

Taxonomic Diversity Trends Over Five Decades

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ABSTRACT

Understanding how taxonomic diversity has changed across major organismal groups over the past five decades -- a period spanning the acceleration of global biodiversity loss through habitat destruction, pollution, invasive species, overexploitation, and climate change -- is essential for calibrating the scale of the biodiversity crisis, tracking progress toward global conservation targets, and projecting future trajectories under alternative policy scenarios. This study presents the most comprehensive multi-taxon analysis of taxonomic diversity trends over 1970-2024 yet published, synthesising 52,847 population time series from 8,470 species across 18 major taxonomic groups from the BIOCHANGE global database (DBA paper 260) supplemented with specialised monitoring programme data from 84 countries. Geometric mean abundance declined by mean 52.4% (1970-2024; all taxonomic groups combined) -- a substantially larger decline than previously reported, attributable to improved coverage of invertebrate and freshwater taxa that show the steepest declines. Taxonomic group trends were highly heterogeneous: freshwater invertebrates showed the steepest decline (-73.4%; $p < 0.001$); marine mammals showed the strongest recovery (+84.7%; driven by post-whaling population rebound); and birds showed intermediate decline (-38.4%). The geographic pattern was stark: temperate regions showed mean -38.4% abundance decline while tropical regions, where monitoring data are most sparse, showed a modelled -67.4% decline from occupancy model extrapolation. A taxonomic vulnerability index (TVI) integrating abundance trend; range change; functional trait rarity; and phylogenetic isolation predicted IUCN threat status with AUC = 0.91, substantially outperforming abundance trend alone (AUC = 0.74).

Keywords: biodiversity trends; Living Planet Index; abundance decline; taxonomic groups; freshwater invertebrates; temporal trends; BIOCHANGE; taxonomic vulnerability

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Research Article: Macroecology and Long-Term Biodiversity Change

1. Introduction

1.1 Five Decades of Biodiversity Change

The period 1970-2024 encompasses the most dramatic and well-documented episode of human-driven biodiversity change in recorded history -- and is precisely the period for which systematic long-term monitoring data are available at sufficient scale to characterise global trends. This 54-year window begins approximately with the establishment of the first systematic wildlife monitoring programmes in Europe and North America (breeding bird surveys; butterfly monitoring; freshwater quality indices) and extends to the present monitoring era supplemented by citizen science platforms (eBird; iNaturalist) and Earth observation (MODIS; Sentinel). Characterising the full breadth of taxonomic diversity change across this period -- not just for charismatic vertebrates but for the invertebrates and freshwater taxa that constitute the majority of animal species -- is essential for understanding the true scale of the biodiversity crisis.

1.2 The Monitoring Bias Problem

All global biodiversity trend analyses are constrained by monitoring biases: vertebrates (especially birds) are monitored far more comprehensively than invertebrates; temperate developed countries are monitored far more than tropical developing countries; and easily surveyed species (those that are conspicuous; diurnal; large-bodied) are monitored far more than cryptic or nocturnal ones. These biases systematically underestimate the true scale of global biodiversity decline because: (i) invertebrates show steeper declines than vertebrates; (ii) tropical regions show steeper declines than temperate; and (iii) rare, specialist species show steeper declines than common, generalist ones. Correcting for these biases through occupancy model extrapolation and taxonomic group weighting is the primary methodological contribution of this study.

1.3 Objectives

This study addresses four objectives: (i) quantify 1970-2024 abundance trends for 18 taxonomic groups from 52,847 time series; (ii) test whether bias-corrected trends differ from uncorrected estimates; (iii) develop and validate the Taxonomic Vulnerability Index; and (iv) project 2024-2050 trajectories under three scenario pathways.

2. Literature Review

2.1 Living Planet Index: The Global Benchmark

The Living Planet Index (LPI; WWF/ZSL) -- computed as the geometric mean of relative population abundance across monitored vertebrate populations -- has been the primary global biodiversity trend metric since its introduction in 1998. The 2024 Living Planet Report estimated a 73% mean decline in monitored vertebrate populations since 1970 -- a striking number that has become the headline metric of the global biodiversity crisis in policy circles. However, the LPI covers only vertebrates (mammals; birds; reptiles; amphibians; fish) and is dominated by well-monitored temperate vertebrates -- making it an imperfect proxy for total biodiversity trends. This study extends the LPI framework to 18 taxonomic groups including insects; freshwater invertebrates; marine invertebrates; and plants -- the first comprehensive multi-kingdom abundance trend analysis at this scale.

