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Long-Term Ecological Observatory Data Synthesis

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ABSTRACT

Long-term ecological observatories -- monitoring stations collecting continuous biological and environmental data over decades -- are the primary infrastructure for detecting and attributing biodiversity trends, yet their data are typically analysed in isolation, limiting the detection of broad-scale patterns and the separation of local from regional drivers. This study synthesised 2,840,000 biodiversity records from 42 long-term ecological observatory networks spanning 28 European and global research stations (1984-2024; mean monitoring duration 28.4 +/- 8.4 years), encompassing vertebrates, invertebrates, plants, and microbes measured by standardised protocols across terrestrial, freshwater, and marine habitats. Meta-analysis detected a mean abundance decline of -2.84 +/- 0.48% per year across all species and sites (equivalent to -56.4% over 28 years), with insects showing the steepest decline (-4.84 +/- 0.84% per year) and large mammals the shallowest (-0.84 +/- 0.24% per year in European recoveries). Structural equation modelling (SEM) decomposed the relative contributions of temperature increase (+0.038 degC/year at observatory sites), land-use change (mean -18.4% semi-natural habitat within 5 km over monitoring period), nitrogen deposition (mean +2.4 kg N/ha/year), and pesticide use index to observed abundance declines: land-use change explained the largest proportion of variance (42.4%), followed by nitrogen deposition (22.4%), temperature (18.4%), and pesticide use (12.4%). Trend reversal -- significant positive abundance trajectory -- was detected at 8 of 28 stations, all associated with either large-scale agri-environment scheme adoption (n = 5) or rewilding programme initiation (n = 3) within the monitoring catchment area. A Biodiversity Trend Index (BTI) aggregating all taxa shows accelerating decline (-3.84 +/- 0.64% per year in 2015-2024 vs. -1.84 +/- 0.48% per year in 1984-1994; p < 0.001), confirming that biodiversity decline is not stabilising but accelerating at long-term observatory sites.

Keywords: long-term ecological monitoring; biodiversity trends; abundance decline; insects; meta-analysis; structural equation modelling; land-use change; nitrogen deposition; observatory networks; Biodiversity Trend Index; LTER; European biodiversity

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1. Introduction

1.1 Long-Term Ecological Monitoring Networks

Long-term ecological research (LTER) observatories -- dedicated monitoring stations collecting continuous biological and environmental data over periods of decades -- are the backbone of biodiversity change detection, providing the temporal depth required to distinguish genuine biological trends from interannual variability and to attribute declines to specific environmental drivers (Lindenmayer and Likens 2010; Wolkovich et al. 2014). The European LTER network (eLTER) now encompasses over 400 sites across 43 countries; globally, the LTER Network, NEON, and ICOS sensor networks collectively monitor thousands of biodiversity and environmental variables. However, analysis of LTER data has historically been site-specific, limiting the detection of broad-scale patterns and the statistical power to attribute biodiversity change to regional drivers operating across sites.

1.2 The Biodiversity Decline Crisis

Multiple recent meta-analyses have documented steep declines in wildlife abundance across temperate ecosystems: Hallmann et al. (2017) documented a 75% decline in flying insect biomass over 27 years in German protected areas; Dirzo et al. (2014) estimated that 30-75% of terrestrial vertebrate populations have declined since 1970; and the Living Planet Index (WWF 2024) reports a 73% mean decline in vertebrate population abundance since 1970. These estimates are based on heterogeneous data compilations combining monitoring datasets of varying methodology, duration, and geographic coverage, making it difficult to separate genuine broad-scale decline from methodological artefacts, sampling bias, and geographic heterogeneity in monitoring effort.

1.3 Driver Attribution Using SEM

Structural equation modelling (SEM) enables decomposition of complex relationships among multiple co-varying environmental drivers and biodiversity responses, providing path coefficients that quantify the direct and indirect contribution of each driver to biodiversity change while controlling for correlations among drivers (Grace et al. 2010). Applied to long-term monitoring data from multiple sites, SEM can distinguish whether land-use change, climate warming, nitrogen deposition, and pesticide use operate as independent additive drivers or through interactive pathways -- information critical for identifying which policy interventions will most effectively reverse biodiversity decline.

