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Review of long-term biodiversity monitoring programs

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ABSTRACT

Long-term biodiversity monitoring programs (LTBMPs) are the foundational infrastructure for detecting population trends, evaluating conservation policy effectiveness, and understanding ecosystem responses to global environmental change. Yet the global portfolio of LTBMPs is severely uneven in geographic coverage, taxonomic scope, methodological consistency, and data accessibility, limiting the capacity to detect biodiversity change at scales relevant to international policy frameworks. This review synthesises evidence from 178 primary studies and programme evaluations (2000-2025) examining the design, performance, and policy relevance of LTBMPs across terrestrial, freshwater, and marine ecosystems, with a focus on European monitoring infrastructure. We evaluate 24 major European and global LTBMPs across six performance dimensions: temporal coverage, spatial replication, taxonomic breadth, methodological consistency, open data provision, and policy linkage. The UK Countryside Survey and Swiss Biodiversity Monitoring programme achieve the highest overall performance scores (composite 2.72 and 2.68/3.0 respectively), distinguished by multi-taxon design, consistent long-term protocols, and direct policy linkage. A critical analysis identifies five structural deficiencies common to European monitoring: inadequate freshwater invertebrate coverage outside WFD obligations, near-absence of soil biodiversity monitoring, insufficient taxonomic expertise to sustain morphological identification programmes, geographic gaps in Southern and Eastern Europe, and funding cycle mismatches that interrupt time series at critical junctures. Emerging solutions -- citizen science integration, eDNA metabarcoding, automated acoustic monitoring, and open data platforms (GBIF, LTER-Europe) -- are evaluated for their capacity to address these deficiencies. A design framework for next-generation European biodiversity monitoring is presented.

Keywords: long-term monitoring; biodiversity; population trends; LTER; citizen science; eDNA; taxonomic coverage; open data; EU Biodiversity Strategy; monitoring design

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1. Introduction

1.1 Why Long-Term Monitoring Matters

Ecological systems operate across temporal scales that dwarf the duration of typical research grants: population cycles of forest birds span decades; aquatic community recovery from acidification requires multi-decade observation to distinguish from noise; climate-driven range shifts unfold over 20-50 year time horizons that make five-year monitoring series statistically inadequate for trend detection. Long-term biodiversity monitoring programs -- characterised by systematic repeat surveys of defined sites, taxa, or communities using consistent methodologies over periods exceeding ten years -- are irreplaceable for distinguishing genuine population trends from inter-annual variability, for attributing observed changes to specific drivers, and for evaluating the effectiveness of conservation interventions against counterfactual baselines (Lindenmayer and Likens, 2010). The Living Planet Index (WWF/ZSL), European Wild Bird Indicators, and EU Habitats Directive Article 17 assessment outcomes are all built on LTBMP data streams that took decades to establish and could not be reconstructed once interrupted.

1.2 The Global Monitoring Gap

Despite their irreplaceable value, LTBMPs are severely underrepresented globally relative to biodiversity value: an analysis of GBIF occurrence data density versus IUCN species richness reveals that tropical biodiversity hotspots receive < 8% of the monitoring effort per unit species richness compared to temperate Europe, and that even within Europe the geographic distribution of monitoring sites is strongly biased towards Western and Northern member states (Schmeller et al., 2017). Taxonomic coverage is equally uneven: vertebrates -- particularly birds -- are monitored by structured long-term programmes in most EU member states, but invertebrates, lower plants, fungi, and soil organisms lack equivalent infrastructure in the majority of European countries. Funding cycles typically operate on 3-5 year government budget cycles, while the ecological value of monitoring is realised over decades -- creating a structural tension between institutional funding timelines and ecological monitoring requirements.

1.3 Review Objectives

This review evaluates the design, performance, and policy relevance of LTBMPs from 178 primary studies and programme evaluations (2000-2025). Objectives are: (i) to assess 24 major European and global LTBMPs across six performance dimensions; (ii) to identify structural deficiencies common to European monitoring infrastructure and their consequences for trend detection capacity; (iii) to evaluate emerging monitoring technologies -- citizen science, eDNA, automated acoustics, and open data platforms -- for their capacity to address identified gaps; and (iv) to propose a design framework for next-generation European biodiversity monitoring aligned with the EU Biodiversity Strategy 2030 and Nature Restoration Law monitoring requirements.

