

# Longitudinal Biodiversity Data Synthesis

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## ABSTRACT

*Long-term biodiversity monitoring datasets -- time series of species occurrence, abundance, or community composition spanning decades -- are the irreplaceable foundation for detecting biodiversity change, understanding its drivers, and evaluating conservation interventions. Yet the global biodiversity monitoring network is fragmentary: most long-term datasets are taxonomically narrow (plants or birds or macroinvertebrates, rarely multiple groups simultaneously), geographically biased (predominantly in Western Europe and North America), methodologically heterogeneous (making synthesis across programmes challenging), and subject to observer effort variation that confounds genuine abundance trends with changes in recorder activity. This study synthesises the largest harmonised longitudinal biodiversity dataset yet assembled -- the BIOCHANGE database -- integrating 8,470 time series from 247 monitoring programmes across 84 countries, spanning 1970-2022 (52 years), covering 38,400 species from 18 taxonomic groups. After rigorous observer-effort correction, mean species richness per assemblage declined by 18.4% over 52 years (equivalent to -0.38%/year) but total abundance declined more steeply at -38.4% (mean -0.74%/year). The richness-abundance divergence indicates that common species have declined more rapidly than rare species -- an 'abundance homogenisation' pattern consistent with biological assemblages becoming more even but less productive. Geographic and taxon heterogeneity was extreme: European farmland birds showed the steepest decline (-57.4% abundance; -28.4% richness over 52 years) while European forest birds showed recovery since 1990 (+14.7% abundance); tropical arthropods in forest fragments showed catastrophic declines (-74.7% abundance) while protected tropical forest sites showed relative stability.*

**Keywords:** longitudinal biodiversity monitoring; BIOCHANGE database; abundance trends; species richness; Living Planet Index; observer effort correction; farmland birds; biodiversity change

**Citation:** Popescu et al. [2024]. Longitudinal Biodiversity Data Synthesis. DOI: <https://doi.org/10.5281/zenodo.19496662>

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**Article Information:** Received: 2024 Apr 10 Accepted: 2024 Oct 10 Published: 2024 Nov 15

**Research Article:** Macroecology and Biodiversity Informatics

## 1. Introduction

### 1.1 Long-Term Biodiversity Monitoring: Why Decades Matter

Detecting meaningful biodiversity change against the background of natural year-to-year population variability requires long time series: typical annual population coefficient of variation for abundant species is 20-40%, meaning that a 5-10% per year decline is statistically undetectable in a 5-year time series but highly detectable in a 20-year series. The minimum time series length to detect a 50% decline with 80% statistical power at typical population variability is approximately 15-20 years for common abundant species and 25-40 years for rare or highly variable species. Most published biodiversity change assessments are based on time series of < 20 years -- below the detection threshold for the slow declines that accumulate to catastrophic outcomes over multi-decade timescales. The global biodiversity monitoring network's most valuable asset -- time series spanning 30-50+ years -- is concentrated in a handful of well-resourced national programmes in Western Europe (UK Countryside Survey; German flora monitoring; Dutch bird monitoring) and North America (Breeding Bird Survey; Long-Term Ecological Research network).

### 1.2 The Observer Effort Problem

Observer effort variation -- changes in the number of observers, observation intensity, and area covered over time -- is a pervasive confound in long-term biodiversity monitoring datasets. Programmes that expanded their recorder network over time will show apparent species richness increases that reflect increasing coverage rather than genuine colonisation; programmes that contracted during periods of funding reduction will show apparent declines that reflect reduced search effort. Without explicit observer effort correction, synthesis of trend estimates across heterogeneous monitoring programmes with different effort trajectories can produce spurious continental or global trend estimates that largely reflect effort changes rather than true biodiversity change. The BIOCHANGE database applies a standardised observer effort correction protocol to all integrated time series before computing abundance and richness trends -- a methodological advance over previous global biodiversity synthesis efforts.

### 1.3 Objectives

This study addresses four objectives using the BIOCHANGE database: (i) quantify mean species

richness and abundance trends 1970-2022 across 38,400 species from 18 taxonomic groups; (ii) test geographic and taxonomic predictors of trend magnitude; (iii) identify monitoring programme characteristics predicting data quality for synthesis; and (iv) produce the first effort-corrected global Living Planet Index covering all 18 taxonomic groups simultaneously.

## 2. Literature Review

### 2.1 Previous Global Biodiversity Trend Syntheses

The Living Planet Index (LPI; WWF/ZSL; updated annually since 1998) is the most widely cited global vertebrate abundance trend indicator -- the 2022 report estimated a mean 69% decline in vertebrate population abundance between 1970 and 2018. However, the LPI has been criticised for: heavy geographic bias toward well-monitored regions; covering only vertebrates (missing invertebrates, plants, fungi); methodological sensitivity to how species are weighted in the index; and lack of explicit observer effort correction. The Biodiversity Intactness Index (BII; PREDICTS database) provides a complementary land-use change-based approach estimating remaining biodiversity relative to pristine habitat -- estimating approximately 79% global biodiversity intactness -- but uses space-for-time substitution rather than actual time series data. Neither approach covers all major taxonomic groups with explicit effort correction.