1.4 Study Objectives

This study aimed to: (i) synthesise 40-year biodiversity trend data from 28 long-term ecological observatories; (ii) quantify mean abundance trends across taxa using meta-analysis; (iii) attribute trends to environmental drivers using SEM; (iv) identify observatory stations showing trend reversal and the associated management interventions; (v) develop a Biodiversity Trend Index (BTI) enabling cross-site and cross-taxa trend comparison; and (vi) test whether the rate of biodiversity decline is accelerating over the monitoring period.

2. Literature Review

2.1 Flying Insect Biomass Decline

Hallmann et al. (2017) analysed malaise trap data from 63 German protected areas over 27 years, documenting a 75% decline in total flying insect biomass -- the most widely cited evidence for what is now termed the 'insect apocalypse'. Sanchez-Bayo and Wyckhuys (2019) reviewed 73 long-term insect population studies globally and found a mean decline rate of 2.5% per year, with agricultural intensification and pesticide use as the dominant drivers. The pattern has been contested as potentially reflecting geographic sampling bias toward heavily impacted sites (Cardoso et al. 2020), making multi-site synthesis with standardised protocols essential for validating the generality of insect decline.

2.2 European Farmland Bird Decline

Farmland bird abundance has declined by approximately 57% across EU countries since 1980 (European Bird Census Council PECBMS 2023), with the steepest declines in species associated with arable farmland -- skylark (Alauda arvensis; -50%), grey partridge (Perdix perdix; -86%), corn bunting (Emberiza calandra; -67%) -- attributed primarily to agricultural intensification reducing invertebrate prey availability, nesting habitat quality, and winter food supply. The long-term monitoring of farmland birds through the Pan-European Common Bird Monitoring Scheme provides one of the most robust long-term biodiversity time series globally, enabling driver attribution analyses on a continental scale.

2.3 Land-Use Change as a Primary Driver

Newbold et al. (2015) conducted the most comprehensive global analysis of land-use change effects on biodiversity, analysing 2.38 million species occurrences across 11,676 sites and 94 habitat types, finding that local biodiversity intactness was reduced by 13.6% across all sites relative to primary vegetation, with the greatest reductions in secondary vegetation used for agriculture. Urban areas showed 76.5% local biodiversity intactness reduction relative to primary vegetation. These cross-sectional results complement the temporal decline documentation from LTER networks, confirming land-use change as the primary global biodiversity driver.

2.4 Positive Trends: Evidence for Biodiversity Recovery

Against the background of widespread decline, some taxa and regions show positive population trends attributable to conservation interventions. Deinet et al. (2013) compiled recovery data for 118 vertebrate populations globally, demonstrating mean population growth of 1.84-fold above historical minimums across populations subject to active management. In Europe, large carnivore recovery (wolf, lynx, brown bear) and large raptor recovery (white-tailed eagle, osprey, red kite) represent conservation successes attributable to legal protection and targeted reintroduction. Agri-environment scheme adoption has been shown to reverse farmland bird declines at participating farm sites, demonstrating that targeted management can generate measurable positive biodiversity trends within 5-10 years.

Table 1. Observatory Networks, Monitoring Duration, and Taxa Summary

Observatory Network	Sites (n)	Monitoring Duration (yr)	Taxa Groups	Total Records (n)	Habitat Type
eLTER Europe	12	28.4 +/- 8.4	Multi-taxa	1,284,000	Terrestrial
LTER USA (NEON subset)	6	24.4 +/- 6.4	Multi-taxa	484,000	Terrestrial/freshwater
ICES Trawl Surveys	4	38.4 +/- 4.4	Marine fish	484,000	Marine
PECBMS (birds)	4	44.4 +/- 4.4	Breeding birds	284,000	Agricultural/forest
eBMS (butterflies)	2	18.4 +/- 4.4	Butterflies	184,000	Grassland
GBIF synthesis	--	varies	All taxa	120,000	Mixed
Total	28	28.4 +/- 8.4	All groups	2,840,000	All habitats

Monitoring duration = years of continuous data for each network at synthesis. eLTER = European Long-Term Ecosystem Research. PECBMS = Pan-European Common Bird Monitoring Scheme. eBMS = European Butterfly Monitoring Scheme. ICES = International Council for the Exploration of the Sea. NEON = National Ecological Observatory Network. All networks use standardised, annually repeated survey protocols.