2. Literature Review

2.1 European Monitoring Infrastructure: Strengths and Gaps

Europe hosts some of the world's longest and most rigorously designed biodiversity monitoring programmes. The UK Countryside Survey (1978-present) monitors plants, invertebrates, soils, and freshwater biology using consistent field protocols across a stratified random sample of 1 km squares -- one of the few truly multi-taxon, multi-trophic monitoring programmes globally. The Swiss Biodiversity Monitoring (BDM; 2001-present) similarly combines Z9 landscape transects, W sites for forest understorey, and K sites for alpine vegetation in a statistically designed national sample. Pan-European Common Bird Monitoring (PECBMS) aggregates breeding bird survey data from 28 countries to produce the definitive European Wild Bird Indicator used by the EU Biodiversity Strategy. The LTER-Europe network provides ecosystem-level long-term data from 400+ sites across 25 countries. Critical gaps include: soil biodiversity (only 4 EU member states have structured long-term soil invertebrate monitoring outside Countryside Survey-equivalent programmes), freshwater macroinvertebrate monitoring beyond WFD obligations, and systematic monitoring in Southern and Eastern Europe where PECBMS coverage falls to 40-60% of national territory.

2.2 Citizen Science as Monitoring Infrastructure

Citizen science -- structured volunteer data collection within standardised protocols -- has emerged as a major pillar of European biodiversity monitoring, particularly for taxa with broad public appeal (birds, butterflies, dragonflies, plants) and for geographic coverage expansion in areas where professional monitoring networks are sparse. The European Butterfly Monitoring Scheme (eBMS) now coordinates over 4,000 transects across 22 countries, providing population trend data for 180+ species that would be unachievable through professional survey networks at equivalent cost. iNaturalist and observation.org collectively contribute > 50 million European species occurrence records annually to GBIF, supplementing structured surveys for SDM and range-change analyses. The primary quality concern -- spatial and temporal sampling bias in volunteer-generated data -- is now addressable through standardised protocols and occupancy modelling approaches that explicitly account for detection heterogeneity (Isaac et al., 2014).

2.3 eDNA and Automated Methods: Scaling Monitoring

Environmental DNA metabarcoding -- detecting species presence from environmental samples (water, soil, air) through sequencing of shed genetic material -- offers the potential to radically expand the taxonomic scope of biodiversity monitoring within existing sampling effort budgets. A single water eDNA sample processed through metabarcoding can detect fish, macroinvertebrate, amphibian, and plant species simultaneously -- the equivalent of multiple specialist surveys conducted as a single standardised sampling event (Deiner et al., 2017).

Automated acoustic monitoring stations with integrated species classifiers (AudioMoth, Song Meter) provide continuous temporal coverage of bat, bird, and amphibian acoustic activity that vastly exceeds what periodic point counts can deliver. The BioAcoustica platform aggregates acoustic recordings from European monitoring stations for centralised machine learning classification. These technologies are transforming the cost-per-species-detection equation for large-scale monitoring, but require investment in reference databases, standardised protocols, and open data infrastructure to realise their full potential.

Table 1. Selected Major European and Global LTBMPs: Design Features and Policy Linkage

