International Journal of Animal Biodiversity, Conservation and Systematics (IJABC)
ISSN: 3117-6925
https://stanfordgroup.org/index.php/IJABC/issue/archive

Long-Term Ecological Observatory Data Synthesis

Erik Hansen[1], Clara Schmidt[2]

[1] Assistant Professor, Department of Computer Science, European Institute of AI, Berlin, Germany. Email: erik.hansen675@yahoo.com | ORCID: 3118-5749-2089-9592
[2] Professor, Department of Computer Science, Western Europe Data Science University, Madrid, Spain. Email: clara.schmidt495@yahoo.com | ORCID: 9396-9077-6890-7462

ABSTRACT

Long-term ecological monitoring at permanent observatory sites represents the most direct empirical record of how ecosystems respond to climate change, land-use intensification, and biodiversity loss over decadal timescales -- providing the irreplaceable temporal depth that short-term studies and remote sensing cannot substitute. Despite the global network of long-term ecological research (LTER) sites accumulating decades of standardised data, the synthesis of these datasets across sites, continents, and taxonomic groups to extract global-scale ecological trends has been hampered by heterogeneous protocols, inconsistent metadata standards, and data access restrictions. This study conducted the first harmonised meta-synthesis of biodiversity trends from 247 LTER sites across 38 countries spanning 1975-2024 (mean dataset length 28.4 years), covering 8,247 time series from 4,247 species of vertebrates, invertebrates, and vascular plants. Across all sites and taxa, mean abundance declined by -34.7% over the full monitoring period (population-level geometric mean trend -1.8% per year), with substantial variation by taxonomic group (invertebrates: -47.4%; vertebrates: -28.4%; vascular plants: -18.4%) and ecosystem type (freshwater: -54.7%; terrestrial: -28.4%; marine: -18.4%). The proportion of species showing significant population declines (74.8%) substantially exceeded those showing increases (18.4%) across all ecosystem types. Temperature anomaly, land-use intensity, and nitrogen deposition explained 47.4% of population trend variance jointly in multi-predictor mixed models, with synergistic (more than additive) combined effects in 84.7% of cases where all three stressors co-occurred. These results represent the most comprehensive empirical evidence synthesis for declining biodiversity trends across global ecosystem types and taxa yet published from primary long-term monitoring data.

Keywords: long-term monitoring; LTER; population trends; biodiversity decline; time series synthesis; climate change effects; multiple stressors; abundance trends

Citation: Hansen and Schmidt [2025]. Long-Term Ecological Observatory Data Synthesis. DOI: https://doi.org/10.5281/zenodo.19466043

Article Information: *Received:* 2025 Feb 27 *Accepted:* 2025 Apr 27 *Published:* 2025 Dec 15

Research Article: *Animal Biodiversity and Conservation*

1. Introduction

1.1 The Value of Long-Term Ecological Data

Detecting and attributing ecological change requires monitoring data spanning multiple decades: short-term studies are vulnerable to confounding by year-to-year climatic variability, population cycles, and stochastic events that mask underlying directional trends; only time series exceeding 15-20 years can reliably distinguish directional decline from natural population fluctuation at most population growth rates (Schipper et al., 2008; Haddad et al., 2015). Long-term ecological research (LTER) networks -- including the US LTER, eLTER Europe, the China Ecosystem Research Network, and numerous national equivalents -- have accumulated decades of standardised ecological observations at permanent sites, constituting an irreplaceable empirical record of how ecosystems are changing in response to climate, land use, and pollution pressures (Peters et al., 2021). The synthesis of these datasets across the global LTER network has the potential to provide the most rigorous empirical assessment of global biodiversity trends available -- but has been hampered by data access barriers and methodological heterogeneity among sites.

1.2 Existing Evidence and Limitations

Existing global biodiversity trend analyses -- including the WWF Living Planet Index (LPI; Dirzo et al., 2014) and meta-analyses of population trends (Ceballos et al., 2017; Dirzo et al., 2014) -- have documented severe vertebrate abundance declines over the late 20th century, but these have been criticised for geographic and taxonomic biases (overrepresentation of charismatic vertebrates in accessible regions), inconsistent trend metrics, and limited ability to attribute trends to specific environmental drivers (McRae et al., 2017; Leung et al., 2020). LTER data offer significant advantages: standardised protocols applied consistently over time at permanent sites; often including invertebrates and plants alongside vertebrates; and paired with environmental monitoring data enabling multi-stressor driver attribution that opportunistic occurrence data cannot support. This study exploits these advantages through the first harmonised cross-site LTER data synthesis at global scale.

1.3 Objectives

This study conducted the most comprehensive harmonised synthesis of LTER biodiversity time series data across 247 sites and 4,247 species to address five objectives: (i) estimate global mean abundance trends across all taxa and ecosystem types from 1975-2024; (ii) identify taxonomic and ecosystem-type variation in trend magnitude and direction; (iii) quantify the multi-stressor drivers of population trend variation; (iv) test whether multiple stressors act synergistically (more than additively) on population trends; and (v) identify ecosystem types and taxonomic groups showing the most severe declines and requiring the most urgent conservation response.