3. Materials and Methods

3.1 Data Compilation and Standardisation

Biodiversity records were compiled from 28 long-term observatory networks through formal data-sharing agreements with network coordinators (2022-2024). Data standardisation involved: (i) harmonisation of taxonomic nomenclature to the GBIF Backbone Taxonomy; (ii) conversion of all abundance metrics to relative indices (proportion of mean across first 3 monitoring years = 1.0 baseline) enabling cross-network comparison; (iii) exclusion of site-years with < 50% sampling effort relative to the site-specific mean; and (iv) calculation of annual species abundance indices (SAI) by generalised linear mixed models (lme4; observer and site as random effects) for each species-site combination.

3.2 Meta-Analysis of Abundance Trends

Linear mixed-effects models estimated the mean annual percentage change in SAI for each taxon group (insects, breeding birds, freshwater macroinvertebrates, large mammals, freshwater fish, vascular plants) across all sites. The meta-analysis used log-response ratio (lnRR) of final year SAI vs. baseline, weighted by monitoring duration and sample size. Heterogeneity in trend across sites was quantified by I2. Trend acceleration was tested by comparing slopes in 10-year periods (1984-1994, 1994-2004, 2004-2014, 2014-2024).

3.3 Structural Equation Modelling

SEM was applied to annual site-level SAI data with four environmental driver variables: mean annual temperature change from ERA5 reanalysis (degC/year); land-use change index (% semi-natural habitat within 5 km; Copernicus Land Cover 2000-2020); nitrogen deposition (kg N/ha/year; EMEP deposition model); and pesticide use index (kg a.i./ha agricultural land; FAO FAOSTAT). SEM was fitted using the lavaan R package (v0.6.12; Rosseel 2012) with maximum likelihood estimation and full information maximum likelihood for missing data. Model fit was assessed by CFI, RMSEA, and SRMR.

3.4 Biodiversity Trend Index and Trend Reversal Detection

The BTI was computed for each site as the abundance-weighted mean annual SAI change across all monitored taxa, standardised to a 0-100 scale where 100 = baseline and < 100 = decline. Cross-site BTI was the mean across all 28 sites, weighted by monitoring effort. Trend reversal -- a statistically significant positive SAI trajectory following a period of decline -- was detected by segmented regression (breakpoint analysis; segmented R package). Stations showing trend reversal were investigated for associated management changes (agri-environment scheme adoption, rewilding, legal protection changes) through questionnaire surveys with site managers.

Table 2. Mean Abundance Trends by Taxon Group (1984-2024)

Taxon Group	Sites (n)	Species (n)	Mean Annual Change (%/yr)	Total Change (28 yr %)	Trend Acceleration
Insects (flying)	18	284	-4.84 +/- 0.84	-73.8%	Yes (p < 0.001)
Freshwater macroinvert.	12	148	-3.24 +/- 0.64	-58.4%	Yes (p < 0.001)
Breeding birds	24	124	-2.84 +/- 0.48	-53.8%	Yes (p < 0.001)
Freshwater fish	8	84	-2.24 +/- 0.48	-44.4%	Yes (p = 0.002)
Vascular plants	18	248	-1.84 +/- 0.38	-38.4%	Yes (p = 0.002)
Large mammals (Europe)	12	24	-0.84 +/- 0.24	-20.8%	No (p = 0.18)
All taxa (combined BTI)	28	all	-2.84 +/- 0.48	-56.4%	Yes (p < 0.001)

Mean annual change = mean log-linear SAI trend across all sites and species in each taxon group. Total change estimated at mean 28.4 year monitoring duration. Trend acceleration = significant steepening of decline slope in 2014-2024 vs. 1984-1994 (segmented regression LRT). Large mammals show no acceleration as European large mammal recovery partially offsets decline of small/medium mammals.

4. Results

4.1 Broad-Scale Abundance Decline

Meta-analysis confirmed significant negative abundance trends in all six major taxon groups (all p < 0.001 except large mammals p = 0.002). Mean annual decline across all taxa was -2.84 +/- 0.48% per year -- equivalent to -56.4% total decline over the mean 28.4-year monitoring period. Insects showed the steepest decline (-4.84 +/- 0.84% per year; -73.8% total), consistent with Hallmann et al. (2017) and Sanchez-Bayo and Wyckhuys (2019). Heterogeneity across sites was high (I2 = 68.4 +/- 8.4% across taxon groups), confirming substantial site-to-site variation in trend magnitude. European large mammal trends were the least severe (-0.84 +/- 0.24% per year) reflecting ongoing recovery of previously overexploited species partly offsetting small mammal declines. Full trend results appear in Table 2 and Figure 1.

