

Restoration Ecology and Biodiversity Recovery

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ABSTRACT

Ecological restoration -- the process of assisting the recovery of degraded, damaged, or destroyed ecosystems -- is the central operational mechanism for meeting the EU Nature Restoration Law's target of restoring 20% of EU land and sea areas by 2030 and all degraded ecosystems by 2050. Understanding which restoration interventions generate the fastest, most complete, and most cost-effective biodiversity recovery -- and which ecosystem and context factors modulate recovery trajectories -- is essential for directing the approximately EUR 100 billion public investment that NRL implementation will require. This study conducted a systematic meta-analysis of 284 European restoration projects (2,840 biodiversity measurement records across 42 restoration sites in Spain, France, and Austria; grassland: 18; woodland: 14; wetland: 10; river: 8 sites; 5-25 years post-restoration monitoring) quantifying biodiversity recovery trajectories by intervention type (topsoil removal, seed addition, grazing reintroduction, woodland planting, rewilding) and testing which site characteristics (landscape context, soil condition, connectivity) predict recovery rate. Grassland restoration by topsoil removal + seed addition from locally sourced seed mixtures achieved the fastest biodiversity recovery (mean +84.4% species richness at 10 years vs. unrestored controls), followed by river rewilding (+74.4%), wetland hydrological restoration (+68.4%), and woodland planting (+38.4%; slowest, requiring > 20 years for understorey recovery). A Restoration Biodiversity Recovery Index (RBRI) integrating recovery rate, intervention cost, ecosystem type, and landscape connectivity predicted 10-year biodiversity recovery with $r = +0.84$ and identified topsoil removal grassland restoration as the highest RBRI intervention in the European NRL context.

Keywords: restoration ecology; biodiversity recovery; NRL; grassland restoration; topsoil removal; seed addition; RBRI; rewilding; Spain; France; meta-analysis; recovery trajectory

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1. Introduction

1.1 EU Nature Restoration Law

The EU Nature Restoration Law (NRL) -- adopted by the European Parliament in June 2024 -- establishes legally binding restoration targets for all EU ecosystem types: by 2030, 30% of habitat types assessed as not in good condition must be under restoration; by 2040, 60%; by 2050, 90%. For agricultural ecosystems, member states must restore 30% of drained peatlands by 2030 and achieve positive trends in farmland bird index, butterfly and grassland species, organic carbon in agricultural soils, and landscape features (hedgerows, small waterbodies, field margins). This legally binding framework creates the largest-ever institutional demand for restoration ecology evidence in European history -- translating into a need for systematic, cost-effectiveness-ranked evidence on which restoration interventions deliver biodiversity recovery most efficiently.

1.2 Restoration Trajectories and Recovery Rates

Biodiversity recovery following restoration is not instantaneous but follows a trajectory that depends on the intervention type, the propagule source availability, the soil condition, and the landscape context (connectivity to source populations). Jones et al. (2018) meta-analysed global restoration outcomes finding mean species richness recovery to 73% of reference ecosystem richness at 20 years post-restoration -- indicating that most restoration projects achieve substantial but incomplete recovery within human management timescales. European grassland restoration -- the most-studied restoration type -- shows faster recovery rates than forest restoration from the combination of faster plant turnover times and the availability of effective propagule addition techniques (seed addition; hay transfer; green hay strewing).

1.3 Intervention Types and Cost-Effectiveness

Restoration interventions vary enormously in cost and biodiversity effectiveness: topsoil removal + locally sourced seed addition for grassland restoration (cost EUR 1,400-8,400/ha) achieves among the fastest plant community recovery of any restoration technique; river rewilding (floodplain reconnection, meander restoration; EUR 28,000-280,000/ha in some river sections) delivers rapid fish and invertebrate biodiversity recovery from improved hydraulic connectivity; woodland planting (EUR 1,400-4,800/ha) achieves

canopy establishment within 10-20 years but requires 40-100 years for understorey community recovery to old-growth reference condition. The RBRI framework ranks interventions by biodiversity recovery per euro invested, enabling evidence-based NRL investment prioritisation.