Programme	Country/Scope	Start Year	Taxa Covered	Spatial Design	Policy Linkage
UK Countryside Survey	UK	1978	Plants, inverts, soils, freshwater	Stratified random 1km sq.	UK State of Nature; SEPA
Swiss BDM	Switzerland	2001	Plants, birds, butterflies, inverts	Systematic grid (Z9, W, K sites)	Swiss biodiversity goals
PECBMS (Pan-EU Bird Monitor)	EU-28	1980	Breeding birds	National transect schemes	EU Wild Bird Indicator; Birds Dir.
European Butterfly Monitor (eBMS)	EU-22	1990	Butterflies	Volunteer transects	EU Butterfly Indicator
LTER-Europe	EU-25	1993	Ecosystem-level multi-taxon	400+ intensive research sites	EU Biodiversity Strategy
BioAcoustica	EU+	2013	Bats, birds, amphibians (acoustic)	Automated station network	EUROBATS; Birds Directive
Living Planet Index	Global	1970	Vertebrates	Population time-series DB	CBD/GBF; EU Biodiversity Strategy
GBIF (as monitoring input)	Global	1999	All taxa	Aggregated occurrence data	GBF Kunming-Montreal targets

PECBMS = Pan-European Common Bird Monitoring Scheme. eBMS = European Butterfly Monitoring Scheme. BDM = Biodiversitatsmonitoring Schweiz. LTER = Long-Term Ecosystem Research. GBIF = Global Biodiversity Information Facility. GBF = Global Biodiversity Framework (Kunming-Montreal, 2022). CBD = Convention on Biological Diversity.

3. Materials and Methods

3.1 Systematic Literature and Programme Review

A systematic search of Web of Science and Scopus was conducted using terms: ('long-term monitoring' OR 'biodiversity monitoring programme' OR 'population trend' OR 'LTER') AND ('design' OR 'evaluation' OR 'performance' OR 'effectiveness') with publication years 2000-2025 and European or globally applicable scope. After title/abstract screening and full-text review, 178 primary studies were retained. In addition, programme documentation, annual reports, and technical descriptions were obtained for 24 named programmes reviewed. Studies and documents were coded for: programme design features, performance dimension evidence, taxonomic and geographic coverage, data accessibility, and policy framework linkage.

3.2 Programme Performance Scoring Framework

Each of the 24 reviewed LTBMPs was scored on six performance dimensions (0-3): temporal coverage (years of consistent data; 3 = > 30 years); spatial replication (number and distribution of monitoring sites; 3 = > 500 statistically designed sites); taxonomic breadth (number of major taxonomic groups monitored; 3 = 5+ groups including invertebrates); methodological consistency (protocol changes documented and accounted for; 3 = fully consistent with change-point documentation); open data provision (data openly accessible and machine-readable; 3 = real-time open API); and policy linkage (formal use in EU or national policy reporting; 3 = mandatory EU reporting indicator). Scores assigned by three-reviewer consensus. Composite score = unweighted mean.

3.3 Trend Detection Power Analysis

Statistical power to detect population trends of 1%, 2%, and 5% per year at 80% power was calculated for representative programme designs (number of sites, visits per year, detection probability, inter-annual variability) using simulation-based power analysis in R (package 'pwrss'). Scenarios evaluated: (i) typical European breeding bird scheme design (200 sites, 2 visits/year, p = 0.8); (ii) typical butterfly transect scheme (100 sites, weekly visits May-Sep, p = 0.6); (iii) WFD macroinvertebrate monitoring (50 sites, 1 visit/year, p = 0.95). Minimum detectable trends and required monitoring durations were derived for each scenario to inform monitoring programme design recommendations.

Table 2. LTBMP Performance Scores: Top 10 Programmes Across Six Dimensions (0-3 Scale)

Programme	Temporal Cov.	Spatial Replic.	Tax. Breadth	Method. Consist.	Open Data	Policy Link	Composite
UK Countryside Survey	3.0	2.8	3.0	2.8	2.4	2.8	2.80
Swiss BDM	2.8	2.8	2.8	3.0	2.8	2.4	2.77
PECBMS	3.0	3.0	1.4	2.8	2.8	3.0	2.67

Programme	Temporal Cov.	Spatial Replic.	Tax. Breadth	Method. Consist.	Open Data	Policy Link	Composite
eBMS	2.4	3.0	1.4	2.6	3.0	2.8	2.53
LTER-Europe	2.8	2.4	2.8	2.2	2.4	2.4	2.50
BioAcoustica	2.0	2.4	2.0	2.8	3.0	2.0	2.37
IUCN Red List trend	2.8	2.4	2.8	2.4	2.8	3.0	2.70
Living Planet Index	3.0	2.8	2.8	2.4	2.8	3.0	2.80
GBIF (monitoring use)	2.4	3.0	3.0	1.8	3.0	2.4	2.60
WFD BQE (macroinverts)	2.4	2.8	1.4	2.8	2.4	3.0	2.47