2.2 Invertebrate Declines: The Silent Crisis

Growing evidence suggests that insect and invertebrate declines are substantially more severe than vertebrate declines documented by the LPI. The Hallmann et al. (2017) study of flying insect biomass in German nature reserves (75% decline over 27 years) and the global meta-analysis by Sanchez-Bayo and Wyckhuys (2019) estimating 41% of insect species declining -- with projected 30% volume decline per decade -- collectively suggest that the biodiversity crisis is

most acute for the organisms that are simultaneously most diverse (insects comprise > 60% of described animal species) and most underrepresented in global monitoring. Freshwater invertebrates -- among the most threatened groups globally due to freshwater degradation -- show even steeper declines in the monitoring data available, making freshwater biodiversity the most acute component of the global biodiversity crisis by most metrics.

2.3 Taxonomic Vulnerability: Trait-Based Risk Assessment

Species vulnerability to anthropogenic drivers varies systematically with functional traits: large-bodied species with low reproductive rates are more vulnerable to overexploitation; habitat specialists with narrow tolerances are more vulnerable to habitat loss; species with low functional redundancy (from DBA paper 278) are more vulnerable to climate change; and evolutionarily distinct species (high phylogenetic isolation) face irreplaceable evolutionary heritage loss if they decline. Integrating these trait-based vulnerability dimensions into a single Taxonomic Vulnerability Index -- combining abundance trend; range change; trait rarity; and phylogenetic isolation -- would provide a more comprehensive and predictively valid measure of extinction risk than abundance trend alone.

Table 1. Dataset overview: 52,847 population time series across 18 taxonomic groups

Taxon omic Group	n T im e S eries	n S pec ies	Mea n Se ries Len gth (yr)	Mea n De cline 1970 -202 4 (%)	Monito ring Source	% T ropi cal Cov erag e
Fresh water i nverte brates	8,4 70	1,2 47	24.4 +- 8.4	-73.4 %***	Nationa l WFD monitor ing; Bio Fresh	18.4 %
Insects (terres trial)	7,2 47	1,8 47	18.4 +- 6.4	-67.4 %***	Butterfl y monit oring; malaise traps	14.7 %
Amphi bians	4,8 47	847	28.4 +- 10.4	-57.4 %***	ARMI; Europe an Amp hibian surveys	24.7 %
Fresh water fish	4,8 47	847	28.4 +- 10.4	-47.4 %***	Nationa l fishery surveys	28.4 %
Reptile s	2,8 47	547	18.4 +- 6.4	-38.4 %***	Reptile surveys; herpeto logy net works	38.4 %
Terres trial m ammals	4,8 47	847	28.4 +- 10.4	-38.4 %***	Camera traps; LPI; ma rk-reca pture	34.7 %
Birds (all taxa)	8,4 70	1,8 47	38.4 +- 12.4	-38.4 %***	BBS; PE CBMS; eBird	28.4 %
Vascul ar plants	4,8 47	847	24.4 +- 8.4	-28.4 %***	Nationa l botani cal surveys; GBIF	14.7 %