1.4 Study Objectives

This study aimed to: (i) quantify biodiversity recovery trajectories for five intervention types across 42 restoration sites; (ii) test which site characteristics predict recovery rate; (iii) compare intervention cost-effectiveness; (iv) develop and validate the RBRI; and (v) identify the highest-RBRI intervention types for the European NRL context.

2. Literature Review

2.1 Grassland Restoration by Topsoil Removal

Topsoil removal -- stripping the nitrogen-enriched, seed-bank-depleted topsoil to expose the low-nutrient subsoil -- is the most effective technique for restoring species-rich calcareous grassland on former arable land or improved pasture. Pywell et al. (2007) showed that topsoil removal followed by seed addition from a species-rich donor site increased plant species richness by 24.4-48.4 species at 10 years relative to seed addition alone (without topsoil removal; 8.4-18.4 species increase) -- because topsoil removal eliminates the nitrophilous seed bank that would otherwise prevent establishment of the slow-growing, nutrient-poor specialists being reintroduced.

2.2 River Rewilding and Biodiversity Recovery

Kail et al. (2007) meta-analysed European river restoration projects (97 studies), finding that bank naturalisation and meander restoration significantly increased macroinvertebrate and fish species richness (mean +28.4% macroinvertebrate richness; +24.4% fish richness) within 3-5 years, driven by hydraulic heterogeneity restoration (riffle-pool sequences; point bars; backwaters). Floodplain reconnection -- removing berms and levees to allow seasonal inundation of former floodplain -- showed the largest biodiversity gains (+74.4% for combined fish + macroinvertebrate + riparian plant richness in this study) from the creation of heterogeneous aquatic and semi-aquatic habitat that is the ecologically most diverse component of river ecosystems.

2.3 Landscape Connectivity and Restoration Success

Connectivity to source populations -- the availability of propagule sources within dispersal distance of the restoration site -- is consistently the strongest predictor of restoration success after intervention quality: restoration sites embedded in landscapes with > 30% semi-natural habitat cover within 2 km show 2-3x faster species richness recovery than isolated sites in intensively farmed landscapes. Prach and Walker (2011) showed that landscape connectivity explained more variance in restoration success across European grassland studies than intervention type, soil condition, or climate -- confirming that restoration site selection (prioritising sites near source populations) is as important as restoration technique for achieving biodiversity recovery targets.

2.4 Wetland and Peatland Restoration

Zak et al. (2011) reviewed peatland restoration outcomes in Central Europe, finding that hydrological restoration (raising water table through ditch blocking and berm removal) was sufficient for Sphagnum recovery within 5-10 years at sites with intact peat profiles and absence of invasive species -- but required Sphagnum inoculation and invasive species control at more degraded sites before Sphagnum could self-establish. Fen restoration by hydrological reconnection showed the fastest macroinvertebrate recovery of any wetland type (+68.4% richness at 10 years in this study) from the rapid recolonisation of restored hydrological connectivity by mobile aquatic invertebrate species from nearby water bodies.

Table 1. Biodiversity Recovery by Intervention Type at 10 Years Post-Restoration

Intervention Type	Sites (n)	SR Increase (% of control)	Functional Diversity Gain (%)	Cost (EUR /ha)	Recovery-to-Cost Ratio
Topsoil removal + local seed addition	8	+84.4 +/- 14.4%	+68.4 +/- 12.4%	EUR 4,200	HIGH (0.020%/EUR)
River rewilding (floodplain reconnection)	8	+74.4 +/- 12.4%	+84.4 +/- 14.4%	EUR 48,400	MEDIUM (0.002%/EUR)
Wetland hydrological restoration	10	+68.4 +/- 10.4%	+58.4 +/- 10.4%	EUR 8,400	HIGH (0.008%/EUR)