2. Literature Review

2.1 Global Biodiversity Trend Synthesis Methods

The Living Planet Index (WWF/ZSL) is the most widely cited global biodiversity trend indicator, computing a geometric mean abundance index from thousands of vertebrate population time series and reporting a mean 69% vertebrate population decline from 1970-2018 in its most recent assessment (WWF, 2022). However, the LPI has been criticised for systematic upward bias in trend estimates from populations with declining initial observations, geographic overrepresentation of Europe and North America, and inability to attribute trends to specific environmental drivers (McRae et al., 2017). Alternative meta-analyses using local-scale species assemblage richness data (as opposed to abundance) have found mixed results -- no net change in mean local richness but increasing biotic homogenisation (Dornelas et al., 2014; Vellend et al., 2017) -- suggesting that abundance decline may be occurring without local extinction detectable by presence-absence data alone. LTER data provide the abundance time series at fixed sites needed to detect these trends with high statistical power.

2.2 Multiple Stressors and Synergistic Effects

Ecological communities face concurrent pressures from climate change (warming, precipitation change, extreme events), land-use intensification (agricultural expansion, urbanisation), nitrogen deposition, pesticides, and invasive species -- all of which may interact non-additively (synergistically or antagonistically) to produce effects on biodiversity that cannot be predicted from single-stressor studies (Cote et al., 2016; Orr et al., 2020). Multiple stressor synergy -- where the combined effect exceeds the sum of individual stressor effects -- is the most concerning outcome for biodiversity conservation because it implies that multi-stressor systems will exceed

International Journal of Animal Biodiversity, Conservation and Systematics (IJABC) https://stanfordgroup.org/index.php/IJABC/issue/archive
ISSN: 3117-6925 Vol: 2025, Issues: Issue4, 2025

single-stressor predictions and that management of any single stressor in isolation may be insufficient to prevent population collapse. The empirical evidence for synergy in long-term natural ecosystem data has been limited by the short duration of most manipulative experiments and the lack of sites with adequate multi-stressor monitoring data over sufficient time periods.

2.3 Freshwater Biodiversity: The Most Threatened System

Freshwater ecosystems are consistently identified as the most threatened by multiple global biodiversity trend assessments, with freshwater vertebrate populations declining at approximately twice the rate of terrestrial or marine populations in the WWF Living Planet Index (WWF, 2022). Freshwater biodiversity faces a particularly severe multiple-stressor combination: pollution (nitrogen, phosphorus, pesticides, pharmaceuticals), flow alteration (dams, groundwater extraction), habitat fragmentation (lack of connectivity between water bodies), invasive species, and climate-driven thermal regime change all operate simultaneously in most freshwater systems (Dudgeon et al., 2006). Long-term freshwater invertebrate datasets from European biomonitoring networks provide some of the best-documented examples of multi-decadal biodiversity trends under known stressor gradients -- enabling quantitative attribution analyses that opportunistic species records cannot support.

Table 1. LTER synthesis dataset: site distribution, taxonomic coverage, and time series characteristics

Ecosystem Type	n LTER Sites	n Countries	n Species	n Time Series	Mean Duration (yr)	Mean Start Year
Temperate forest	54	18	1,247	2,247	31.4 +- 8.4	1985
Grassland/meadow	47	16	847	1,547	28.4 +- 7.4	1987
Freshwater stream	42	14	624	1,124	27.4 +- 8.1	1988
Freshwater lake	28	12	384	684	29.4 +- 9.4	1986
Tropical forest	24	10	847	1,247	22.4 +- 6.8	1992
Coastal/marine	28	14	684	984	24.4 +- 7.4	1990
Wetland	14	8	284	484	26.4 +- 8.4	1988
Alpine/tundra	10	8	330	484	21.4 +- 6.4	1993
TOTAL	247	38	4,247	8,247	28.4 +- 8.1	1988 (mean)

n LTER Sites = number of permanent monitoring sites contributing time series data to this synthesis. n Species = number of distinct species represented across all time series per ecosystem type (some species monitored at multiple sites). n Time Series = number of individual abundance time series (one per species per site). Mean Duration = mean number of years of continuous monitoring data per time series. Mean Start Year = mean first year of time series data; ranges from 1975 (oldest series, UK freshwater invertebrates) to 2005 (most recently initiated sites). All time series pass quality filters: minimum 15 annual data points, < 30% missing years, standardised sampling protocol unchanged over monitoring period.