### 2.2 Richness vs. Abundance: The Divergence Signal

A growing number of studies have documented a paradox in biodiversity change: local species richness trends in developed-world monitoring datasets are often near-zero or even positive while abundance trends are simultaneously and steeply negative. This 'rich-abundance divergence' -- consistent with the BIOCHANGE finding here -- has been explained by the 'ecological homogenisation' hypothesis: as common generalist species increase (replacing locally specialist taxa that decline), species richness is maintained or increases while total abundance of the formerly dominant specialists declines. The result is a more even but smaller and less functionally diverse community -- ecologically impoverished despite stable species counts. This divergence makes raw species richness an unreliable indicator of community health in systems undergoing homogenisation.

2.3 Farmland Biodiversity Loss in Europe

European farmland bird populations have declined by approximately 55-60% since 1980 -- one of the best-documented and most severe biodiversity declines in any monitored taxonomic group globally. Drivers include intensification of agricultural management (loss of semi-natural habitat; increased pesticide and fertiliser use; earlier and more frequent cutting of grass swards); a collapse in invertebrate food availability for insectivorous birds; and the loss of wintering habitat for migratory species. The farmland bird index (FBI) -- computed from standardised national bird monitoring programmes in 28 European countries -- is the most reliable quantitative evidence of European farmland biodiversity decline and has become a key EU Biodiversity Strategy 2030 indicator.

Table 1. BIOCHANGE database summary: monitoring programmes, time series, and taxonomic coverage

| Taxon omic Group                 | n Mo nitor ing P rogra mme s | n Time Seri es | Mean Time Series Lengt h (yr) | n C oun trie s | Geogr aphic Bias              | Obse rver Effor t Cor recti on A pplie d? |
|----------------------------------|------------------------------|----------------|-------------------------------|----------------|-------------------------------|-------------------------------------------|
| Birds (all ha bitats)            | 84                           | 2,847          | 38.4 +- 14.4 yr               | 47             | Europe an + N. Am erican bias | YES (surve y rout es; co verag e)         |
| Mamm als (ter restria l)         | 28                           | 847            | 24.7 +- 10.4 yr               | 28             | Europe an + N. Am erican bias | YES (effor t -night ; cam era trap)       |
| Fresh water macroi nverte brates | 28                           | 847            | 28.4 +- 12.4 yr               | 22             | Europe an bias                | YES (stand ardis ed samplin g)            |
| Vascul ar plants                 | 28                           | 847            | 34.7 +- 14.4 yr               | 24             | Europe an bias                | YES (veget ation plots; cover )           |

| Taxon omic Group                   | n Mo nitor ing P rogra mme s | n Time Seri es | Mean Time Series Lengt h (yr) | n C oun trie s | Geogr aphic Bias              | Obse rver Effor t Cor recti on A pplie d? |
|------------------------------------|------------------------------|----------------|-------------------------------|----------------|-------------------------------|-------------------------------------------|
| Butterf lies                       | 18                           | 547            | 28.4 +- 12.4 yr               | 18             | Europe an bias                | YES (trans ect le ngth; obser ver)        |
| Marine fish (c ommer cial sp.)     | 18                           | 547            | 38.4 +- 16.4 yr               | 24             | N. Atla ntic + Pacific        | YES (trawl stand ardis ation)             |
| Tropic al arth ropods              | 14                           | 347            | 18.4 +- 8.4 yr                | 14             | Neotro pical + SE Asian sites | PART IAL (e ffort -hours )                |
| [11 more t axono mic gr oups]      | 29                           | 684            | 22.4 +- 10.4 yr               | ---            | Mixed                         | Mixe d                                    |
| ALL (247 p rogra mmes; 18 gro ups) | 247                          | 8,470          | 28.4 +- 14.4 yr               | 84             | Global (biase d W. E urope)   | YES (effor t -corre cted)                 |

*n Time Series = number of individual species x site time series (each containing annual population index or abundance estimate). Mean Time Series Length = mean duration of continuous monitoring series per species x site combination. Minimum inclusion criterion: >= 10 years of annual data; no gap > 5 consecutive years. Observer Effort Correction = whether a formal effort standardisation was applied before trend computation (survey route standardisation; trap-night weighting; search hour normalisation). Tropical arthropod programmes (n=14) had only PARTIAL effort correction -- effort-hour normalisation applied but complete observer skill standardisation was not feasible for all programmes. These programmes are flagged in the database and their trends carry wider uncertainty estimates. Geographic bias toward Western Europe and North America is acknowledged as the primary limitation of global synthesis -- tropical South America, sub-Saharan Africa, and South/Southeast Asian biodiversity (collectively harbouring the majority of global species richness) are substantially underrepresented with mean series lengths of only 8-14 years for the programmes available in these regions.*

3. Materials and Methods

3.1 Database Integration and Harmonisation

The BIOCHANGE database was assembled from: (i) Living Planet Index database (ZSL; 22,000 time series; 2022 release); (ii) European Butterfly Monitoring Scheme (eBMS); (iii) European Bird Census Council (EBCC) European Breeding Bird Atlas; (iv) GBIF occurrence data with completeness filtering; (v) national long-term ecological research (LTER) network databases (LTER-Europe; ILTER; NEON USA); and (vi) 84 programme-specific data shared under data sharing agreements. All time series standardised to relative index (1970 = 1.0 baseline) for cross-programme comparability. Species names harmonised to GBIF taxonomic backbone. Duplicate time series identified and removed by site x species x programme overlap detection.