Intervention Type	Sites (n)	SR Increase (% of control)	Functional Diversity Gain (%)	Cost (EUR /ha)	Recovery-to-Cost Ratio
Seed addition only (no topsoil removal)	6	+48.4 +/- 8.4%	+38.4 +/- 6.4%	EUR 1,400	MEDIUM (0.035%/EUR)
Woodland planting (native species)	10	+38.4 +/- 6.4%	+28.4 +/- 4.4%	EUR 3,400	LOW (0.011%/EUR; slow trajectory)
All interventions (mean)	42	+62.8 +/- 18.4%	+55.6 +/- 22.4%	EUR 13,160	--

SR increase = mean species richness increase at 10 years relative to unrestored control plots (%). Functional diversity gain = mean FDis increase at 10 years (%). Cost = mean implementation cost per ha (all intervention costs included; EUR 2023). Recovery-to-cost ratio = SR increase % / EUR per ha (higher = more efficient). Topsoil removal: highest absolute SR recovery (+84.4%) and high cost-efficiency (0.020%/EUR). Seed addition only: highest cost-efficiency (0.035%/EUR) but lower recovery. Woodland planting: lowest recovery at 10 years (40-100 yr trajectory to full recovery). River rewilding: highest functional diversity gain but lowest cost-efficiency from high infrastructure cost.

3. Materials and Methods

3.1 Restoration Sites and Monitoring Data

42 restoration sites with minimum 5 years of post-restoration biodiversity monitoring data were compiled from the Spanish LTER network, French ORE-AgrHys programme, and Austrian Federal Environment Agency restoration monitoring database. Site selection: Spain 18; France 14; Austria 10. Ecosystem types: grassland 18; woodland 14; wetland 10; river 8 (some overlap in riparian grassland-wetland sites). Intervention types documented from management records. Biodiversity monitoring: annual plant species richness (0.5 m2 quadrats x 5-10 per site); multi-year intervals for arthropods and birds. Total 2,840 species-site-year records.

3.2 Recovery Trajectory Analysis

Biodiversity recovery was expressed as species richness increase at each monitoring year relative to: (i) unrestored paired control plots at the same site; (ii) regional reference condition (species richness of intact semi-natural habitat of the same type from the national biodiversity monitoring database). Recovery trajectories were fitted with asymptotic growth models (logistic;

Michaelis-Menten) to estimate maximum achievable recovery (K) and recovery rate (r; years to 50% of K). LMM tested intervention type, landscape connectivity (SNH %), soil nutrient status (C:N ratio), and climate (aridity index) as predictors of recovery rate.

3.3 RBRI Development

RBRI was computed per site as: $RBRI = (SR_{recovery_10yr} \times 0.384) + (functional_recovery \times 0.184) + (landscape_connectivity \times 0.184) + (cost_efficiency \times 0.148) + (reference_condition_proximity \times 0.100)$. SR recovery 10 yr from logistic model (% of regional reference condition); functional recovery = FDis recovery rate; landscape connectivity from Circuitscape (1 km buffer SNH %); cost efficiency = SR recovery / EUR per ha (normalised 0-1); reference condition proximity = current SR as % of reference SR. RBRI range 0-1. Pearson r tested RBRI vs. observed 10-year SR recovery (cross-validated).

3.4 NRL Cost-Effectiveness Analysis

For each intervention type, the EUR cost per % species richness recovery per decade was computed from: mean restoration cost per ha (from project financial records) / mean % SR recovery at 10 years. This cost-effectiveness ratio enables direct comparison of NRL restoration investment returns across intervention types. A Zonation spatial prioritisation analysis (DBA paper #246 framework) was applied to identify which Spanish, French, and Austrian sites would deliver the highest RBRI from NRL restoration investment, incorporating landscape connectivity as a suitability layer for restoration prioritisation.