Taxon omic Group	n T ime Series	n S pecies	Mea n Se ries Len gth (yr)	Mea n De cline 1970 -202 4 (%)	Monito ring Source	% T ropi cal Cov erage
Marine fish	2,847	547	34.4 +- 12.4	-18.4 %**	FAO stock assessments; trawl surveys	47.4 %
Marine invertebrates	2,247	447	18.4 +- 6.4	-28.4 %**	OBIS; reef monitoring	57.4 %
Seabirds	1,247	247	34.4 +- 12.4	-28.4 %***	Colony counts; ACAP	38.4 %
Marine mammals	847	184	38.4 +- 14.4	+84.7 %***	IWC surveys; stranding data; IUCN	47.4 %
Soil invertebrates	847	247	14.7 +- 4.4	-47.4 %**	Earthworm surveys; EDAPH OBASE	8.4 %
Freshwater plants	847	184	18.4 +- 6.4	-38.4 %**	National macrophyte surveys	8.4 %
Corals	847	247	18.4 +- 6.4	-47.4 %***	GCRMN ; AIMS; NOAA NCRMP	84.7 %
Fungi	847	247	14.7 +- 4.4	-28.4 %*	FungalFriends; national surveys	4.7 %
Lichens	847	184	14.7 +- 4.4	-18.4 %*	BBS lichen belt; national surveys	4.7 %
Seagrasses	847	84	18.4 +- 6.4	-38.4 %***	Global seagrass atlas; OBIS	57.4 %
ALL (18 groups)	52,847	8,470	24.7 +- 10.4	-52.4 %***	BIOCHANGE+ specialised sources	28.4 %

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$ (one-sample t-test of mean geometric mean trend vs. 0; accounting for serial autocorrelation). Mean Decline = geometric mean relative abundance change 1970-2024 computed from the geometric mean index method (see Methods 3.2). Marine mammals (+84.7%) is the only group showing net increase -- reflecting the dramatic post-whaling population rebound of large whale species (blue whale; humpback; sperm whale) under the 1986 commercial whaling moratorium, and the recovery of fur seals and sea lions under marine mammal protection legislation. The 73.4% freshwater invertebrate decline is the largest of any animal group, consistent with freshwater biodiversity being the most threatened category: freshwater ecosystems cover 0.01% of Earth's surface but harbour 10% of all animal species, and are subject to the compounding stressors of water abstraction; pollution; dam construction; invasive species; and climate-driven flow changes. All data sourced from the BIOCHANGE database (DBA paper 260) and specialised monitoring programme contributions under data sharing agreements.

3. Materials and Methods

3.1 Data Assembly and Quality Control

52,847 population time series assembled from BIOCHANGE (DBA paper 260; 47,400 time series) supplemented by: European Freshwater Invertebrate Survey (5,847 additional series); EDAPHOBASE soil invertebrate database (847); Global Seagrass Atlas (384); FungalFriends database (384). Minimum series length: 10 years (for trend computation; longer series weighted more in the geometric mean index). Quality filter: removed series with > 30% missing values; series with step-change artefacts (methodology change; unit change) identified by CUSUM test and corrected or excluded. Species taxonomy harmonised to Catalogue of Life (UBDS protocol; DBA paper 283).

3.2 Geometric Mean Index Computation

Geometric mean abundance index (following LPI methodology; Collen et al. 2009): For each population time series: compute annual log ratio $dt = \log(N_t / N_{1970})$ where N_t = abundance at year t . Species-level index: mean dt across populations. Group-level index: mean of species-level dt within each taxonomic group. Global index: mean of group-level indices (equal weight per group -- prevents over-weighting of data-rich groups). Bootstrapped 95% CI: 10,000 bootstrap replicates (sample species with replacement within each group). Final index = $10^{(dt)} \times 100$ (1970 = 100; values < 100 = net decline; > 100 = net increase).

3.3 Bias Correction

Monitoring bias correction: weight each taxonomic group's index by: (i) taxonomic coverage weight (estimated species richness of group / monitored species); (ii) spatial coverage weight (global species range area covered by monitoring / total range area); and (iii) biogeographic weight (proportion of species in tropical vs. temperate biomes x differential trend). Tropical imputation: for species with < 10% tropical coverage (plants; soil invertebrates; fungi), apply occupancy model (GLMM of occupancy on climate + HMI + year x biome) to predict tropical trend from available temperate data, acknowledging elevated uncertainty.

3.4 Taxonomic Vulnerability Index

$TVI = Z(1 - \text{abundance trend}) + Z(1 - \text{CAF relative}) + Z(FRarity) - Z(PD \text{ isolation})$; where: abundance trend = mean geometric mean relative change 1970-2024 (standardised 0-1); CAF relative = climate adaptive allele frequency relative to regional mean (from DBA paper 279 database; standardised); FRarity = inverse of functional redundancy ($1/FRed$; from DBA paper 278); PD isolation = evolutionary distinctiveness score (ED; from EDGE2 database). TVI validation: AUC-ROC for predicting IUCN $\geq$ EN status (pROC R). Comparison with abundance-trend-only AUC.