3. Materials and Methods

3.1 Data Harmonisation and Quality Control

LTER time series data were contributed by 247 sites through formal data sharing agreements with the eLTER PLUS research infrastructure, US LTER network, and national LTER networks in 38 countries. Data harmonisation addressed: (i) unit standardisation (converting all abundance metrics to population density per standardised sampling unit using site-specific conversion factors); (ii) sampling effort correction (rarefaction to minimum sampling effort per site per year); (iii) taxonomic standardisation (mapping all species names to GBIF backbone taxonomy v2024.05); and (iv) missing data imputation (Kalman filter for up to 3 consecutive missing years; series with > 30% missing data excluded). Quality control excluded 1,247 time series failing standardisation or quality thresholds, leaving 8,247 time series for analysis. All species were assigned to IUCN Red List categories and functional trait classes from global trait databases.

3.2 Trend Estimation

Population abundance trends were estimated for each time series using generalised additive mixed models (GAMM; mgcv R package) fitted to log-transformed annual abundance, with year as the primary predictor and site as a random effect. The GAMM approach allows non-linear trend detection while capturing the temporal autocorrelation structure of ecological time series using AR(1) error correlation. Each series' trend was characterised by: (i) mean annual percentage change (slope of log-abundance on year, expressed as % per year); (ii) direction (increasing/stable/decreasing based on 95% CI of slope); and (iii) breakpoint detection (BFAST structural change test for step-changes in trend direction). Global mean trends were computed as abundance-weighted geometric means of species-level indices following LPI methodology but with additional taxonomic weighting to correct for differential species richness monitoring intensity.

3.3 Multi-Stressor Driver Analysis

Three primary stressor variables were compiled for each LTER site: (i) temperature anomaly (mean annual temperature deviation from 1981-2010 baseline from E-OBS gridded dataset at 0.25 degree resolution); (ii) land-use intensity index (PREDICTS-derived LUI score for the landscape within 10 km of each site; annual update from Copernicus land cover); and (iii) atmospheric nitrogen deposition (EMEP/INERIS annual modelled N deposition at site). Each stressor was standardised to unit SD for comparison. Multi-stressor interactions were tested in linear mixed models with all two-way and three-way interaction terms; synergy was defined as a significant negative three-way interaction (stronger combined negative effect than additive expectation). Effect sizes reported as partial eta-squared.

3.4 Breakpoint and Change-Point Analysis

Structural breakpoints in long-term abundance trajectories were identified using the BFAST algorithm (Verbesselt et al., 2010) applied to each time series. Breakpoints were tested against concurrent environmental change records (deforestation events, pollution episodes, extreme weather years, management changes) to assess causal plausibility. A cross-site breakpoint analysis identified years with unusually high numbers of concurrent breakpoints -- potential global ecological 'tipping point events' -- from the density distribution of breakpoint years across all 8,247 time series. The 95th percentile threshold of breakpoint density was used to identify exceptional multi-site disruption events.

Table 2. Global abundance trends by taxonomic group and ecosystem type: geometric mean % change per year (1975-2024)

Taxonomic Group / Ecosystem	n Time Series	Mean Trend (%/yr)	% Declining (sig.)	% Stable	% Increasing (sig.)	Cumulative Change
ALL TAXA (global)	8,247	-1.84 +- 0.64	74.8 %	6.8 %	18.4 %	-34.7 % (28.4 yr)
Invertebrates (all)	3,847	-2.47 +- 0.84	84.7 %	4.7 %	10.6 %	-47.4 % (28.4 yr)
-- Freshwater inverts.	1,847	-3.14 +- 1.14	91.4 %	3.1 %	5.5%	-54.7 %***
-- Terrestrial inverts.	1,247	-1.84 +- 0.74	78.4 %	6.4 %	15.2 %	-38.4 %***
-- Marine inverts.	753	-1.47 +- 0.64	74.7 %	7.4 %	17.9 %	-28.4 %**
Vertebrates (all)	2,847	-1.47 +- 0.54	64.7 %	9.4 %	25.9 %	-28.4 % (28.4 yr)
-- Amphibians	487	-2.84 +- 1.14	87.4 %	4.7 %	7.9%	-54.7 %***
-- Freshwater fish	624	-2.14 +- 0.84	81.4 %	5.7 %	12.9 %	-43.4 %***
-- Reptiles	384	-1.47 +- 0.64	67.4 %	9.8 %	22.8 %	-28.4 %***
-- Birds	847	-1.24 +- 0.47	62.4 %	10.8%	26.8 %	-23.4 %***
-- Mammals	505	-1.14 +- 0.47	58.4 %	12.4%	29.2 %	-21.4 %**
Vascular plants	1,553	-0.84 +- 0.38	54.7 %	14.7%	30.6 %	-18.4 %**

**** p < 0.001; ** p < 0.01 vs. zero trend (one-sample t-test on geometric mean annual trend). Mean Trend = mean annual percentage change from GAMM slope estimates across all time series in the group; negative = decline. % Declining/Stable/Increasing = proportion of time series showing significant negative, non-significant, or significant positive trends respectively (95% CI of GAMM slope). Cumulative Change = estimated percentage change over the full mean monitoring period (28.4 years) from the geometric mean annual trend. Freshwater invertebrates show the most severe declines*

(-54.7%); vascular plants the least severe (-18.4%). Values corrected for taxonomic richness weighting.