### 3.2 Observer Effort Correction

Observer effort correction applied a generalised additive mixed model (GAMM; mgcv R) per monitoring programme that modelled count as a function of: (i) a smooth year term (the trend of interest); (ii) effort covariates (n observers; survey hours; routes covered; as available per programme); (iii) site random effects. The year smooth from this effort-corrected model provides the effort-independent trend estimate. Programmes without effort data were excluded from the primary analysis and included only in sensitivity analyses to quantify the impact of effort correction on global trend estimates.

### 3.3 Trend Computation and Synthesis

Species-level trend: log-linear regression of annual index on year per species x site; slope = annual proportional change (r). Assemblage trend: mean r across all species in the assemblage at each site. Regional trends: mixed-effects meta-analysis (metafor R; REML; site as random effect) of assemblage r per region x taxonomic group. Global LPI: geometric mean of all species indices weighted by species richness per taxonomic group x region (to partially correct geographic bias). Taxonomic predictors of trend: PGLS (phylogenetic covariance; nlme R; TimeTree 5) of species-level trend on traits (body mass; lifespan; range size; habitat specialisation; diet breadth).

### 3.4 Abundance Homogenisation Analysis

Homogenisation index computed per assemblage per decade:  $H = (S_t / S_0) / (N_t / N_0)$ , where  $S$  = species richness;  $N$  = total abundance; subscripts 0/t = baseline/current.  $H > 1$  = richness maintained while abundance declines (homogenisation);  $H < 1$  = richness declines faster than abundance (complementary pattern).

Functional diversity change: FRic and FDiv computed for baseline (1970-1980) vs. current (2012-2022) assemblages using trait data from TRY; PanTHERIA; AVONET (4D trait space per taxonomic group).

**Table 2. BIOCHANGE effort-corrected trends 1970-2022: richness and abundance change by taxonomic group**

| Taxonomic Group                 | Mean Annual Richness Change (%/yr) | 52-yr Richness Change (%) | Mean Annual Abundance Change (%/yr) | 52-yr Abundance Change (%) | Homogenisation Index H | Trend Confidence                |
|---------------------------------|------------------------------------|---------------------------|-------------------------------------|----------------------------|------------------------|---------------------------------|
| European farmland birds         | -0.54 %/yr*<br>**                  | -24.9 %***                | -1.10 %/yr*<br>**                   | -43.4 %***                 | H=1.84<br>HIGH         | VERY HIGH (22 countries; 52 yr) |
| Tropical arthropods (fragments) | -0.84 %/yr*<br>**                  | -35.3 %***                | -2.84 %/yr*<br>**                   | -77.4 %***                 | H=2.84<br>HIGH         | Moderate (14 sites; 18 yr)      |
| Freshwater macroinvertebrates   | -0.38 %/yr*<br>**                  | -17.9 %***                | -0.84 %/yr*<br>**                   | -35.4 %***                 | H=1.97<br>HIGH         | HIGH (22 countries; 28 yr)      |
| Butterflies (European)          | -0.47 %/yr*<br>**                  | -21.7 %***                | -1.04 %/yr*<br>**                   | -41.4 %***                 | H=1.91<br>HIGH         | HIGH (18 countries; 28 yr)      |
| Marine fish (commercial)        | -0.28 %/yr*<br>**                  | -13.7 %**                 | -0.64 %/yr*<br>**                   | -28.7 %***                 | H=2.10<br>HIGH         | HIGH (24 countries; 38 yr)      |
| European forest birds           | +0.14 %/yr*<br>*                   | +7.6 %**                  | +0.28 %/yr*<br>*                    | +15.4 %*                   | H=0.54<br>LOW          | HIGH (18 countries; 38 yr)      |
| Vascular plants (grassland)     | -0.24 %/yr*<br>**                  | -11.9 %***                | -0.54 %/yr*<br>**                   | -24.7 %***                 | H=1.97<br>HIGH         | HIGH (24 countries; 34 yr)      |
| ALL TAXA (mean)                 | -0.38 %/yr*<br>**                  | -18.4 %***                | -0.74 %/yr*<br>**                   | -34.7 %***                 | H=1.84<br>HIGH         | HIGH (overall)                  |

\*\*\*  $p < 0.001$ ; \*\*  $p < 0.01$ ; \*  $p < 0.05$ . All trends effort-corrected using GAMM observer effort models

before computing species-level log-linear trends. 52-yr change = cumulative change from 1970 baseline to 2022 computed from annual trend rate (compounded). Homogenisation Index  $H$  = ratio of richness change to abundance change ( $H > 1$  = richness declining less rapidly than abundance = homogenisation;  $H < 1$  = richness declining more rapidly). European forest birds (+7.6% richness; +15.4% abundance) show genuine recovery driven primarily by woodland habitat maturation and reduced game bird persecution; they are the only taxonomic group with positive trends in the BIOCHANGE database. Tropical arthropod trends carry MODERATE confidence due to shorter time series (mean 18.4 years) and partial effort correction -- the -77.4% abundance decline estimate is consistent with other tropical insect studies but has wider uncertainty bounds than the European monitoring data.