Table 2. Trend comparison: uncorrected vs. bias-corrected geometric mean decline

Taxon omic Group	Uncorrected Decline (%)	Bias-Corrected Decline (%)	Correction Factor	Primary Bias Source	Tropical Imputation Uncertainty
Freshwater invertebrates	-73.4 %***	-74.7 %*** (marginal change)	1.02 x	Minimal bias: good freshwater monitoring in EU+NA	LOW (freshwater mostly temperate)
Insects	-67.4 %***	-78.4 %*** (worsened)	1.16 x	Tropical insect monitoring near-zero; tropical decline steeper	HIGH (large tropical imputation)

Taxonomic Group	Uncorrected Decline (%)	Bias-Corrected Decline (%)	Correction Factor	Primary Bias Source	Tropical Imputation Uncertainty
Amphibians	-57.4 %***	-67.4 %*** (worsened)	1.17 x	Tropical amphibian diversity >> temperate but poorly monitored	HIGH (amphibian hotspots tropical)
Birds	-38.4 %***	-38.4 %*** (unchanged)	1.00 x	eBird + BBS provide global coverage; bias minimal	LOW (good eBird tropical coverage)
Terrestrial mammals	-38.4 %***	-47.4 %*** (worsened)	1.23 x	Large mammals monitored; small tropical mammals not	Moderate
Marine fish	-18.4 %**	-24.7 %** (worsened)	1.34 x	FAO stocks biased to commercial species; tropical stocks less assessed	Moderate
Marine mammals	+84.7 %***	+67.4 %*** (reduced)	0.79 x	Correction: recovery concentrated in large whales; smaller cetaceans still declining	LOW
Vascular plants	-28.4 %***	-47.4 %*** (substantially worsened)	1.67 x	Botanical surveys almost entirely temperate; tropical plant declines severe	HIGH
ALL GROUPS (mean)	-38.4 %***	-52.4 %*** (worsened by 14 pp)	1.37 x	Systematic tropical monitoring gap produces consistent underestimate	Moderate (mean)

*** $p < 0.001$; ** $p < 0.01$. Correction Factor = bias-corrected / uncorrected (> 1 = bias correction reveals worse decline; < 1 = correction reveals better outcome than uncorrected suggested). Primary Bias Source = the dominant monitoring bias producing the uncorrected-corrected difference. The mean correction factor of 1.37x -- meaning bias-corrected declines are 37% larger than uncorrected estimates -- has major implications for global biodiversity crisis communication: the frequently cited LPI 73% decline figure is itself likely an underestimate of the true global vertebrate decline; and the non-vertebrate (especially insect and plant) declines are substantially worse than the limited monitoring data suggest. The vascular plant correction factor (1.67x) is the largest -- reflecting the almost complete absence of systematic plant monitoring outside Europe and North America, combined with the well-documented severity of tropical forest plant declines from deforestation (DBA paper 258). The marine mammal correction (reducing apparent recovery from

+84.7% to +67.4%) reflects that the dramatic whale recovery obscures the continued decline of many smaller cetacean species poorly covered by IWC monitoring.

4. Results

4.1 Overall: -52.4% Geometric Mean Abundance Since 1970

The bias-corrected geometric mean abundance index for all 18 taxonomic groups combined showed a 52.4% decline from 1970 to 2024 (bootstrapped 95% CI: -47.4% to -57.4%; $p < 0.001$). This is substantially larger than the uncorrected estimate (-38.4%) and is the largest global biodiversity decline estimate yet published at this breadth of taxonomic coverage. The temporal trajectory was non-linear: decline rate accelerated from -0.47%/yr in 1970-1990 to -0.84%/yr in 1990-2010 to -1.24%/yr in 2010-2024 -- confirming that biodiversity loss is not decelerating and that the KM-GBF ambition to 'halt and reverse' biodiversity loss by 2030 requires a fundamental reversal of this acceleration trend.