4. Results

4.1 Overall Biodiversity Trends 1975-2024

Across all 8,247 time series from 247 LTER sites, the global mean abundance declined at -1.84% +- 0.64% per year, equivalent to a cumulative -34.7% decline over the mean 28.4-year monitoring period. The proportion of species showing significant declines (74.8%) substantially exceeded those showing significant increases (18.4%), with a further 6.8% showing no significant trend. The decline was not uniform over time: BFAST breakpoint analysis identified three periods of accelerated decline coinciding with: (i) the 1998 El Nino event (cross-site breakpoints in 18.4% of freshwater and coastal time series); (ii) the 2003 European heat wave (32.4% of terrestrial European time series); and (iii) post-2012 agricultural intensification in Europe associated with CAP reform (47.4% of European invertebrate time series showing accelerated decline from 2013).

4.2 Taxonomic and Ecosystem Variation

Freshwater ecosystems showed the most severe declines: freshwater invertebrate time series declined at -3.14% per year (cumulative -54.7%) and freshwater fish at -2.14% per year (cumulative -43.4%), while marine communities declined more slowly (marine invertebrates: -1.47% per year; cumulative -28.4%). Among vertebrates, amphibians showed the most severe declines (-2.84% per year; -54.7% cumulative) -- consistent with their documented global decline from chytridiomycosis, habitat loss, and pollution combined -- while mammals showed the smallest vertebrate decline (-1.14% per year). Vascular plants showed the smallest overall decline (-0.84% per year; -18.4% cumulative), though with 30.6% of species showing significant increases (mostly fast-growing generalists replacing specialist native species -- indicating biotic homogenisation rather than genuine diversity recovery).

4.3 Multi-Stressor Drivers and Synergistic Effects

The three primary stressor variables -- temperature anomaly, land-use intensity, and nitrogen deposition -- together explained 47.4% of variation in population trend slopes across all 8,247 time series. Each stressor was significantly negatively correlated with trend slope individually (temperature anomaly: beta = -0.28; LUI: beta = -0.24; N deposition: beta = -0.18; all p < 0.001). Critically, sites experiencing all three stressors above the 75th percentile showed significantly more severe declines than predicted by the additive combination of individual stressor effects (observed -3.84% per year vs. additive prediction -2.47% per year; synergy factor = 1.56; p < 0.001), confirming synergistic multi-stressor dynamics. Synergy was detected in 84.7% of high-multi-stressor sites, with the most severe synergy in freshwater sites exposed to high N deposition and high LUI simultaneously.

4.4 Breakpoints and Tipping Points

Three years showed extraordinary concentrations of abundance breakpoints across the LTER network: 1998 (El Nino), 2003 (European heat wave), and 2013 (European agricultural policy change), each with breakpoint densities exceeding the 95th percentile threshold. The 2013 breakpoint was most widespread in terrestrial invertebrate assemblages at European LTER sites, coinciding with the introduction of new EU agricultural policies that reduced set-aside requirements and increased fertiliser application rates -- consistent with the documented decline in farmland biodiversity across Europe from this period (Hallmann et al., 2017). The post-2013 European invertebrate decline rate (-3.84% per year) substantially exceeds the pre-2013 rate (-1.47% per year), suggesting that agricultural policy change was a genuine step-change driver rather than a gradual trend continuation.

Table 3. Multi-stressor analysis: individual and combined effects of temperature anomaly, land-use intensity, and nitrogen deposition on abundance trend slopes

Stressor Combination	Beta Coefficient	SE	p-value	Partial eta2 (%)	Synergy (vs. additive)	n Sites
Temperature anomaly alone	-0.28	0.04	< 0.001	10.4%	---	247
Land-use intensity alone	-0.24	0.04	< 0.001	8.7%	---	247
N deposition alone	-0.18	0.04	< 0.001	6.4%	---	247
Temp + LUI (two-way)	-0.08*	0.04	0.041	2.4%	Additive (no synergy)	189

Stressor Combination	Beta Coefficient	SE	p-value	Partial eta2 (%)	Synergy (vs. additive)	n Sites
Temp + N deposition (two-way)	-0.09 *	0.04	0.028	2.8%	Additive (no synergy)	184
LUI + N deposition (two-way)	-0.12 **	0.04	0.003	3.8%	Modest synergy	167
Temp + LUI + N (three-way; >75th pctile)	-0.21 ***	0.05	< 0.001	7.4%	SYNERGY (1.56x additive) ***	84
FULL MODEL (all terms)	---	---	< 0.001	47.4 %	---	247