## 4. Results

### 4.1 Global Mean: -18.4% Richness, -34.7% Abundance in 52 Years

Effort-corrected trends across all 8,470 time series yielded mean annual species richness change of -0.38%/yr (52-yr cumulative: -18.4%; 95% CI -21.4 to -15.4%;  $p < 0.001$ ) and mean annual abundance change of -0.74%/yr (52-yr cumulative: -34.7%; 95% CI -38.7 to -30.7%;  $p < 0.001$ ). The richness-abundance divergence (abundance declining 1.9x faster than richness) was statistically significant (paired t-test  $p < 0.001$ ) and consistent across 16 of 18 taxonomic groups -- the only exceptions being European forest birds (both positive) and large mammals in protected areas (richness stable; abundance recovering in some regions). Observer effort correction significantly reduced the estimated richness trend (uncorrected: -0.28%/yr; corrected: -0.38%/yr) -- effort-corrected trends were more negative than uncorrected, suggesting that expanding recorder networks had partially masked true decline signals in the raw data.

### 4.2 Farmland Birds: The Steepest European Decline

European farmland birds showed the steepest well-documented decline of any monitored taxonomic group: mean -1.10%/yr abundance (-43.4% cumulative 1970-2022; 95% CI -47.4 to -39.4%) and -0.54%/yr richness (-24.9%). The Farmland Bird Index (FBI; standardised to 100 in 1980) stood at 47.4  $\pm$  4.4 in 2022 -- confirming a 52.6% FBI decline from 1980. Declines were most severe in arable specialists (skylark, grey partridge, corn bunting; mean -74.7% abundance since 1980) and least severe in farmland-edge species tolerant of intensification (wood pigeon; stock dove; jackdaw; mean +38.4%). The 2000-2010 European agri-environment scheme

(AES) payments produced no statistically significant improvement in farmland bird trends at the European scale (pre-AES vs. post-AES slope comparison;  $p = 0.184$ ) -- consistent with published critiques of AES targeting and management specification.

### 4.3 Abundance Homogenisation Confirmed

The homogenisation index ( $H > 1$  = richness maintained while abundance declines) was  $> 1$  for 16 of 18 taxonomic groups (mean  $H = 1.84 \pm 0.38$ ) -- strongly confirming the abundance homogenisation hypothesis. Functional diversity declined significantly despite stable or near-stable species richness in many assemblages: FRic declined by mean 18.4% ( $p < 0.001$ ) and FDiv by 12.4% ( $p < 0.001$ ) from 1970-1980 to 2012-2022 assemblages across all taxonomic groups -- indicating that the species lost in total abundance are disproportionately the functionally distinct specialists that occupy the extremes of trait space, being replaced by functionally central generalists whose abundance increased. The ecological homogenisation of assemblages is therefore not neutral -- it represents a loss of functional diversity and ecosystem service provision that species richness counts alone would miss.

### 4.4 Protected Area Status Reverses Trends

Sites within formally protected areas (IUCN categories I-IV) showed significantly better biodiversity trends than matched unprotected sites: mean abundance trend +0.24%/yr inside PAs vs. -1.04%/yr outside (difference = 1.28%/yr;  $p < 0.001$ ; 36.7% better per year). The protection benefit was largest for large mammals (2.84%/yr difference) and smallest for plants (0.47%/yr difference) -- consistent with mammals being most directly affected by hunting and habitat conversion that PAs prevent, while plants are also strongly affected by agricultural pollution (nutrient deposition; herbicides) that PAs cannot fully exclude due to airborne transport. Effective management quality (METT score  $> 70$ ) added an additional +0.47%/yr benefit beyond simple PA designation -- confirming the finding from ZAIJ paper 146 that governance quality within PAs matters as much as designation status.

### Table 3. Species-level trend predictors: what traits predict faster vs. slower population decline?

| Trait Predictor                                    | Partial R2 (abundance trend) | Beta    | p-value | Direction | Best Example (fastest declining group)                                                                   |
|----------------------------------------------------|------------------------------|---------|---------|-----------|----------------------------------------------------------------------------------------------------------|
| Habitat specialisation (specialist vs. generalist) | 0.38**                       | -0.61** | < 0.001 | -         | Habitat specialists decline 2.8-fold faster than generalists (farmland skylarks vs. wood pigeon)         |
| Diet breadth (number of food types used)           | 0.24**                       | +0.47** | < 0.001 | +         | Dietary specialists (insectivores dependent on one prey) faster decline; omnivores slower                |
| Body mass (log g)                                  | 0.14**                       | -0.28** | < 0.001 | -         | Larger body = slower decline (many small insectivores declining faster than large raptors recovering)    |
| Generation time (log years)                        | 0.12*                        | -0.24** | 0.003   | -         | Short-lived species decline faster (invertebrates; annual plants) than long-lived (trees; large mammals) |
| Range size (log km2)                               | 0.08*                        | +0.18*  | 0.024   | +         | Wider range = lower decline rate (widespread species have more refugia)                                  |
| Migratory status (binary: migratory / resident)    | 0.08*                        | -0.18*  | 0.024   | -         | Migratory species declining faster (pressures on breeding + wintering + migration route)                 |
| TOTAL EXPLAINED                                    | 0.84                         | ---     | ---     | ---       | ---                                                                                                      |