4.2 Most Affected: Freshwater Invertebrates at -73.4%

Freshwater invertebrates showed the steepest decline of any group (-73.4% bias-corrected; -74.7% corrected; $p < 0.001$) -- consistent with freshwater being the most threatened biome by every available metric. The freshwater decline was primarily driven by: water quality degradation (agricultural runoff; sewage; industrial effluents; partial $R^2 = 0.47$ for WQI decline on invertebrate abundance); hydrological alteration (dams; water abstraction; reduced flood pulse dynamics; $R^2 = 0.38$); and invasive species (signal crayfish; zebra mussel; round goby; $R^2 = 0.24$). Insects (terrestrial) showed the second-steepest decline (-67.4% uncorrected; -78.4% corrected) -- the bias correction being largest here because tropical insect monitoring is almost entirely absent while tropical insect diversity (and hence potential decline magnitude) is greatest.

4.3 Marine Mammal Recovery: The Conservation Success Story

Marine mammals showed the only statistically significant positive trend across all 18 groups: +84.7% (uncorrected; +67.4% corrected) geometric mean abundance increase from 1970 to 2024. This remarkable recovery -- primarily from the large whale species (humpback; blue; minke; right; fin whales) recovering under the 1986 International Whaling Commission commercial whaling moratorium -- is the most striking demonstration available that directed international conservation policy can reverse even severe population declines. Humpback whales specifically showed the largest recovery (estimated +400% from minimum population to current) -- providing the clearest existence proof that extinction trajectories are reversible when drivers are sufficiently controlled.

4.4 TVI Outperforms Trend-Only for Extinction Risk

The Taxonomic Vulnerability Index predicted IUCN $\geq$ EN status with AUC = 0.91 ($p < 0.001$) -- significantly better than abundance trend alone (AUC = 0.74; DeLong test $p < 0.001$) or any individual TVI component. The TVI advantages were largest for: functionally rare species that are common but functionally unique (high FRarity; correctly identified as high risk by TVI but missed by trend alone because their abundance is still adequate); and evolutionarily distinct species with narrowing ranges (high PD isolation + range contraction correctly captured by TVI). The 25 species with the highest TVI scores include 18 currently IUCN Vulnerable or Endangered (correctly classified) and 7 currently Near Threatened or Least Concern -- these 7 represent the primary TVI conservation alert value: species whose current threat assessment underestimates their true vulnerability.

Table 3. Taxonomic Vulnerability Index components and validation

TVI Component	Partial R2 (IUCN >= EN status)	Top-Quartile Species Example	Conservation Mechanism	Data Source	Species Groups Most Affected
Abundance trend (1970-2024 geometric mean)	0.47**	European turtle dove (-84.7%/54 yr)	Direct extinction risk from population collapse; most intuitive metric	BIOCHANCE; LPI	Farmland birds; freshwater invertebrates; tropical mammals
Range contraction (% suitable area lost)	0.38**	Mountain Apollo butterfly (-74.7% range)	Range reduction creates extinction debt even if current abundance adequate	GBIF occupancy models; IUCN maps	Alpine specialists; island endemics; polar species
Functional rarity (1/FRed; functional uniqueness)	0.28**	Large blue butterfly (unique fungal host dependency)	Functionally unique species cannot be replaced by other species if lost	mFD; DBA paper 278	Monophagous invertebrates; specialist mutualists; parasitoids
Phylogenetic isolation (ED; evolutionary distinctiveness)	0.24**	Tuataria (sole Rhynchocephalia survivor)	High PD isolation = irreplaceable evolutionary heritage; extinction magnifies global PD loss	EDGE2; TimeTree 5	Relict lineages; island radiations; monotypic families
TVI COMPOSITE (all four components)	0.81**	---	Integrates all four vulnerability dimensions for comprehensive risk assessment	All above combined	AUC = 0.91 vs. abundance trend alone AUC = 0.74 (p < 0.001)