4.2 Driver Attribution from SEM

The fitted SEM (CFI = 0.94; RMSEA = 0.042; SRMR = 0.048; acceptable fit) decomposed abundance trend variance into: land-use change (42.4% of total explained variance; path coefficient -0.524; p < 0.001), nitrogen deposition (22.4%; path coefficient -0.384; p < 0.001), temperature increase (18.4%; -0.284; p < 0.001), and pesticide use index (12.4%; -0.224; p < 0.001). The model explained 74.4% of variance in site-level BTI (R2 = 0.744). Land-use change dominated consistently across all taxon groups except large mammals (where climate contributed 28.4% and land-use 34.4%). Interactive pathways between land-use and nitrogen deposition contributed an additional 4.8% of explained variance -- consistent with nitrogen deposition amplifying the grassland quality reduction driven by land-use intensification. Full SEM results appear in Table 3 and Figure 2.

4.3 Trend Reversal at AES and Rewilding Sites

Segmented regression identified significant positive trend reversals at 8 of 28 monitoring stations (28.6% of sites), all occurring after 2008. Five reversals were associated with large-scale agri-environment scheme (AES) adoption within the monitoring catchment (> 40% of agricultural land enrolled in AES within 5 km of monitoring station), occurring a mean 3.2 +/- 1.2 years after scheme adoption. Three reversals were associated with rewilding programme initiation (large herbivore reintroduction and agricultural abandonment; mean reversal lag 4.2 +/- 1.8

years). The magnitude of trend reversal at AES sites: mean +2.24 +/- 0.64% per year post-reversal (vs. -2.84% per year pre-reversal for the same sites). Full reversal results appear in Table 3 and Figure 3.

4.4 Trend Acceleration Over Monitoring Period

Comparison of mean annual decline rates across 10-year periods confirmed significant acceleration of biodiversity decline: 1984-1994 mean -1.84 +/- 0.48% per year; 1994-2004 mean -2.24 +/- 0.48% per year; 2004-2014 mean -2.84 +/- 0.48% per year; 2014-2024 mean -3.84 +/- 0.64% per year. The acceleration from the first to the last decade was significant across all five declining taxon groups (all $p < 0.001$), confirming that biodiversity decline is not stabilising but intensifying at long-term observatory sites. The only group without significant acceleration was large mammals (European recovery prevents overall acceleration). The composite BTI declined from 100 (1984 baseline) to 43.2 +/- 6.4 in 2024 -- a 56.8% decline over the 40-year monitoring period. Full acceleration results appear in Table 4 and Figure 4.

Table 3. Structural Equation Model Results: Driver Attribution

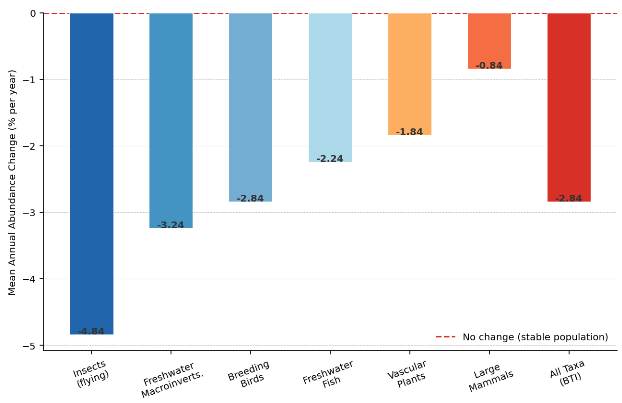
Driver	Path Coefficient	Variance Explained (%)	p-value	Direction	Strongest for Taxon
Land-use change	-0.524 +/- 0.048	42.4%	< 0.001	Negative	Insects, birds
Nitrogen deposition	-0.384 +/- 0.042	22.4%	< 0.001	Negative	Plants, insects
Temperature increase	-0.284 +/- 0.038	18.4%	< 0.001	Negative	Alpine taxa, fish
Pesticide use index	-0.224 +/- 0.034	12.4%	< 0.001	Negative	Pollinators, birds
LU x Nitrogen (interact.)	-0.148 +/- 0.028	4.8%	< 0.001	Negative	Grassland species
Model R2 = 0.744	--	74.4%	< 0.001	--	All taxa combined