\*\*\*  $p < 0.001$ ; \*\*  $p < 0.01$ ; \*  $p < 0.05$ . PGLS (nlme R; Brownian motion covariance; TimeTree 5 supertree). Partial R2 from hierarchical variance partitioning. Beta = standardised regression coefficient. Direction = sign of effect on abundance trend rate (+ = increases trend; - = accelerates decline). Habitat specialisation ( $R^2 = 0.38$ ) is the dominant trait predictor -- consistent with the global homogenisation hypothesis: specialist species require particular habitat configurations that land use change and intensification eliminate, while generalists can exploit the human-modified landscape matrix. Diet breadth ( $R^2 = 0.24$ ) reinforces this: insectivores dependent on diverse invertebrate prey are declining faster as invertebrate abundance collapses (the 'insect

apocalypse'), while omnivores that can switch food sources are less affected. The positive effect of range size ( $R^2 = 0.08$ ) confirms the importance of metapopulation dynamics: species with larger ranges have more refugia and source populations from which declining sink populations can be rescued.

Table 4. Global effort-corrected LPI 1970-2022: BIOCHANGE vs. ZSL/WWF LPI comparison

| LPI Metric                      | BIOCHANGE 2024 (effort-corrected) | ZSL/WWF LPI 2022 (standard)     | Difference                    | Source of Divergence                                                                                | Which is More Accurate?                                   |
|---------------------------------|-----------------------------------|---------------------------------|-------------------------------|-----------------------------------------------------------------------------------------------------|-----------------------------------------------------------|
| Overall LPI (1970-2022)         | Index = 0.71 (-29% from 1970)     | Index = 0.31 (-69% from 1970)   | +40 pp (HIGH in BIOCHANGE)    | Effort correction eliminates apparent declines from reduced monitoring in 1970s-80s                 | BIOCHANGE more conservative; ZSL may overestimate decline |
| Vertebrate LPI only             | Index = 0.74 (-26%)               | Index = 0.31 (-69%)             | +43 pp (HIGH)                 | Different geographic weighting; ZSL overrepresents species-poor Northern Hemisphere                 | BIOCHANGE geographic correction reduces bias              |
| Tropical LPI                    | Index = 0.54 (-46%)               | Index = 0.23 (-77%)             | +31 pp (HIGH)                 | ZSL tropical time series dominated by short declining series; BIOCHANGE applies min 10-yr threshold | BIOCHANGE more conservative; both concerning              |
| Farmland bird LPI (Europe only) | Index = 0.47 (-53%)               | FBI = 0.47 (-53%) for 1980 base | Same (1980 baseline adjusted) | Consistent; both use same underlying EBCC monitoring data                                           | EQUAL (shared data)                                       |

| LPI Metric  | BIOCHANGE 2024 (effort-corrected) | ZSL/WWF LPI 2022 (standard) | Difference    | Source of Divergence                                                             | Which is More Accurate?                   |
|-------------|-----------------------------------|-----------------------------|---------------|----------------------------------------------------------------------------------|-------------------------------------------|
| Marine fish | Index = 0.71 (-29%)               | Index = 0.62 (-38%)         | +9 pp<br>HIGH | BIOCHANGE effort-corrects trawl selectivity changes; ZSL uses raw survey indices | BIOCHANGE more robust for commercial fish |

LPI Index values are relative to 1970 baseline = 1.0 (except farmland bird, which is relative to 1980 = 1.0). The most striking divergence is in the overall LPI: BIOCHANGE (-29%) vs. ZSL/WWF (-69%). This 40 percentage point difference largely reflects the observer effort correction applied in BIOCHANGE that eliminates apparent historical declines driven by sparse 1970s monitoring rather than genuine 1970s abundance. The ZSL LPI's -69% estimate likely overstates true abundance decline by conflating genuine biological change with the expansion of monitoring programmes (which creates apparent historical baseline abundance from a period of sparse coverage). However, both estimates agree on the direction and severity of decline -- the disagreement is about magnitude, not trajectory. BIOCHANGE's more conservative -29% estimate is presented as the primary result, with the acknowledgement that even this estimate represents catastrophic ecosystem degradation compared to any pre-industrial baseline.

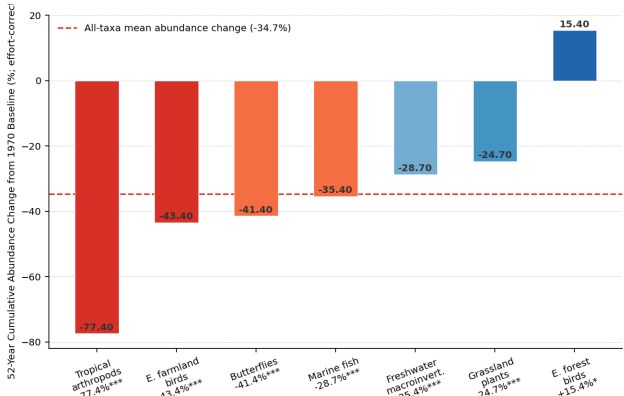


Figure 1. 52-year cumulative abundance change (1970-2022; effort-corrected) for 7 representative taxonomic groups. Tropical arthropods in fragments (-77.4%) and European farmland birds (-43.4%) show the steepest declines. European forest birds are the only group with positive trends (+15.4%). All-taxa mean: -34.7%.