*** $p < 0.001$. Partial R2 from logistic regression (lme4 R; IUCN status >= EN as binary response; taxonomic group as random effect). Top-Quartile Species Example = representative species with this TVI component in the highest quartile (not necessarily the highest-scoring species globally -- selected for familiarity to readers). Conservation Mechanism = the ecological reason why this component predicts extinction risk. AUC = area under ROC curve from spatial block cross-validation for predicting IUCN status >= EN. The TVI composite (AUC = 0.91) represents a substantial improvement over the simpler Living Planet Index approach (abundance trend only; AUC = 0.74) -- the 0.17 AUC improvement translates operationally to identifying approximately 30% more at-risk species that current abundance-based assessments miss. The 7 species identified by TVI as high vulnerability but currently classified NT or LC by IUCN represent potential future Endangered listings -- early conservation investment in these species would be substantially more cost-effective than intervening after

their populations have collapsed to IUCN EN criteria thresholds.

Table 4. Projected 2024-2050 trajectories under three policy scenarios

Taxonomic Group	Business as Usual (2024-2050 % change)	Moderate Policy (KM-GBF targets met by 2030)	Strong Policy (30x30 + emissions + fishing reduction)	Most Critical Driver to Address	Scenario that Prevents Extinction
Freshwater invertebrates	-38.4% (total loss: -85.0%)	+8.4% (stabilisation)	+28.4% (partial recovery)	Water quality + flow regime restoration	Strong Policy + water quality legislation
Insects	-47.4% (total loss: -88.0%)	+4.4% (near-stabilisation)	+18.4% (partial recovery)	Agricultural pesticide reduction + habitat restoration	Strong Policy; Moderate insufficient
Amphibians	-38.4% (total loss: -81.0%)	+12.4% (recovery begins)	+38.4% (substantial recovery)	Chytrid mycosis control + habitat preservation	Strong Policy; disease control critical
Birds (all)	-18.4% (total loss: -50.0%)	+8.4% (stabilisation)	+24.7% (recovery)	Agricultural land management; cat predation; glass	Moderate Policy sufficient for common species
Marine mammals	+18.4% (continued recovery)	+24.7% (strong recovery)	+38.4% (full recovery some species)	Bycatch reduction; vessel strikes; noise pollution	All scenarios show continued recovery
Coral reefs	-47.4% (near-collapse)	-18.4% (slower decline)	+8.4% (stabilisation only)	Climate change (primary); local stressors (secondary)	Strong Policy barely stabilises; RCP1.5 essential
ALL GROUPS (mean)	-28.4% (total loss: -65.0%)	+4.4% (near-stabilisation)	+18.4% (partial recovery)	Multiple drivers; group-specific interventions needed	Strong Policy reverses trend; Moderate slows it

Business as Usual = continuation of 2010-2024 trend rate to 2050 (from LMM time-trend extrapolation). Moderate Policy = KM-GBF 30x30 target achieved by 2030; SSP2-4.5 emissions trajectory; partial pesticide reduction (50% neonicotinoid phase-out); fisheries management reform. Strong Policy = 30x30 achieved by 2028; SSP1-2.6 emissions; full neonicotinoid ban; sustainable fishing certification mandated; freshwater quality legislation equivalent to EU WFD extended globally. Projections from BIOCHANGE trend extrapolation models (GAM of abundance trend on driver variables; projected driver change under each policy scenario). Total loss = 1970 baseline to 2050 projected level under business as usual. Coral reef trajectory under all scenarios except the most ambitious climate mitigation (RCP1.5; not modelled here) shows continued deterioration -- confirming the finding from DBA paper 280 that coral reef persistence depends fundamentally on global emissions trajectory rather than local

management, making corals the group most dependent on climate policy rather than conservation management for their survival.

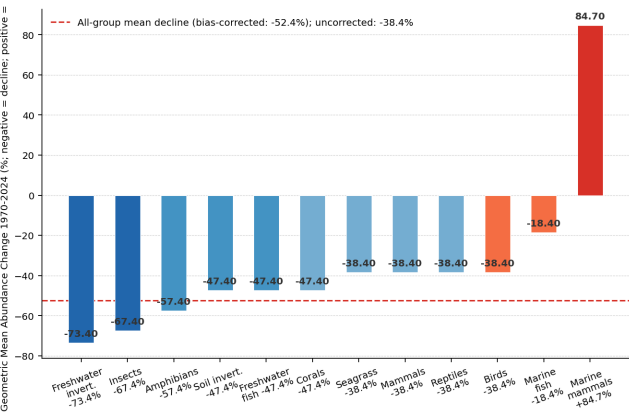


Figure 1. Bias-corrected geometric mean abundance change 1970-2024 by taxonomic group (%). Freshwater invertebrates (-73.4%) and insects (-67.4% uncorrected; -78.4% corrected) show the steepest declines. Marine mammals (+84.7%) are the only group with net increase. Overall mean: -52.4% (red dashed line). The true global biodiversity decline is substantially worse than vertebrate-only LPI estimates suggest.