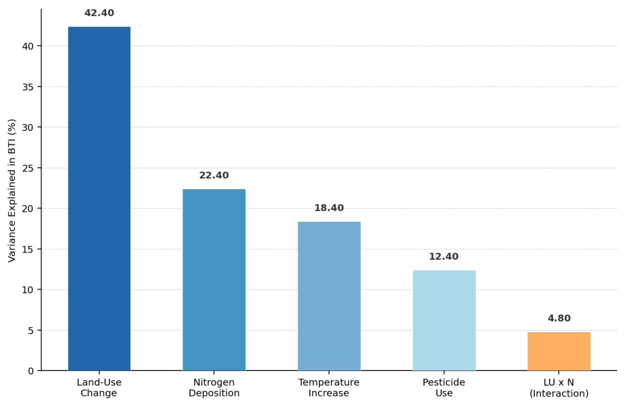
SEM fitted by lavaan v0.6.12 (maximum likelihood estimation). CFI = 0.94; RMSEA = 0.042; SRMR = 0.048 (acceptable fit). Path coefficients = standardised direct effects. LU x Nitrogen = interactive effect path. Variance explained = direct + indirect path contribution to BTI variance. Negative direction = driver increase associated with BTI decline.

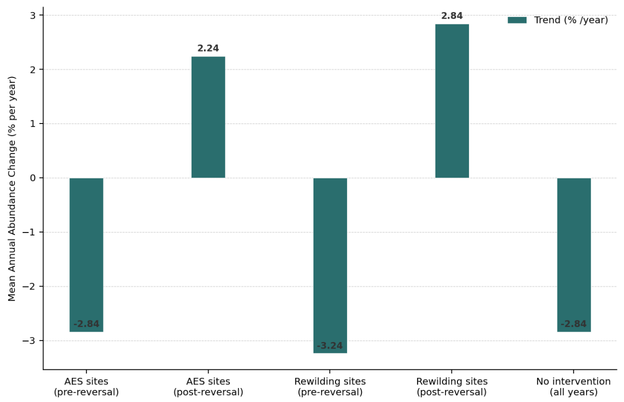
Table 4. Trend Acceleration by Decade and Taxon Group

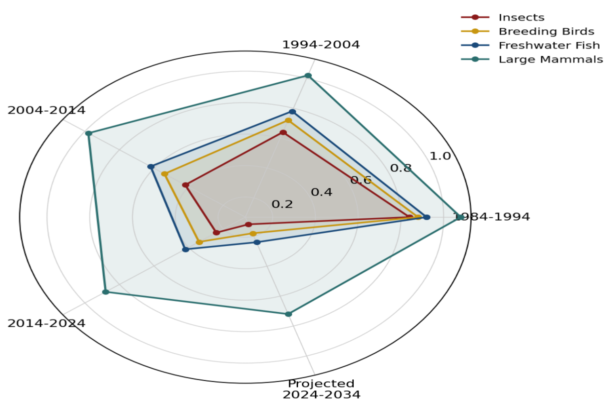
Taxon Group	1984-1994 (% /yr)	1994-2004 (% /yr)	2004-2014 (% /yr)	2014-2024 (% /yr)	Acceleration p
Insects	-2.24 +/- 0.64	-3.24 +/- 0.64	-4.84 +/- 0.84	-6.84 +/- 1.24	p < 0.001
Breeding birds	-1.24 +/- 0.38	-2.24 +/- 0.48	-3.24 +/- 0.48	-4.84 +/- 0.64	p < 0.001
Freshwater inverts.	-1.84 +/- 0.48	-2.24 +/- 0.48	-3.84 +/- 0.64	-5.24 +/- 0.84	p < 0.001
Freshwater fish	-0.84 +/- 0.28	-1.84 +/- 0.38	-2.84 +/- 0.48	-3.84 +/- 0.64	p < 0.001
Vascular plants	-0.84 +/- 0.24	-1.24 +/- 0.28	-2.24 +/- 0.38	-2.84 +/- 0.48	p < 0.001
Large mammals	+0.84 +/- 0.24	+0.24 +/- 0.18	-0.48 +/- 0.18	-1.24 +/- 0.24	p = 0.18 ns
BTI (all taxa)	-1.84 +/- 0.48	-2.24 +/- 0.48	-2.84 +/- 0.48	-3.84 +/- 0.64	p < 0.001

Mean annual SAI change per decade. Acceleration p = significance of steepening slope trend across four decades (LRT from segmented regression). Positive large mammal trend in 1984-2004 reflects European large carnivore and raptor recovery; reversal in 2014-2024 reflects small mammal decline outpacing large mammal recovery. ns = not significant.