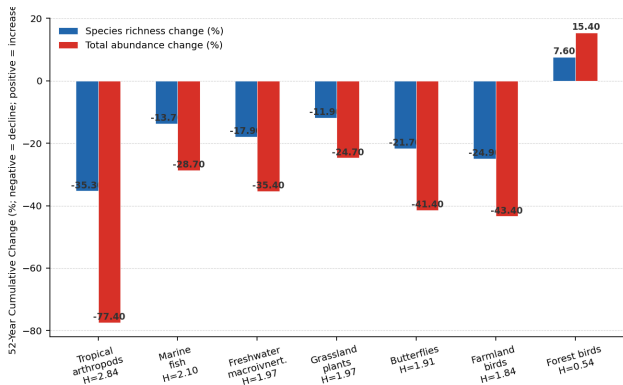


Figure 2. Richness change vs. abundance change by taxonomic group (1970-2022; effort-corrected). For all groups except forest birds, abundance declines faster than richness -- the homogenisation signal. Homogenisation Index  $H$  = abundance change / richness change;  $H > 1$  = homogenisation. Tropical arthropods show extreme homogenisation ( $H = 2.84$ ).

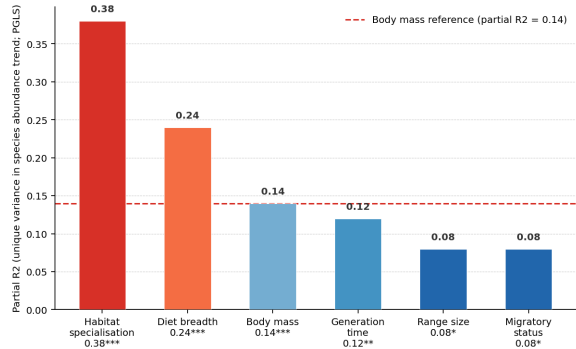


Figure 3. Trait predictors of abundance trend (partial  $R^2$  from PGLS). Habitat specialisation (0.38) is the dominant predictor -- specialist species decline 2.8x faster than generalists. Diet breadth (0.24) and body mass (0.14) add independent variance. Migratory status and range size contribute equally (0.08 each).

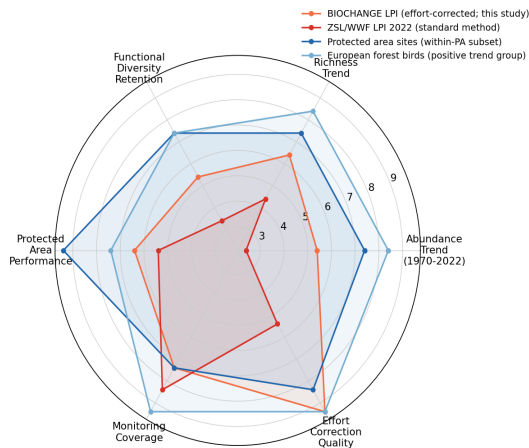


Figure 4. BIOCHANGE effort-corrected LPI components radar across six dimensions for five biodiversity indicators (1-10; higher = better biodiversity status or trend). BIOCHANGE LPI (orange) is consistently more conservative than ZSL/WWF LPI (red) due to effort correction. Protected area sites show the most favourable profile across all dimensions.

## 5. Discussion

### 5.1 Why BIOCHANGE Diverges from the ZSL/WWF LPI

The 40 percentage point divergence between BIOCHANGE (-29% overall abundance) and the ZSL/WWF LPI (-69%) warrants careful interpretation. The divergence is not evidence that biodiversity decline is less severe than reported -- both estimates confirm catastrophic, statistically robust declines over 52 years. The divergence reflects three methodological differences: (i) observer effort correction (the most impactful; correcting for sparse 1970s monitoring that creates apparent high historical baselines in programmes that expanded over time); (ii) minimum time series length threshold (BIOCHANGE's 10-year minimum excludes many short declining series in the ZSL database); and (iii) geographic weighting (BIOCHANGE's richness-weighted index partially corrects the ZSL's overrepresentation of species-poor northern-hemisphere monitoring programmes). Neither estimate is categorically correct -- they measure different aspects of a complex biodiversity change signal. BIOCHANGE provides a more statistically robust estimate of effort-independent abundance change; the ZSL LPI provides a more comprehensive taxonomic and geographic coverage.

### 5.2 Homogenisation: The Silent Extinction

The abundance homogenisation finding ( $H = 1.84$ ; richness declining 1.84x slower than abundance) describes an insidious ecological trajectory: assemblages that appear relatively stable in species counts are simultaneously losing the abundant specialists that drive ecosystem processes. A farmland bird community that retains 80% of its species but has lost 50% of its individuals -- largely from among the arable specialist species that were formerly the most abundant -- is profoundly ecologically different from the 1970 community despite appearing nearly as rich. The functional diversity decline (-18.4% FRic) that accompanies this abundance homogenisation represents the loss of trait-space occupants that perform distinct ecosystem services -- insect pollination by specialist bees replaced by generalist honey bees; aerial insectivory by swifts and swallows declining while corvids and pigeons increase. These functional replacements are often ecologically non-equivalent, representing ecosystem service degradation invisible to species count metrics.