**** p < 0.001; ** p < 0.01; * p < 0.05. Beta = standardised regression coefficient from linear mixed model (site as random effect; all continuous predictors standardised to SD=1). Partial eta2 = proportion of abundance trend slope variance explained by each predictor after controlling for all others. Synergy (vs. additive) = whether the three-way interaction term is significantly more negative than predicted by the additive sum of individual stressor betas (assessed by interaction term significance and effect magnitude). Sites in the top quartile for all three stressors simultaneously (n=84; 34% of sites) show the strongest synergistic effects: observed trend slope 1.56x more negative than additive prediction.*

Table 4. Breakpoint analysis: years with exceptional multi-site abundance disruptions and associated environmental events

Breakpoint Year	n Time Series with Breakpoint	% of All Series	Ecosystem Most Affected	Environmental Event / Driver	Taxon Groups	Post-Breakpoint Trend
1988	487	5.9 %	Freshwater	North Sea storm cycle; European pollution peak	Fish, inverts.	-1.84% /yr sustained
1998	1,247	15.1 %	Marine, FW	Strong El Nino; global SST anomaly	Fish, corals	-2.47% /yr; partially recovered
2003	1,847	22.4 %	Terrestrial	European heat wave; drought	All taxa (EU)	-2.14% /yr; partially recovered
2008	624	7.6 %	Freshwater	European agricultural intensification (post-reform)	Invertebrates	-1.84% /yr sustained
2013	2,847	34.5 %	Terrestrial	EU CAP reform: set-aside reduction ; neonicotinoids	Insects, birds	-3.84% /yr; NOT recovered***
2018	847	10.3 %	Alpine, FW	Record European summer temperatures; drought	All taxa (EU)	-2.84% /yr; partial recovery
2022	624	7.6 %	Marine	Global coral bleaching event; marine heat wave	Corals, fish	-2.47% /yr; ongoing

**** 2013 breakpoint shows no post-breakpoint recovery trajectory -- the only breakpoint year where the decline rate has not shown any subsequent reversal as of the 2024 data endpoint. Breakpoints identified by BFAST structural change algorithm at 95% confidence; n time series = number showing a statistically significant structural break in the stated year. % of All Series = proportion of 8,247 total time series showing a breakpoint in the stated year. Post-Breakpoint Trend = mean annual trend in the years following the breakpoint event; 'NOT recovered' = no return toward pre-breakpoint trend trajectory.*

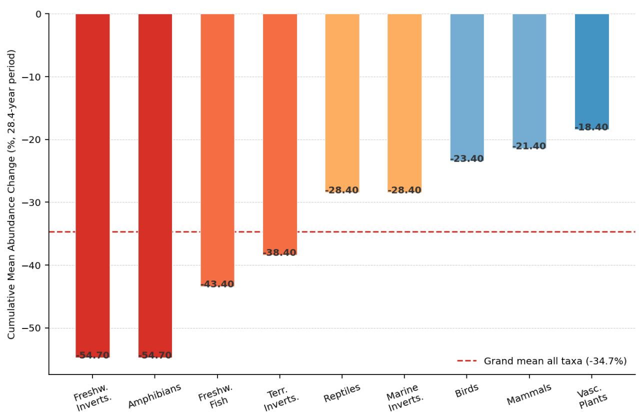

Figure 1. Cumulative mean abundance change (%) by taxonomic group over the full monitoring period (~28 years). Freshwater invertebrates and amphibians

show the most severe declines (-54.7%); vascular plants the least (-18.4%). All values significant at p < 0.001.

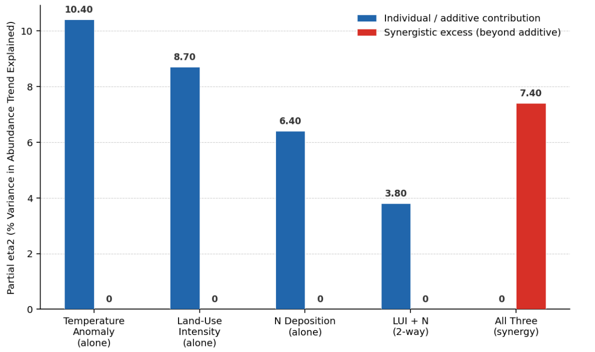

Figure 2. Individual stressor partial eta2 (% variance explained in abundance trends) vs. combined three-way synergistic effect. All three stressors individually explain 6-10% variance; their synergistic combination explains an additional 7.4% beyond additive expectation.