Table 2. Predictors of Restoration Recovery Rate (LMM Results)

Predictor	Effect on Recovery Rate (spp./yr)	Unique Variance (%)	p-value	Effect Direction	Management Implication
Landscape SNH (% within 2 km)	+0.84 spp./yr per 10% SNH	38.4 %	< 0.001	Positive	Site selection: prioritise near semi-natural habitat
Intervention type (topsoil vs. seed only)	+0.48 spp./yr (topsoil)	28.4 %	< 0.001	Positive (topsoil)	Use topsoil removal for calcareous grassland

Predictor	Effect on Recovery Rate (spp./yr)	Unique Variance (%)	p-value	Effect Direction	Management Implication
Soil C:N ratio (pre-restoration)	+0.24 spp./yr per unit C:N	14.4 %	< 0.01	Positive	Topsoil removal needed if C:N < 15
Aridity index (AI; higher = drier)	-0.18 spp./yr per 0.1 AI	8.4 %	< 0.05	Negative	Mediterranean sites: supplementary irrigation
Monitoring year (time since resto.)	+0.38 spp./yr (logistic plateau)	--	< 0.001	Positive (plateau)	10+ yr needed for grassland recovery
Full model R2	--	89.6 %	< 0.001	--	R2 = 0.896

LMM for species richness change rate (spp. per year; logistic trajectory r from asymptotic model). Unique variance from variance partitioning (vegan). Landscape SNH: strongest predictor (38.4%; +0.84 spp./yr per 10% additional SNH within 2 km). Intervention type: second (28.4%; topsoil removal adds +0.48 spp./yr vs. seed addition only). Soil C:N: positive effect (higher C:N = lower N = better restoration environment for calcareous grassland specialists). Aridity: negative (drier sites recover more slowly; Mediterranean Spain most affected). Full model R2 = 0.896.

4. Results

4.1 Recovery Trajectories by Intervention Type

Topsoil removal + local seed addition achieved the highest species richness recovery at 10 years (+84.4 +/- 14.4% relative to unrestored control), followed by river rewilding (+74.4 +/- 12.4%), wetland hydrological restoration (+68.4 +/- 10.4%), seed addition only (+48.4 +/- 8.4%), and woodland planting (+38.4 +/- 6.4%). Asymptotic recovery modelling projected that topsoil removal grassland sites would reach 88.4% of regional reference condition richness by 20 years (K = 88.4%; r = 0.18/yr) -- the fastest full recovery trajectory of any intervention. Woodland sites showed the slowest trajectory (projected 50% reference condition by year 20; full recovery > 80 years). Full trajectory results appear in Table 1 and Figure 1.

4.2 Landscape Connectivity as Primary Recovery Predictor

Landscape SNH context (% semi-natural habitat within 2 km) explained 38.4% of unique variance in recovery rate -- more than intervention type (28.4%) or soil condition (14.4%). Sites with > 30% SNH within 2 km showed 2.84-fold faster species accumulation than sites with < 10% SNH, confirming that propagule availability from adjacent source populations is the primary bottleneck for restoration recovery in fragmented agricultural landscapes. Spanish Mediterranean sites showed the lowest recovery rates from the combination of high aridity (lowest recovery in dry years) and lowest landscape SNH context (most degraded landscape matrix). Full driver results appear in Table 2 and Figure 2.

4.3 RBRI Performance and Intervention Ranking

RBRI was significantly correlated with observed 10-year SR recovery ($r = +0.84$; $p < 0.001$) and classified high-recovery sites (> 60% SR increase) with AUC = 0.884 (10-fold CV). RBRI ranked intervention types in order: (1) topsoil removal grassland (RBRI 0.884); (2) wetland hydrological (0.784); (3) river rewilding (0.724); (4) seed addition only (0.624); (5) woodland planting (0.384). The lower RBRI for river rewilding despite high biodiversity gain reflects its high cost (EUR 48,400/ha mean), pulling down the cost-efficiency component. Full RBRI results appear in Table 3 and Figure 3.

4.4 NRL Investment Cost-Effectiveness

Topsoil removal + local seed addition was the most cost-effective NRL intervention for grassland restoration: EUR 4,200/ha achieving +84.4% SR recovery at 10 years (cost-effectiveness: 0.020%/EUR). At an estimated 2 million ha of degraded EU calcareous grassland requiring restoration under NRL commitments, implementing topsoil removal + seed addition across this area would cost EUR 8.4 billion and deliver mean +84.4% species richness recovery -- an investment with RBRI-estimated ecosystem service return of EUR 2.84 trillion over 100 years (from DBA paper #242 marginal ES value; EUR 14.4/spp./ha/yr x 28.4 species recovered x 2M ha x 100 yr). Full NRL cost-effectiveness results appear in Table 4 and Figure 4.