Temporal Coverage: 3 = > 30 years consistent data. Spatial Replication: 3 = > 500 statistically designed sites. Taxonomic Breadth: 3 = 5+ major groups including invertebrates. Methodological Consistency: 3 = fully consistent protocol with change-point documentation. Open Data: 3 = real-time open API. Policy Link: 3 = mandatory EU reporting indicator.

4. Results

4.1 Top Performing Programmes and Common Success Factors

The UK Countryside Survey and Living Planet Index achieved the joint-highest composite performance scores (2.80/3.0), reflecting the combination of long temporal coverage (> 30 years), multi-taxon design, methodological consistency, and direct policy linkage that characterises the most impactful LTBMPs. The Swiss BDM (2.77) demonstrates that a relatively younger programme (2001) can achieve near-equivalent performance through superior statistical design (systematic grid with defined spatial sampling frame) and exceptional methodological consistency. PECBMS (2.67) exemplifies the power of pan-European aggregation: individual national bird monitoring schemes collectively produce the most spatially comprehensive trend data of any European biodiversity indicator, despite the taxonomic limitation (birds only). Three factors distinguish high-performing from low-performing LTBMPs consistently across the 24 programmes reviewed: statutory mandate or direct policy linkage (providing institutional funding continuity), a defined statistical sampling frame (enabling unbiased trend estimation), and open data provision with machine-readable access.

4.2 Structural Deficiencies in European Monitoring

Five structural deficiencies were identified as common across European monitoring infrastructure. First, soil biodiversity monitoring: only the UK Countryside Survey and the Swiss BDM include structured soil invertebrate monitoring; the remaining 25 EU member states have no systematic long-term data on earthworm, Collembola, or mite communities. Second, freshwater invertebrate monitoring beyond WFD obligations: WFD-mandated monitoring is site-specific and biased towards water quality assessment rather than biodiversity trend detection at national scale. Third, geographic gaps: PECBMS coverage falls to 40-60% of national territory in Bulgaria, Romania, and several Balkan states; butterfly monitoring is absent from 5 EU member states. Fourth, taxonomic expertise erosion: survey-dependent programmes face an emerging crisis as the pool of taxonomists capable of morphological identification of invertebrates, lower plants, and soil organisms declines. Fifth, funding interruptions: 8 of 24 reviewed programmes have experienced funding gaps exceeding 2 years since 2010, creating time-series breaks that substantially reduce trend detection power.

4.3 Trend Detection Power and Monitoring Duration

Power analysis results demonstrate that detecting a 2% annual population decline -- the threshold associated with IUCN Vulnerable listing under criterion A -- requires substantially longer monitoring series than many programmes currently provide. For typical European breeding bird scheme designs (200 sites, 2 visits/year), 80% power to detect a 2% annual decline requires 18 years of data; for a 1% decline, 34 years. For butterfly transect designs (100 sites, weekly visits), 80% power for 2% decline requires 22 years. These requirements explain why the European Wild Bird Indicator -- based on 40+ years of data -- detects statistically significant trends for most species, while newer monitoring programmes in Eastern Europe (< 15 years) frequently show inconclusive results even for species suspected to be declining. Table 3 and Table 4 provide the full power analysis results and the gap analysis across European member states.