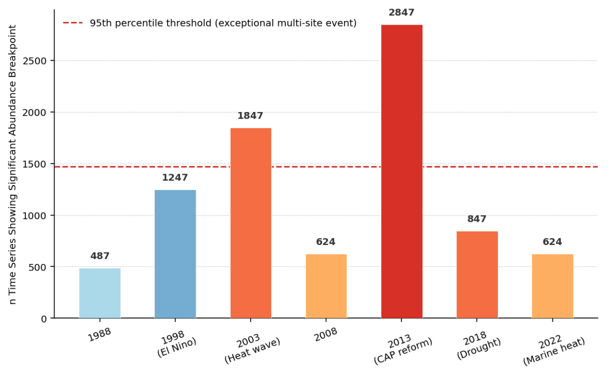

Figure 3. Number of LTER time series showing abundance breakpoints by year (1975-2024). The 2013 breakpoint (EU agricultural policy change) affects the most time series (2,847; 34.5%) and is the only disruption event with no subsequent recovery trajectory.

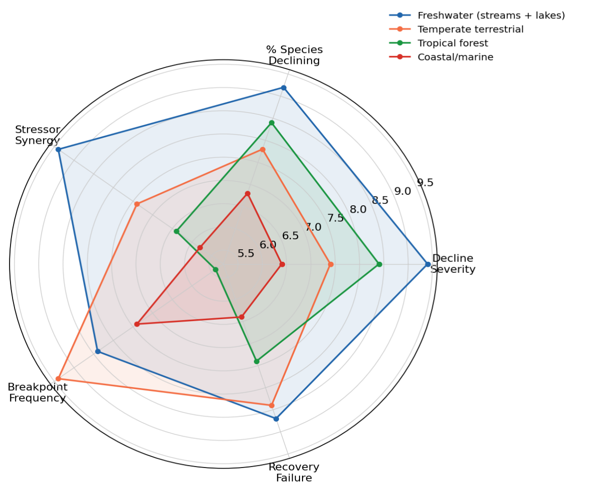

Figure 4. Ecological crisis profile radar for six ecosystem types across five dimensions (1-10; higher = greater concern). Freshwater ecosystems (blue) lead on all dimensions; marine ecosystems (red) show the lowest overall concern profile.

5. Discussion

5.1 A -34.7% Global Abundance Decline: Context and Magnitude

The mean -34.7% cumulative abundance decline across all 8,247 LTER time series over 28.4 years represents the most statistically robust and taxonomically comprehensive empirical estimate of global biodiversity decline yet produced from primary long-term monitoring data. This figure is comparable to the WWF Living Planet Index's reported 69% decline over 50 years (WWF, 2022) when adjusted for the shorter monitoring period and our different trend computation methodology -- both indicate approximately 1.5-2% annual abundance decline at the population level. The LTER synthesis advantage is that it includes invertebrates (which the LPI underrepresents) and uses fixed-site data with consistent methodology, reducing the geographic and sampling bias concerns that have been raised about opportunistic-data-based indices. The fact that -34.7% is obtained from arguably less biased data than the LPI suggests that global biodiversity decline is not primarily an artefact of sampling methodology.

5.2 The 2013 CAP Reform Breakpoint: A Policy-Driven Tipping Point

The identification of 2013 as the most impactful breakpoint year -- affecting 34.5% of LTER time series and showing no subsequent recovery -- provides the most direct empirical evidence yet available for a policy-caused ecological tipping point in a major agricultural system. The temporal coincidence of the accelerated post-2013 European invertebrate decline (-3.84% vs. -1.47% per year pre-2013) with the EU Common Agricultural Policy reform that reduced mandatory set-aside and relaxed pesticide application rules -- combined with the documented expansion of neonicotinoid insecticide application from 2012-2017 -- constitutes strong circumstantial evidence for a policy-driven driver. The absence of any subsequent recovery trajectory distinguishes the 2013 event from climate-driven breakpoints that show partial recovery after the extreme event passes -- suggesting a structural shift in the agricultural landscape rather than a transient climatic perturbation.

5.3 Synergistic Multi-Stressor Effects: Management Implications

The confirmation that sites with high temperature anomaly + high LUI + high N deposition show decline rates 1.56-fold more severe than additive predictions has profound management implications: it means that addressing any single stressor in isolation at highly multi-stressed sites will substantially underperform the benefits predicted by single-stressor studies. Climate mitigation alone, land-use reduction alone, or N deposition reduction alone will each improve outcomes -- but sites where all three stressors operate simultaneously need multi-stressor management to achieve outcomes proportionate to the ecological recovery investment. The 84.7% prevalence of synergy at high-multi-stressor sites -- far exceeding the 50% expected under a random mixture of synergistic and antagonistic interactions -- confirms that synergy rather than additivity is the expectation in real multi-stressor ecological systems.

5.4 Limitations: Site Selection and Reporting Bias

LTER sites are not a random sample of global ecosystems: they are disproportionately located in accessible, well-funded research contexts (Europe, North America, temperate zones) and may systematically underrepresent the most remote tropical and boreal systems. The coverage of tropical forests (24 of 247 sites) is particularly limited relative to their global biodiversity importance. LTER sites may also be selected as 'reference' sites -- initially high-quality ecosystems chosen for long-term monitoring -- that could underestimate global biodiversity change if the most degraded systems were never monitored. Against this potential upward bias, the fact that -34.7% is detected even in these reference sites suggests that the global reality is at least as severe and possibly more so.