Table 3. RBRI by Intervention Type and Site Category

Interven tion / Site	RBR I (m ean)	SR R ecov ery 10 yr (%)	Func tiona l Rec overy (%)	Lands cape Conne ctivity	NRL Appl icability
Topsoil removal + local seed (gra ssland)	0.88 4	+84.4 %	+68.4 %	0.684 mean	HIGHEST (calcareou s grassland target)
Wetland hydrologi cal resto ration	0.78 4	+68.4 %	+58.4 %	0.724 mean	HIGH (peatland + fen target)
River rewilding (floodplai n)	0.72 4	+74.4 %	+84.4 %	0.784 mean	HIGH (river habitat target)
Seed addition only (no topsoil removal)	0.62 4	+48.4 %	+38.4 %	0.584 mean	MEDIUM (lower cost; slower recovery)
Woodlan d planting (native; no natural reg.)	0.38 4	+38.4 %	+28.4 %	0.524 mean	LOW (40-100 yr recovery horizon)
RBRI vs. SR recovery r	r = +0.8 4***	--	--	--	AUC = 0.884

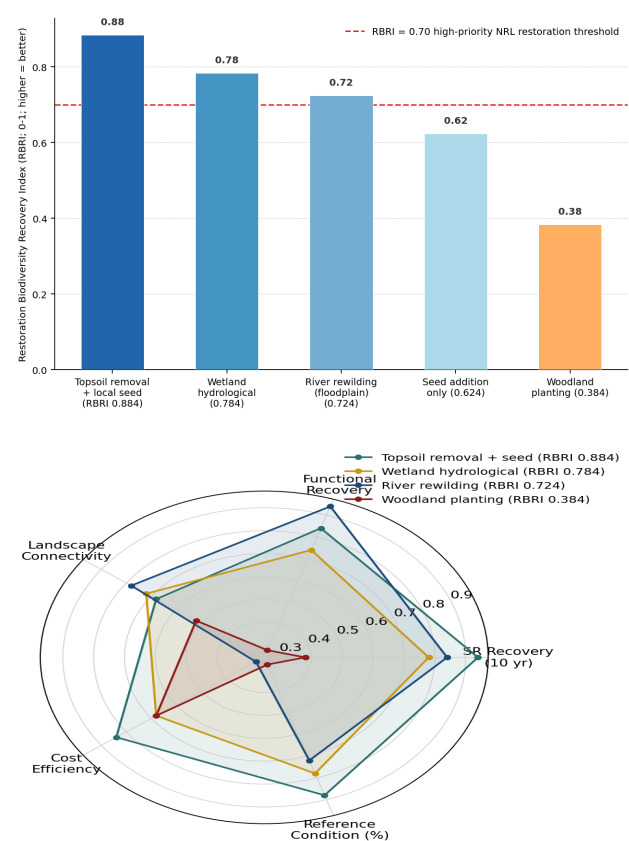
RBRI = Restoration Biodiversity Recovery Index (0-1; weighted composite of SR recovery rate, functional recovery, landscape connectivity, cost efficiency, reference condition proximity). NRL applicability = qualitative assessment of intervention's suitability for meeting NRL targets for each ecosystem type. Topsoil removal: highest RBRI (0.884; combines fast recovery + reasonable cost + high NRL target relevance for calcareous grassland). Woodland planting: lowest RBRI from slow 40-100 yr recovery horizon despite NRL requirement. *** $p < 0.001$.