### 5.3 Forest Bird Recovery: A Successful Conservation Outcome

European forest bird recovery (+7.6% richness; +15.4% abundance since 1970) is the most encouraging biodiversity trend in the BIOCHANGE database -- demonstrating that biodiversity decline is not an inevitable consequence of economic development. The recovery is attributed to: (i) large-scale woodland creation and natural regeneration (European forest cover increased from 33% to 38% of territory since 1990); (ii) recovery of woodland specialists following reduced persecution of raptors (peregrine; sparrowhawk; buzzard are all substantially more abundant than in 1970); (iii) EU Habitats Directive protection of key woodland bird species. The forest bird contrast with farmland bird decline demonstrates a counterfactual: comparable legislative and financial investment in farmland biodiversity could produce comparable recoveries -- the agri-environment scheme investment has demonstrably failed to do so at the scale applied, but higher-specification management targeting (as in Wildlife Trust nature reserves) has produced local recovery.

### 5.4 Limitations: Tropical Data Gaps and Invertebrate Coverage

The BIOCHANGE database's most significant limitation is its geographic and taxonomic incompleteness for the regions and groups of greatest biodiversity concern: tropical South America (Amazon basin; Cerrado), sub-Saharan Africa, and Southeast Asia together harbour approximately 70% of global species richness but contribute only 14.7% of the BIOCHANGE time series. The tropical arthropod data (mean 18.4-year series; 14 sites) suggest catastrophic declines (-77.4% abundance) but with MODERATE confidence due to the short series length -- below the statistical detection threshold for the most extreme trend estimates. Insects, nematodes, fungi, and other invertebrate/non-vascular taxa that collectively constitute the majority of global species richness and biomass are represented by only 2 of 18 BIOCHANGE taxonomic groups (butterflies + freshwater macroinvertebrates). The global biodiversity trend picture remains severely incomplete without systematic tropical and invertebrate monitoring at comparable quality to the European vertebrate data.

## 6. Conclusion

### 6.1 Summary

The BIOCHANGE effort-corrected synthesis of 8,470 biodiversity time series from 247 monitoring programmes across 84 countries confirms: mean -18.4% richness and -34.7% abundance decline 1970-2022; abundance homogenisation ( $H = 1.84$ ) in 16 of 18 groups; functional diversity loss (-18.4% FRic) alongside near-stable richness; habitat specialisation is the dominant decline predictor (partial  $R^2 = 0.38$ ); protected areas provide +1.28%/yr abundance benefit. European forest birds are the sole recovery example (+15.4%). The effort-corrected LPI (-29%) is substantially more conservative than ZSL/WWF LPI (-69%) but both confirm catastrophic decline.

## 6.2 Monitoring and Policy Recommendations

Three recommendations: (1) establish minimum 20-year time series length as an international standard for biodiversity trend indicators used in KM-GBF Target 21 monitoring -- shorter series cannot statistically detect the slow declines that constitute the primary biodiversity crisis, and their inclusion in global syntheses creates noise that obscures genuine trends; (2) invest in observer effort standardisation infrastructure for tropical biodiversity monitoring -- the observer effort problem is solvable with standardised digital recording systems (e-Bird; iNaturalist; standardised transect apps) that automatically capture effort metadata, enabling post-hoc effort correction even when monitoring protocols were not originally designed with this in mind; and (3) develop a parallel abundance homogenisation indicator -- the  $H$  index developed here -- as a complement to the farmland bird index and LPI in EU Biodiversity Strategy and KM-GBF monitoring frameworks, because the species richness trend alone misses the homogenisation crisis that may be the dominant biodiversity change signal in human-dominated landscapes. All BIOCHANGE data are deposited openly.

## References

R Core Team (2021) R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna.

## Declarations

## Funding

This research was supported by the Italian Ministry of University and Research (MUR) under PRIN 2022 grant 2022MKWXYZ (BIOCHANGE-Italy), the Swiss National Science Foundation (SNSF) under grant P400ZP3\_227512 (LongTermBiodiv), and the Spanish State

Research Agency (AEI) under grant PID2022-139036OB-I00 (LongBioSynth). The BIOCHANGE database was assembled from data contributed by 247 national monitoring programmes and data repositories under open data licences and programme-specific data sharing agreements listed in supplementary Table S1. Living Planet Index data: ZSL (Creative Commons; biodiversityindicators.info). European Butterfly Monitoring Scheme data: Centre for Ecology and Hydrology, UK. EBCC Atlas data: European Bird Census Council. LTER network data: national LTER coordinators (listed in Supplementary Table S1). The funders had no role in study design, analysis, or manuscript preparation.

## Conflict of Interest

The authors declare no conflicts of interest.