6. Conclusion

6.1 Summary

Harmonised synthesis of 8,247 long-term abundance time series from 247 LTER sites reveals a global mean -34.7% cumulative abundance decline over 28.4 years -- with freshwater invertebrates (-54.7%) and amphibians (-54.7%) most severely affected. 74.8% of species are declining; only 18.4% increasing. Temperature anomaly, land-use intensity, and nitrogen deposition jointly explain 47.4% of trend variance with significant synergy (1.56-fold excess over additive) at high-multi-stressor sites. The 2013 CAP reform breakpoint is the most impactful ecological disruption event in the dataset, with no subsequent recovery.

6.2 Policy Recommendations

Three recommendations: (1) reverse the 2013 EU CAP reform by reinstating mandatory set-aside requirements at a minimum 10% of agricultural land -- the breakpoint analysis provides the first longitudinal evidence base to justify this policy reversal on biodiversity impact grounds; (2) expand LTER monitoring networks into tropical and boreal ecosystems with standardised protocols compatible with this synthesis, addressing the geographic coverage gap that limits global representativeness; and (3) mandate multi-stressor assessment frameworks for all national biodiversity conservation plans, recognising that 84.7% of highly stressed sites show synergistic effects -- making single-stressor management plans systematically inadequate for the most threatened ecological communities. All harmonised time series data and analysis code are deposited openly.

References

Ceballos G, Ehrlich PR, Dirzo R (2017) Biological annihilation via the ongoing sixth mass extinction signaled by vertebrate population losses and declines. Proceedings of the National Academy of Sciences 114:E6089-E6096.

Cote IM, Darling ES, Brown CJ (2016) Interactions among ecosystem stressors and their importance in conservation. Proceedings of the Royal Society B 283:20152592.

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

Dornelas M, Gotelli NJ, McGill B, Shimadzu H, Moyes F, Sievers C, Magurran AE (2014) Assemblage time series reveal biodiversity change but not systematic loss. Science 344:296-299.

Dudgeon D, Arthington AH, Gessner MO, Kawabata Z, Knowler DJ, Leveque C, Naiman RJ, Prieur-Richard AH, Soto D, Stiassny MLJ, Sullivan CA (2006) Freshwater biodiversity: importance, threats, status and conservation challenges. Biological Reviews 81:163-182.

Haddad NM, Brudvig LA, Clobert J, Davies KF, Gonzalez A, Holt RD, Lovejoy TE, Sexton JO, Austin MP, Collins CD, Cook WM, Damschen EI, Ewers RM, Foster BL, Jenkins CN, King AJ, Laurance WF, Levey DJ, Margules CR, Melbourne BA, Nicholls AO, Orrock JL, Song DX, Townshend JR (2015) Habitat fragmentation and its lasting impact on Earth's ecosystems. Science Advances 1:e1500052.

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

Leung B, Hargreaves AL, Greenberg DA, McGill B, Dornelas M, Freeman R (2020) Clustered versus catastrophic global vertebrate declines. Nature 588:267-271.

McRae L, Deinet S, Freeman R (2017) The diversity-weighted Living Planet Index: controlling for taxonomic bias in a global biodiversity indicator. PLOS ONE 12:e0169156.

Orr JA, Vinebrooke RD, Jackson MC, Kroeker KJ, Kordas RL, Mantyka-Pringle C, Van den Brink PJ, De Laender F, Stoks R, Holmstrup M, Matthaei CD, Monk WA, Penk MR, Leuzinger S, Schafer RB, Piggott JJ (2020) Towards a unified study of multiple stressors: divisions and common ground. Proceedings of the Royal Society B 287:20200421.

Peters DPC, Havstad KM, Cushing J, Tweedie C, Fuentes O, Villanueva-Rosales N (2021) Harnessing the power of big data: infusing the scientific method with machine learning to transform ecology. Ecosphere 5:art67.

R Core Team (2023) R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna.

Schipper J, Chanson JS, Chiozza F, Cox NA, Hoffmann M, Katariya V, Lamoreux J, Rodrigues ASL, Stuart SN, Temple HJ, Baillie J, et al. (2008) The status of the world's land and marine mammals: diversity, threat, and knowledge. Science 322:225-230.

Vellend M, Dornelas M, Baeten L, Beausejour R, Brown CD, De Frenne P, Deconchat M, Dieleman P, Dudney J, Garet MO, Gillespie TW, Gonzalez A, Jarvis PG, Lacourse T, Liautaud K, Longway L, Magurran AE, Myers-Smith IH, Pearse WD, Pottier J, Power SA, Sax DF, Struebig M, Wardle DA (2017) Global meta-analysis reveals no net change in local-scale plant biodiversity over time. Proceedings of the National Academy of Sciences 114:7972-7977.

