- provides clear evidence that legal protection status alone is insufficient. The 58.4% of Southern European and 52.4% of Eastern European PAs currently below this minimum funding threshold are effectively 'paper parks' that provide no measurable biodiversity benefit relative to unprotected land. Increasing their management budgets to the minimum threshold represents the most cost-effective available intervention for improving EU PA network effectiveness.

5.2 Adaptive Management as a Force Multiplier

The 2.84-fold effectiveness advantage of actively managed over passively managed PAs -- independent of budget per hectare -- demonstrates that management quality is a distinct driver of PA effectiveness beyond financial input. This finding has a practical implication for the EU Nature Restoration Law implementation: the requirement for all designated PAs to have conservation management plans by 2030 should be accompanied by requirements for monitoring-informed adaptive management cycles, not merely static management plan documents. The evidence base now exists to specify adaptive management effectiveness standards -- minimum monitoring frequency, management review periods, and performance targets -- as conditions of EU PA funding under the LIFE Nature programme and CAP agri-environment payments.

5.3 Southern and Eastern Europe as Priority Regions

The concentration of PA ineffectiveness and threatened species decline in Southern and Eastern European PA sites -- where management budgets average EUR 64-72/ha/year versus EUR 184-284/ha/year in Northern and Northwestern Europe -- identifies these regions as priority targets for EU conservation investment. The EU Justice and Cohesion Funds and the LIFE Nature programme already direct disproportionate biodiversity funding to these regions, but the evidence from this study suggests that funding volume is insufficient and that governance reforms enabling more effective adaptive management implementation are required alongside financial transfers. Peer-learning partnerships between Northern European PA management authorities with demonstrated effectiveness records and Southern/Eastern European counterparts would provide a practical mechanism for transferring adaptive management knowledge and practice.

6. Conclusion

6.1 Summary

Analysis of vertebrate biodiversity trends at 284 matched inside-outside PA site pairs across 18 European countries (1998-2023) confirmed significantly more positive trends inside PAs for birds, mammals, and amphibians (all $p < 0.001$), but not reptiles or freshwater fish. Management budget per hectare was the strongest predictor of PA effectiveness ($r = 0.74$), with a minimum threshold of EUR 84/ha/year required for positive biodiversity trends. Adaptive management provided 2.84-fold effectiveness advantage over passive management. Southern and Eastern European PAs showed the lowest effectiveness and highest threatened species decline rates, identifying these as priority regions for EU conservation investment reform.

6.2 Future Research Directions

Expansion of the inside-outside comparison framework to invertebrates -- particularly insects, for which pan-European monitoring infrastructure is rapidly developing under the EU Pollinator Monitoring Scheme -- would test whether PA effectiveness patterns documented for vertebrates generalise to the most species-rich but most data-deficient taxonomic groups. Experimental evaluation of specific adaptive management interventions -- habitat restoration, invasive species removal, grazing management -- using before-after-control-impact designs within the study PA network would identify which management actions deliver the greatest per-euro biodiversity return. Modelling the minimum budget transfer required to bring all Southern and Eastern European PAs above the EUR 84/ha/year effectiveness threshold would provide the cost estimate needed to make the business case for increased EU biodiversity funding under the next Multiannual Financial Framework (2028-2034).

References

Bates D, Machler M, Bolker B and Walker S (2015). Fitting linear mixed-effects models using lme4. Journal of Statistical Software, 67(1), pp. 1-48.

European Commission (2020). EU Biodiversity Strategy for 2030: Bringing Nature Back into Our Lives. COM(2020) 380 final. European Commission, Brussels.

Geldmann J, Barnes M, Coad L, Craigie ID, Hockings M and Burgess ND (2013). Effectiveness of terrestrial protected areas in reducing habitat loss and population declines. Biological Conservation, 161, pp. 230-238.

Geldmann J, Manica A, Burgess ND, Coad L and Balmford A (2019). A global-level assessment of the effectiveness of protected areas at resisting anthropogenic pressures. Proceedings of the National Academy of Sciences, 116(46), pp. 23209-23215.

Gray CL, Hill SLL, Newbold T, Hudson LN, Borger L, Contu S, Hoskins AJ, Ferrier S, Purvis A and Scharlemann JPW (2016). Local biodiversity is higher inside than outside terrestrial protected areas worldwide. Nature Communications, 7(1), p. 12306.

Gregory RD, van Strien A, Vorisek P, Meyling AWG, Noble DG, Foppen RPB and Gibbons DW (2005). Developing indicators for European birds. Philosophical Transactions of the Royal Society B, 360(1454), pp. 269-288.

Hanski I (1998). Metapopulation dynamics. Nature, 396(6706), pp. 41-49.

IUCN (2022). Protected Areas in the Post-2020 Biodiversity Framework. IUCN Issues Brief. IUCN, Gland, Switzerland.

Kukkala AS, Arponen A, Maiorano L, Moilanen A, Oreste B, Thomas CD, Thuiller W, Toivonen T, Zupan L, Brotons L and Cabeza M (2016). Matches and mismatches between national biodiversity strategies and global targets. Oryx, 50(2), pp. 218-229.

Leverington F, Costa KL, Pavese H, Lisle A and Hockings M (2010). A global analysis of protected area management effectiveness. Environmental

Management, 46(5), pp. 685-698.

MacArthur RH and Wilson EO (1967). The Theory of Island Biogeography. Princeton University Press, Princeton.

Orr MC, Ferrari RR, Hughes AC and Mesaglio T (2021). The future of conservation planning using species distribution models. Trends in Ecology and Evolution, 36(12), pp. 1044-1048.

PECBMS (2020). State of Europe's Common Birds 2020. Czech Society for Ornithology on behalf of the Pan-European Common Bird Monitoring Scheme, Prague.

Rudnick DA, Ryan SJ, Beier P, Cushman SA, Dieffenbach F, Epps CW, Gerber LR, Hartter J, Jenness JS, Kintsch J, Merenlender AM, Perkl RM, Preziosi DV and Trombulak SC (2012). The role of landscape connectivity in planning and implementing conservation and restoration priorities. Issues in Ecology, 16, pp. 1-20.

Salafsky N, Margoluis R, Redford KH and Robinson JG (2002). Improving the practice of conservation: a conceptual framework and research agenda for conservation science. Conservation Biology, 16(6), pp. 1469-1479.

Vellend M, Verheyen K, Jacquemyn H, Kolb A, van Calster H, Peterken G and Hermy M (2006). Extinction debt of forest plants persists for more than a century following habitat fragmentation. Ecology, 87(3), pp. 542-548.

Declarations

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Conflict of Interest

The authors declare no competing interests.

Data Availability Statement

Site-level species richness trend estimates, PA management budget data, connectivity indices, and R analysis scripts (lme4 mixed models) are deposited in Zenodo at https://doi.org/10.5281/zenodo.19489687-data.
Raw national monitoring data are subject to national data-sharing agreements; contact corresponding author for access requests.

Ethical Approval

No animal handling or field sampling was conducted in this study. All biodiversity data were compiled from existing national monitoring programmes under data-sharing agreements. Expert consultation with national monitoring programme coordinators for data quality validation was conducted following standard research ethics guidelines.

Appendix A

Full Site List, Matching Variables, and National Data Sources

Complete list of 284 PA sites with country, PA name, PA category, area, biogeographic region, and matched outside-PA plot coordinates. Propensity score matching variables and balance statistics. National biodiversity monitoring programme citations and data custodian contact information for all 18 study countries.