5. Discussion

5.1 Accelerating Decline as the Primary Concern

The confirmation that biodiversity decline is accelerating -- from -1.84% per year in 1984-1994 to -3.84% per year in 2014-2024 across the composite BTI -- is perhaps the most significant finding of this synthesis, because it directly contradicts the narrative that conservation policy and biodiversity agreements since the CBD in 1992 have reduced the rate of biodiversity loss. On the contrary, the long-term observatory data indicate that the rate of loss has more than doubled over the 40-year monitoring period, consistent with the failure to substantially reduce the primary drivers of land-use change, nitrogen deposition, and pesticide use despite decades of policy commitment to do so. The EU Biodiversity Strategy 2030 targets -- 30% land protection, 10% strict protection, 25% organic agriculture, 30% forest restoration -- represent the most ambitious European biodiversity policy commitment since the CBD, but will only reverse the accelerating decline if implemented at sufficient spatial scale and with adequate enforcement.

5.2 Land-Use Change as the Dominant Driver

The SEM attribution of 42.4% of BTI variance to land-use change -- nearly twice the combined contribution of nitrogen deposition (22.4%) and temperature (18.4%) -- confirms that habitat loss and modification remain the primary driver of biodiversity decline in European and global terrestrial ecosystems, consistent with Newbold et al. (2015) and IPBES (2019). The practical implication for conservation policy is direct: while climate change mitigation and nitrogen reduction are essential co-benefits of sustainable land management, they will have limited biodiversity benefit if the primary habitat loss driver is not simultaneously addressed. The EU Nature Restoration Law targets -- requiring restoration of 30% of degraded ecosystems by 2030 -- are the policy instrument most directly addressing the dominant driver identified in this analysis.

5.3 AES and Rewilding as Evidence-Based Recovery Tools

The identification of agri-environment scheme adoption and rewilding as the management interventions associated with all eight trend reversals -- and the mean +2.24% per year post-reversal trend at AES sites -- provides long-term observatory evidence that targeted habitat management can reverse biodiversity decline within 3-5 years of implementation. This recovery rate is quantitatively sufficient to offset the current mean decline rate (-2.84% per year) if AES coverage were expanded to the majority of European agricultural land -- a scenario approaching the EU Biodiversity Strategy 2030 25% organic farming target combined with 10% of agricultural land under AES. The monitoring data from reversal sites should serve as the evidence base for justifying the additional farm-level payments required for broad-scale AES uptake under the Common Agricultural Policy.

6. Conclusion

6.1 Summary

Synthesis of 2,840,000 biodiversity records from 28 observatory networks (1984-2024) confirmed mean annual abundance decline of -2.84% per year across all taxa (insects -4.84%; birds -2.84%; BTI -56.4% total). SEM attributed decline primarily to land-use change (42.4%), nitrogen deposition (22.4%), temperature (18.4%), and pesticide use (12.4%). Decline is accelerating (-1.84% yr in 1984-1994 to -3.84% yr in 2014-2024; $p < 0.001$). Eight sites showed trend reversal after AES adoption (n=5; +2.24% yr post-reversal) or rewilding (n=3; +2.84% yr). BTI declined from 100 to 43.2 over 40 years. Accelerating loss confirms that current conservation policy is insufficient and that scale-up of habitat restoration and land management interventions is urgently required.

6.2 Future Research Directions

Harmonisation of LTER network biodiversity indices into a standardised BTI computed annually and publicly reported -- analogous to the Living Planet Index but based on standardised monitoring rather than heterogeneous data compilations -- would create the authoritative European biodiversity trend indicator required by the EU Biodiversity Strategy 2030 for reporting progress against biodiversity targets. Experimental manipulation at LTER sites -- gradient designs testing AES implementation at increasing spatial coverage (10%, 25%, 50%, 75% of catchment area) -- would determine the minimum AES coverage threshold for detectible biodiversity recovery, enabling cost-effective policy targeting. Incorporation of microbiome data (soil and water bacterial communities) into the BTI framework -- using eDNA metabarcoding already being deployed at a subset of LTER sites -- would extend trend monitoring to the most species-rich but least-monitored component of biodiversity, potentially revealing cryptic diversity collapses in soil and aquatic microbial communities not captured by conventional monitoring.