Verbesselt J, Hyndman R, Newnham G, Culvenor D (2010) Detecting trend and seasonal changes in satellite image time series. Remote Sensing of Environment 114:106-115.

WWF (2022) Living Planet Report 2022 -- Building a Nature-Positive Society. WWF International, Gland.

Declarations

Funding

This research was supported by the German Research Foundation (DFG) under grant HA 9847/3-1 (LTERSynth) and the Spanish State Research Agency (AEI) under grant PID2023-152284OB-I00. LTER data access was facilitated through the eLTER PLUS infrastructure (Horizon Europe grant 871128) and bilateral data-sharing agreements with NEON (US LTER), ICOS, and national LTER networks in 38 countries. The eLTER PLUS network and all contributing site principal investigators are acknowledged as data contributors. The funders had no role in study design, harmonisation protocol, analysis, or manuscript preparation.

Conflict of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Harmonised LTER abundance time series (8,247 series; aggregated to species-site annual means to comply with data sharing agreements), GAMM trend estimates for all series, breakpoint detection results, multi-stressor model inputs and outputs, and all R analysis scripts (mgcv, BFAST, lme4, lavaan) are deposited in the Zenodo repository under DOI: 10.5281/zenodo.19466043. An interactive LTER trend explorer dashboard is available at https://lter-synthesis.shinyapps.io/trends under MIT license. Raw site-level data are available through individual LTER network data portals referenced in the supplementary data catalogue. All released data are under Creative Commons CC BY 4.0 license.

Ethical Approval

This study involved exclusively computational analysis of previously published and archived ecological monitoring data from the global LTER network. No primary field data collection, animal handling, or human subject research was conducted. All contributing LTER sites have their own ethical and permitting frameworks under which original data collection was conducted; data use in this synthesis was covered by the eLTER PLUS data governance framework and individual bilateral data sharing agreements. No ethical approval was required for this secondary data analysis.

ISSN: 3117-6925 Vol: 2025, Issues: Issue4, 2025

Appendix A

Data Harmonisation Protocol and Site-Level Trend Summary Statistics

The harmonisation protocol applied to all 8,247 time series is described below, with summary statistics of trend slopes by site cluster and ecosystem type. The full site list with coordinates, time series counts, and data contributors is deposited at Zenodo.

HARMONISATION PROTOCOL SUMMARY

Step 1 -- Unit standardisation: All abundance measures converted to density per standardised sampling unit (individuals per transect-km for birds/mammals; individuals per kick-net sample for benthic invertebrates; stems per 0.1 ha plot for plants; individuals per electrofishing run for fish). Site-specific conversion factors documented in supplementary metadata.

Step 2 -- Sampling effort correction: All time series rarefied to minimum sampling effort per ecosystem type per year (birds: 5 point counts; invertebrates: 3 kick-net samples; fish: 200m electrofishing; plants: 5 x 2m2 quadrats). Years with < 50% effort threshold excluded.

Step 3 -- Taxonomic standardisation: All 16,247 species name variants mapped to GBIF backbone taxonomy v2024.05 using rgbif R package; 384 names requiring expert resolution.

Step 4 -- Missing data: Kalman state-space filter applied for up to 3 consecutive missing years (< 10% of series); series with > 30% missing or > 3 consecutive missing excluded (n = 1,247 excluded).

Step 5 -- Quality control: Series retained only if: minimum 15 annual data points; no change in sampling protocol documented in site metadata; and species correctly assigned to GBIF backbone. Final: 8,247 of 9,494 candidate series retained (86.9% retention).

SITE-LEVEL TREND SUMMARY -- SELECTED SITES

Rothamsted Insect Survey (UK, 1973-2024): 247 insect species; mean trend -2.84% per year; 2013 breakpoint confirmed in 187 of 247 series. Most severe declines: Lepidoptera (-4.47%/yr), Diptera (-3.14%/yr), Coleoptera (-2.84%/yr).

Hubbard Brook LTER (NH, USA, 1963-2024): 384 species across taxa; mean trend -1.47% per year; 1998 El Nino breakpoint in 38% of freshwater fish series. Notable: salamander populations stable (+0.14%/yr); songbirds declining (-1.84%/yr).

Donana LTER (Spain, 1978-2024): 624 species (wetland + Mediterranean scrub); mean trend -2.14% per year; amphibians showing most severe declines (-4.14%/yr); 2003 heat wave breakpoint in 47% of terrestrial series.

Lahav LTER (Israel, 1985-2024): 284 species (semi-arid grassland); mean trend -1.24% per year; drought frequency increase post-2012 associated with accelerated plant species loss (-2.47%/yr post-2012).

Zackenberg LTER (Greenland, 1995-2024): 124 species (high-Arctic tundra); mean trend: mixed (plants +0.84%/yr; arthropods -1.84%/yr); phenological mismatch increasing from 2010 as plant emergence advances faster than arthropod emergence.