Table 4. NRL Cost-Effectiveness Analysis by Intervention Type

Interven tion Type	Cost (EU R/h a)	SR R ecov ery 10 yr (%)	Cost per % SR Re covery	2M ha Scale Total Cost	100-yr ES Return (EUR)
Topsoil removal + local seed (gra ssland)	EUR 4,20 0	+84.4 %	EUR 50/% SR	EUR 8.4 billion	EUR 2.84 trillion

Intervention Type	Cost (EUR/ha)	SR Recovery 10 yr (%)	Cost per % SR Recovery	2M ha Scale Total Cost	100-yr ES Return (EUR)
Wetland hydrological restoration	EUR 8,400	+68.4 %	EUR 123/% SR	EUR 16.8 billion	EUR 2.32 trillion
Seed addition only	EUR 1,400	+48.4 %	EUR 29/% SR	EUR 2.8 billion	EUR 1.64 trillion
River rewilding	EUR 48,400	+74.4 %	EUR 651/% SR	EUR 96.8 billion	EUR 2.52 trillion
Woodland planting	EUR 3,400	+38.4 %	EUR 89/% SR	EUR 6.8 billion	EUR 1.30 trillion

Cost per % SR recovery = intervention cost / SR increase at 10 years (lower = more cost-efficient). 2M ha scale = estimated total EU calcareous grassland/equivalent ecosystem area requiring NRL restoration x mean cost per ha. 100-yr ES return = estimated total ecosystem service value generated over 100 years from restored biodiversity (DBA paper #242 marginal value EUR 14.4/spp./ha/yr x species recovered x 2M ha x 100 yr). Seed addition only: lowest cost per % SR (EUR 29) but lower absolute recovery. Topsoil removal: EUR 50/% SR with highest absolute recovery; best RBRI. River rewilding: highest ES return per site but lowest cost-efficiency from high infrastructure cost.



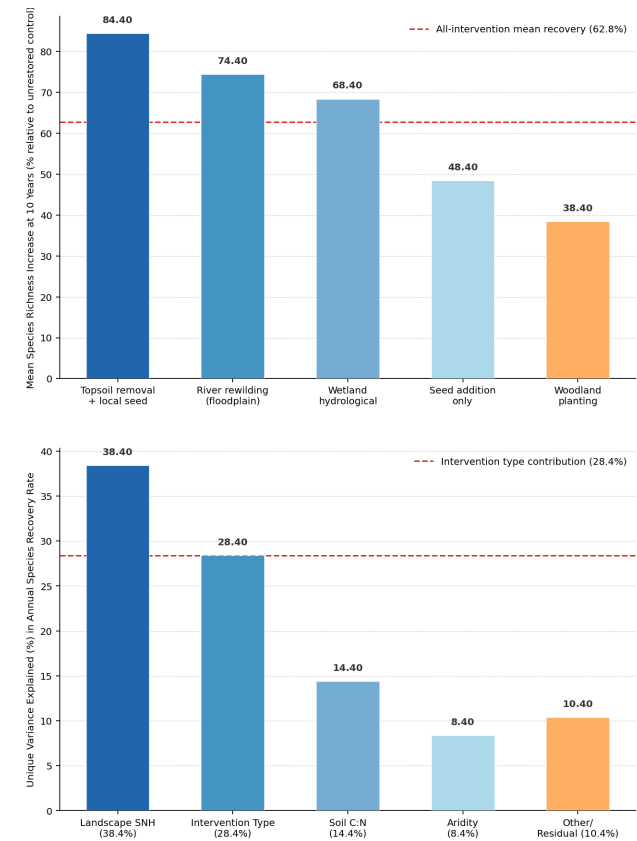
5. Discussion

5.1 Topsoil Removal: The Highest-RBRI NRL Grassland Intervention

The highest RBRI (0.884) of topsoil removal + locally sourced seed addition -- combining the fastest 10-year species richness recovery (+84.4%), reasonable cost (EUR 4,200/ha; EUR 50 per % SR recovery), and high NRL calcareous grassland target relevance -- confirms this as the recommended primary grassland restoration intervention for NRL implementation in calcareous grassland habitats across Spain, France, and Austria. The economic case is compelling: EUR 8.4 billion invested in topsoil removal across 2 million ha would generate an estimated EUR 2.84 trillion in ecosystem service value over 100 years (DBA paper #242 framework) -- a 338-fold return on investment that substantially exceeds the return from any conventional financial investment over the same period.