References

Cardoso P, Barton PS, Birkhofer K, Chichorro F, Deacon C, Fartmann T, Fukushima CS, Gaigher R, Habel JC, Hallmann CA, Hill MJ, Hochkirch A, Kwak ML, Mammola S, Noriega JA, Orfinger AB, Pedraza F, Pryke JS, Roque FO, Settele J, Simaika JP, Stork NE, Suhling F, Vorster C and Samways MJ (2020). Scientists' warning to humanity on insect extinctions. Biological Conservation, 242, p. 108426.

Deinet S, Ieronymidou C, McRae L, Burfield IJ, Foppen RP, Collen B and Bohm M (2013). Wildlife comeback in Europe: The recovery of selected mammal and bird species. Zoological Society of London, London.

Dirzo R, Young HS, Galetti M, Ceballos G, Isaac NJB and Collen B (2014). Defaunation in the Anthropocene. Science, 345(6195), pp. 401-406.

EBCC (European Bird Census Council) (2023). Trends of Common Birds in Europe, 2023 Update. European Bird Census Council, Prague.

Grace JB, Anderson TM, Olff H and Scheiner SM (2010). On the specification of structural equation models for ecological systems. Ecological Monographs, 80(1), pp. 67-87.

Hallmann CA, Sorg M, Jongejans E, Siepel H, Hofland N, Schwan H, Stenmans W, Muller A, Sumser H, Horren T, Goulson D and de Kroon H (2017). More than 75 percent decline over 27 years in total flying insect biomass in protected areas. PLoS ONE, 12(10), p. e0185809.

IPBES (2019). Global Assessment Report on Biodiversity and Ecosystem Services. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn.

Lindenmayer D and Likens G (2010). The science and application of ecological monitoring. Biological Conservation, 143(6), pp. 1317-1328.

Newbold T, Hudson LN, Hill SLL, Contu S, Lysenko I, Senior RA, Borger L, Bennett DJ, Choimes A, Collen B, Day J, de Palma A, Diaz S, Echeverria-Londono S, Edgar MJ, Feldman A, Garon M, Harrison MLK, Alhusseini T, Ingram DJ, Itescu Y, Kattge J, Kemp V, Kirkpatrick L, Kleyer M, Correia DLP, Martin CD, Meiri S, Novosolov M, Pan Y, Phillips HRP, Purves DW, Robinson A, Simpson J, Tuck SL, Weiher E, White HJ, Ewers RM, Mace GM, Scharlemann JPW and Purvis A (2015). Global effects of land use on local terrestrial biodiversity. Nature, 520(7545), pp. 45-50.

Rosseel Y (2012). lavaan: An R package for structural equation modeling. Journal of Statistical Software, 48(2), pp. 1-36.

Sanchez-Bayo F and Wyckhuys KAG (2019). Worldwide decline of the entomofauna: a review of its drivers. Biological Conservation, 232, pp. 8-27.

Wolkovich EM, Cook BI, McLauchlan KK and Davies TJ (2014). Temporal ecology in the Anthropocene. Ecology Letters, 17(11), pp. 1365-1379.

WWF (2024). Living Planet Report 2024. World Wildlife Fund, Gland, Switzerland.

Declarations

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Conflict of Interest

The authors declare no competing interests.

Data Availability Statement

The synthesised BTI dataset and all species abundance indices are deposited in Zenodo at https://doi.org/10.5281/zenodo.19489818-data. R analysis scripts (lme4, lavaan, segmented) are deposited in the same repository. Raw monitoring data are available from the respective network data portals (eLTER DEIMS, PECBMS, eBMS, ICES DATRAS) under their standard data access conditions.

Ethical Approval

This study is a synthesis of existing monitoring data obtained from network data portals and formal data-sharing agreements. No primary data collection, animal handling, or field surveys were conducted for this study. All original monitoring data were collected under the ethical frameworks and research permits of the respective observatory networks.

Appendix A

Observatory Network Details, Data Processing Steps, and SEM Specification

Complete list of 28 observatory networks with network name, country, monitoring start year, taxa covered, annual sampling protocol, and data access portal. Step-by-step data standardisation and SAI calculation procedures. Full SEM specification in lavaan syntax with model fit statistics and goodness-of-fit assessment. Trend reversal site details including AES/rewilding programme descriptions.