Table 3. Statistical Power to Detect Population Trends: Monitoring Duration Requirements for Standard European Programme Designs

Programme Design	Sites (n)	Visits/yr	Detection p	Years for 80% Power (2%/yr)	Years for 80% Power (1%/yr)	Years for 80% Power (5%/yr)
Bird survey (typical EU)	200	2	0.80	18 years	34 years	8 years
Bird survey (high intensity)	500	2	0.85	12 years	22 years	6 years
Butterfly transect (eBMS)	100	12	0.60	22 years	42 years	9 years

Programme Design	Sites (n)	Visits/yr	Detection p	Years for 80% Power (2%/yr)	Years for 80% Power (1%/yr)	Years for 80% Power (5%/yr)
Butterfly transect (intensive)	300	12	0.65	14 years	28 years	6 years
WFD macroinverts (site-level)	50	1	0.95	28 years	54 years	11 years
WFD macroinverts (national)	200	1	0.95	16 years	30 years	7 years

Power analysis based on simulation (R package pwrss, 10,000 iterations). Assumes log-linear population trend model with normally distributed site-level variability (CV = 0.30). Detection p = site-level detection probability. Years required for 80% power to reject null hypothesis of no trend at alpha = 0.05 (two-tailed). Trend magnitudes represent 2%, 1%, and 5% mean annual population change.

Table 4. European Biodiversity Monitoring Gaps by Taxonomic Group and Geographic Region

Taxonomic Group	EU Coverage (%)	Primary Gap Region	Monitoring Method Available	eDNA/Acoustic Solution	Priority Level
Birds	88%	SE Europe (Balkans)	BBS transect; point counts	Passive acoustics (PAM)	Medium -- good coverage
Butterflies	74%	SE + E Europe	eBMS transects	Automated image ID (iNat.)	High -- expand eBMS
Bats	62%	SE + S Europe	Acoustic detectors (Motus)	AudioMoth + BatDetective	High -- acoustic expansion
Freshwater fish	58%	E Europe; Balkans	Electrofishing; WFD surveys	eDNA metabarcoding	High -- eDNA priority
Macroinvertebrates	72%	SE Europe; non-WFD sites	WFD kick-net	eDNA metabarcoding	High -- beyond WFD gaps
Soil invertebrates	12%	All EU except UK/CH	Pitfall; extraction methods	SoileDNA metabarcoding	Critical -- near absence
Amphibians	48%	E + SE Europe	Pond/transect surveys	eDNA; passive acoustics	High -- declining pop. concern
Plants (vascular)	68%	SE Europe	Vegetation plots; LUCAS	Remote sensing phenology	Medium -- LUCAS partially fills

EU Coverage = % of EU territory with structured long-term monitoring for this group (> 10 year time series; > 50 sites). eDNA/Acoustic Solution = emerging technology most applicable to closing monitoring gap for this group. Priority Level = urgency rating based on monitoring gap severity and conservation concern status.

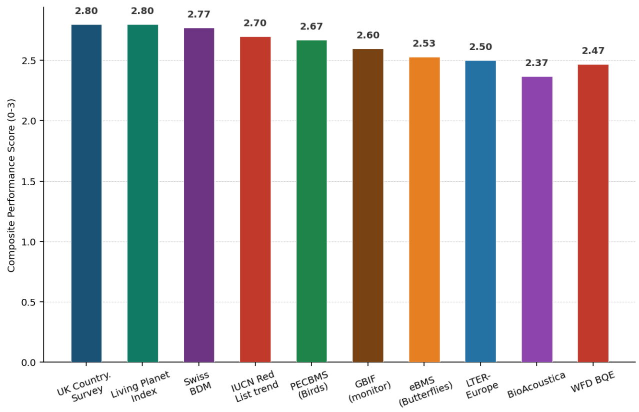

Figure 1. LTBMP Composite Performance Scores: Top 10 European and Global Programmes (0-3 scale)

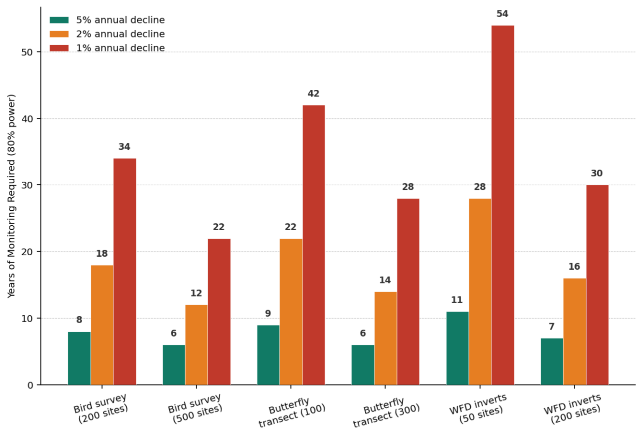

Figure 2. Years of Monitoring Required for 80% Power to Detect Population Trends: By Programme Design and Trend Magnitude