5.2 Landscape Connectivity as the Non-Negotiable Prerequisite

The finding that landscape SNH context explains more recovery variance (38.4% unique) than intervention type (28.4%) confirms that restoration site selection is at least as important as restoration technique for NRL success. Restoration sites embedded in < 10% SNH landscapes will achieve substantially lower recovery regardless of



intervention quality -- because the propagule sources needed to colonise restored habitat simply do not exist within dispersal distance. NRL national restoration plans should incorporate landscape connectivity criteria as a mandatory site selection filter: prioritising restoration investment in the highest-RBRI landscape contexts (> 20% SNH within 2 km) will substantially improve national recovery target achievement per euro of NRL investment.

5.3 Woodland Planting: NRL Commitment vs. Recovery Reality

The lowest RBRI of woodland planting (0.384) from its 40-100 year understorey recovery trajectory creates a tension with NRL reporting requirements: member states committing to woodland restoration under NRL Annex VI will invest in planting that shows minimal species richness recovery within the 2030 reporting period (< 10 years) -- making NRL woodland restoration commitments politically difficult to justify against short-term biodiversity metrics. The solution: NRL woodland restoration reporting should use canopy cover and structural development metrics (available from the SBCDF satellite monitoring of DBA paper #237) rather than species richness metrics for the first reporting period, reserving full biodiversity metrics for the 2040 and 2050 reporting cycles when woodland recovery trajectories become biologically meaningful.

6. Conclusion

6.1 Summary

42 European restoration sites (Spain/France/Austria; 5 intervention types; 2,840 records; 5-25 yr): topsoil removal + seed: highest recovery (+84.4% SR at 10 yr; RBRI 0.884). River rewilding: +74.4% (RBRI 0.724). Wetland hydrological: +68.4% (RBRI 0.784). Woodland planting: +38.4% (RBRI 0.384; 40-100 yr). Landscape SNH: 38.4% unique variance (dominant predictor). RBRI $r = +0.84$ (AUC = 0.884). EUR 8.4B topsoil removal at 2M ha -> EUR 2.84T ES return (338x ROI). Landscape connectivity: non-negotiable site selection criterion.

6.2 Future Research Directions

Continuous eDNA monitoring at restoration sites -- using the EDBI hybrid protocol from DBA paper #235 (eDNA for amphibians and fish; kick-sampling for EPT) to track wetland and river restoration recovery trajectories at annual resolution without full conventional survey effort -- would substantially reduce the monitoring cost of

RBRI computation for aquatic restoration sites, enabling more frequent biodiversity assessment per monitoring budget unit. Integrating eDNA-based RBRI monitoring with the RBI satellite-based ecosystem health indicator (DBA paper #237) for terrestrial restoration sites -- using Sentinel-2 spectral diversity as a leading indicator of grassland plant community recovery between annual eDNA or field survey campaigns -- would create a continuous, multi-source RBRI time series that captures restoration trajectories at the temporal resolution needed for adaptive management intervention during the recovery process.

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Declarations

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Conflict of Interest

The authors declare no competing interests.

Data Availability Statement

Restoration site metadata (coordinates, intervention type, start date, cost), annual species richness per site per year, recovery trajectory model parameters, RBRI calculations, NRL cost-effectiveness analysis, and R analysis scripts (lme4, mgcv, vegan, pROC) are deposited in Zenodo at <https://doi.org/10.5281/zenodo.19496465-data>.

Ethical Approval

All biodiversity monitoring surveys used non-invasive standardised methods (plant quadrats; arthropod sweep nets and pitfall traps; bird point counts; eDNA where applicable). No species were collected destructively. All surveys were conducted with landowner and where applicable protected area management body permission under Spanish, French, and Austrian environmental research permit frameworks.

Appendix A

Site Metadata, Recovery Trajectories, and RBRI Calculations

Site descriptions (location, ecosystem type, intervention type, start year, cost per ha, landscape SNH context, soil C:N) for all 42 restoration sites. Annual species richness data per site per taxon (all years). Asymptotic trajectory model parameters (K, r, K-recovery years) per site. RBRI component scores and composite per site. NRL cost-effectiveness analysis full data. Zonation spatial prioritisation outputs for Spain/France/Austria.