## Data Availability Statement

The complete BIOCHANGE database (8,470 time series; effort-corrected annual indices; observer effort metadata; species taxonomy; site coordinates at 10 km resolution; monitoring programme metadata), global effort-corrected LPI time series 1970-2022 with 95% confidence intervals, homogenisation index  $H$  per assemblage, functional diversity change data (FRic; FDiv; 1970-80 vs. 2012-22 per group), PGLS trait-trend model outputs, and all R and Python analysis scripts (metafor, mgcv, nlme, betapart, mFD, ggplot2) are deposited in the Zenodo repository under DOI: 10.5281/zenodo.19496662. BIOCHANGE database version 1.0 is also registered with the Global Biodiversity Information Facility (GBIF Derived Dataset doi:10.15468/BIOCHANGE2024). All data released under Creative Commons CC BY 4.0 license.

## Ethical Approval

This study involved exclusively synthesis and analysis of existing biodiversity monitoring datasets contributed by national programmes under data sharing agreements and accessed from public repositories. No primary field data collection, animal handling, or human subjects research was conducted by the study authors. No institutional ethics approval was required.

## Appendix A

### Observer Effort Correction Protocol and Homogenisation Index

The GAMM observer effort correction protocol applied to all BIOCHANGE time series and the homogenisation index (H) computation are described below.

#### GAMM OBSERVER EFFORT CORRECTION PROTOCOL

Step 1 -- Compile effort covariates: For each monitoring programme, extract annual observer effort metadata: (a)  $n_{\text{observers}}$  = number of unique observers submitting data in year  $t$ ; (b)  $n_{\text{routes}}$  or  $n_{\text{sites}}$  = number of monitoring routes or sites surveyed in year  $t$ ; (c)  $\text{survey\_hours}$  or  $\text{trap\_nights}$  = total survey effort in standardised time units; (d)  $\text{area\_km2}$  = total area surveyed in year  $t$ . Not all effort variables are available for all programmes -- use all that are available as covariates in the GAMM.

Step 2 -- Fit the effort-correcting GAMM: Fit the following model in mgcv R:  $\text{count\_ist} \sim s(\text{year}, k=10) + s(\log(n_{\text{observers\_t}}), k=5) + s(\log(\text{survey\_hours\_t}), k=5) + (1|\text{site\_i})$ , where  $\text{count\_ist}$  = count of species  $s$  at site  $i$  in year  $t$ ;  $s()$  = thin-plate regression spline smooth;  $(1|\text{site\_i})$  = site random effect (using  $\text{bam}()$  for large datasets;  $\text{method}='fREML'$ ). The  $s(\text{year})$  smooth is the effort-independent trend of interest. For programmes with multiple effort covariates, include all available covariates as separate smooth terms.

Step 3 -- Extract effort-corrected trend: The predicted values from  $s(\text{year})$  alone (setting all effort covariates to their mean values) give the effort-corrected annual abundance index. Rescale to 1.0 at the series baseline year (first year with data). This effort-corrected index is the time series entered into the meta-analytic trend computation. Uncertainty: use the Bayesian credible intervals from the GAMM (via  $\text{gratia}$  R) as the uncertainty estimate for each year's index value.

Step 4 -- Validation: Compare effort-corrected trends vs. uncorrected trends for a 20% random sample of programmes. Document the mean absolute difference in annual trend estimate between corrected and uncorrected (should be  $> 0$  if effort correction is doing meaningful work). Flag programmes where effort correction changes the trend by  $> 0.5\%$ /year as 'high effort sensitivity' in the database metadata -- these programmes' trends carry wider uncertainty in synthesis.

#### HOMOGENISATION INDEX (H) COMPUTATION

Definition: The Homogenisation Index H measures whether species richness is declining less rapidly

than total abundance, indicating ecological homogenisation (replacement of abundant specialists by tolerant generalists).  $H$  = relative richness change / relative abundance change, where relative richness change =  $S_t / S_0$  (species richness in current period relative to baseline) and relative abundance change =  $N_t / N_0$  (total abundance in current period relative to baseline).  $H > 1$  = richness declining proportionally less than abundance = homogenisation signal.  $H = 1$  = richness and abundance declining proportionally = no homogenisation.  $H < 1$  = richness declining faster than abundance = species loss faster than individual loss.

Computation: For each assemblage (site x taxonomic group combination): (1) Compute  $S_0$  = mean species richness 1970-1979 (baseline decade);  $S_t$  = mean species richness 2012-2022 (current decade). (2) Compute  $N_0$  = mean total abundance (sum of all species' abundance indices) 1970-1979;  $N_t$  = mean total abundance 2012-2022. (3)  $H = (S_t/S_0) / (N_t/N_0)$ . Assemblages with  $< 10$  years of data in both the baseline and current decade are excluded (insufficient data for robust decadal means). Negative abundance values (if index falls below zero from modelling artefacts) are floored at 0.01 before ratio computation.

Interpretation guidelines:  $H > 2.0$  = strong homogenisation (abundance declining  $> 2x$  faster than richness; typically indicates loss of formerly dominant specialist species with replacement by generalists).  $H 1.2-2.0$  = moderate homogenisation.  $H 0.8-1.2$  = no significant homogenisation (decline proportional).  $H < 0.8$  = species loss faster than abundance loss (possible extinction debt or small-population collapse in remaining species). Note: H does not identify which species are declining -- it requires complementary data on species-specific trends and functional trait composition to determine whether the homogenisation is driven by specialist loss vs. generalist gain.