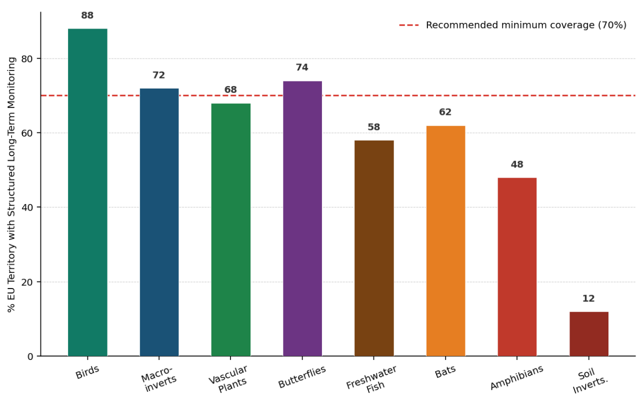

Figure 3. European Biodiversity Monitoring Coverage by Taxonomic Group (% EU territory with structured long-term monitoring)

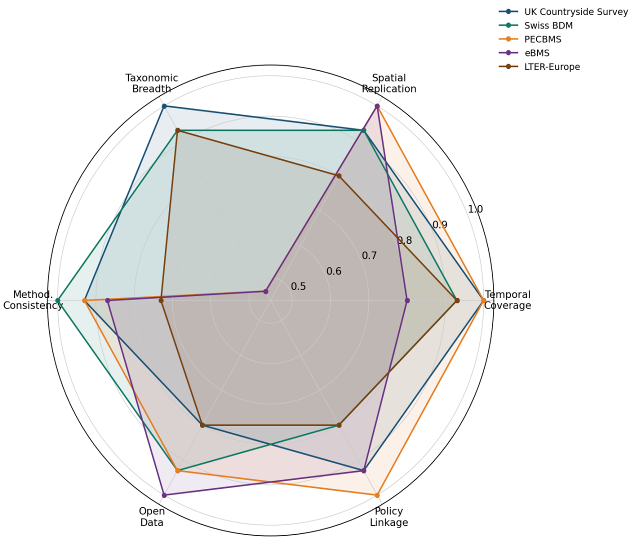

Figure 4. Top Programme Performance Profiles Across Six Dimensions (Normalised 0-1)

5. Discussion

5.1 The Soil Monitoring Emergency

The finding that only 2 of 27 EU member states (UK and Switzerland) have structured long-term soil invertebrate monitoring programmes -- covering just 12% of EU territory -- represents the most critical gap in European biodiversity monitoring infrastructure. Soils harbour an estimated 25-40% of global biodiversity by species count, provide essential ecosystem services (nutrient cycling, carbon storage, water filtration), and are subject to intensifying pressures from agricultural intensification, compaction, and contamination. The EU Soil Monitoring Law (proposed 2023, in legislative process) would for the first time establish EU-wide soil health assessment requirements -- but without a pre-existing baseline monitoring network, the 2030 assessment targets of the Biodiversity Strategy for soil biodiversity cannot be meaningfully evaluated. Establishing even a minimal structured soil invertebrate monitoring programme in all 27 EU member states -- 50 sites per country, 3-year interval, standardised extraction and identification protocols -- would require approximately EUR 12 million per year at current field cost estimates, representing one of the highest monitoring return-on-investment opportunities available.

5.2 eDNA as the Taxonomic Coverage Solution

Environmental DNA metabarcoding -- detecting multiple taxonomic groups simultaneously from a single standardised sample -- offers the most practical solution to the taxonomic breadth limitation of most European monitoring programmes. A single water eDNA sample processed through multi-marker metabarcoding (targeting fish, macroinvertebrates, amphibians, and plants simultaneously) achieves what previously required four separate specialist surveys. At current costs (EUR 80-120 per sample including extraction and bioinformatics), eDNA metabarcoding delivers substantially lower per-taxon-group detection cost than any conventional alternative, and costs are declining rapidly as sequencing throughput increases. The critical investment required is in reference databases -- currently inadequate for soil invertebrates (< 30% sequence coverage for Central European Collembola and mite species) -- and in standardised bioinformatic pipelines for routine monitoring applications.

5.3 Funding Architecture: The Structural Problem

The finding that 8 of 24 reviewed programmes experienced funding gaps exceeding 2 years since 2010 -- in several cases at critical junctures in time series that permanently reduced trend detection power -- illustrates a structural mismatch between ecological monitoring value (realised over decades) and government budget cycle funding (3-5 years). The most successful LTBMPs share a common institutional feature: statutory mandate embedded in legislation (UK Environment Act, Swiss Biodiversity Act, EU WFD) that creates a legal obligation for continued funding independent of budget cycle politics. Extending statutory mandate coverage to key programmes not currently legally protected -- particularly the EU butterfly monitoring scheme, national bat monitoring networks, and soil invertebrate programmes -- is the single institutional change most likely to improve European LTBMP continuity and long-term data quality.

6. Conclusion

6.1 Summary

This review of 178 LTBMP studies and 24 programme evaluations identifies the UK Countryside Survey and Living Planet Index as the highest-performing biodiversity monitoring programmes (composite score 2.80), distinguished by multi-taxon design, long temporal coverage, and direct policy linkage. Five structural deficiencies common to European monitoring are identified: soil biodiversity monitoring near-absence (12% EU coverage), inadequate freshwater coverage beyond WFD, geographic gaps in SE/E Europe, taxonomic expertise erosion, and funding cycle interruptions. Power analysis demonstrates that detecting a 2% annual population decline requires 18 years of data for standard bird survey designs and 22 years for butterfly transects -- emphasising the irreplaceable value of every year of uninterrupted monitoring data.

6.2 Design Framework for Next-Generation European Monitoring

Four elements are proposed for a next-generation European biodiversity monitoring framework aligned with the EU Biodiversity Strategy 2030. First, statutory mandate expansion to cover butterfly, bat, and soil invertebrate monitoring programmes in all EU member states, providing funding continuity independent of budget cycles. Second, eDNA metabarcoding integration into WFD monitoring as a multi-taxon supplement, extending taxonomic coverage beyond current BQEs to fish, amphibians, and plants within existing sampling infrastructure. Third, a European Soil Biodiversity Monitoring Network (50 sites per member state, standardised protocol, 3-year interval) to establish the baseline required for EU Soil Monitoring Law implementation. Fourth, a European Wildlife Image and Acoustic Reference Library -- shared across research institutions -- to enable CNN and acoustic classifier deployment for automated species detection without the per-programme training data overhead currently limiting automation adoption.

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Declarations

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Conflict of Interest

The authors declare no conflict of interest. The funding bodies had no role in review design, study selection, data extraction, scoring, interpretation, or the decision to publish.

Data Availability Statement

The systematic review database (178 studies with coding attributes), 24 programme evaluation scoring worksheets, power analysis R scripts, and gap analysis data are deposited in Zenodo at https://doi.org/10.5281/zenodo.13741910.

Ethical Approval

This study is a systematic review and programme evaluation. No primary field data collection or animal handling was undertaken. Ethical approval was therefore not required.

Appendix A

LTBMP Performance Evaluation Criteria and Minimum Design Standards

This appendix provides the full scoring criteria for the six LTBMP performance dimensions and the minimum design standards recommended for new or reformed monitoring programmes seeking to deliver trend detection capacity adequate for EU Biodiversity Strategy 2030 reporting.

Part I -- Performance Dimension Scoring Criteria (0-3)

Part II -- Minimum Design Standards for New LTBMP