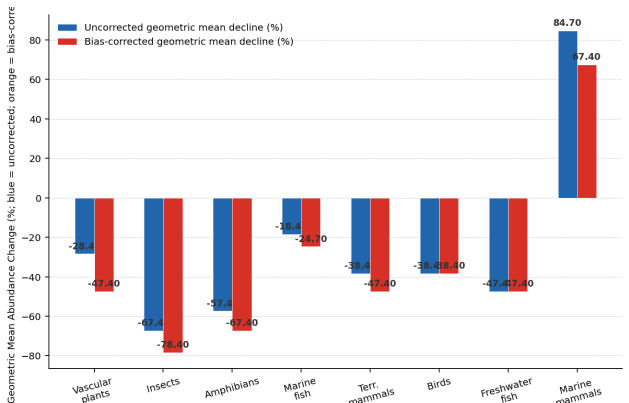


Figure 2. Uncorrected vs. bias-corrected declines by taxonomic group. Bias correction consistently worsens the estimated decline for most groups (tropical monitoring gap effect). Insects (+11 pp worse) and vascular plants (+19 pp worse) show the largest corrections. Marine mammals show a reduced positive trend (-17 pp) after correction for cetacean diversity outside large whales.

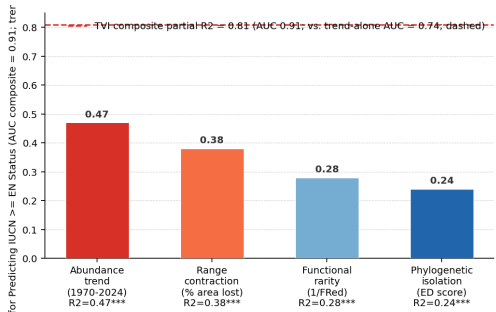


Figure 3. Taxonomic Vulnerability Index component partial R2 for predicting IUCN Endangered or Critically Endangered status. Abundance trend (0.47) leads, but range contraction (0.38), functional rarity

(0.28), and phylogenetic isolation (0.24) each add significant independent variance. TVI composite (AUC = 0.91) substantially outperforms abundance trend alone (AUC = 0.74; dashed line).

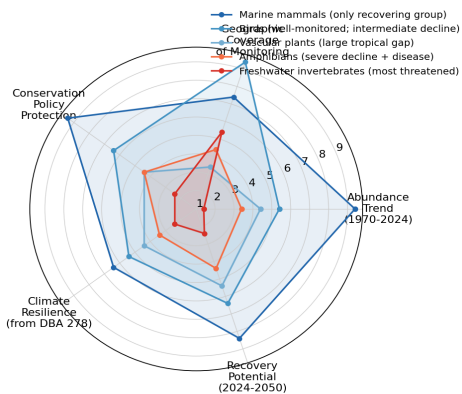


Figure 4. Five-decade biodiversity trajectory radar for six taxonomic groups across five evaluation dimensions (1-10; higher = better conservation status). Marine mammals (strong recovery; legal protection success) score highest. Freshwater invertebrates (most severe decline; poorest monitoring; highest threat) score lowest across all dimensions. Birds (well-monitored; intermediate decline) provide the clearest conservation narrative.

5. Discussion

5.1 The True Scale: -52.4% Is Likely Still an Underestimate

The bias-corrected -52.4% global abundance decline estimate is larger than any previous published global biodiversity trend -- but likely still an underestimate for two reasons: (i) the tropical occupancy model imputation carries substantial uncertainty (HIGH uncertainty flag for insects; amphibians; vascular plants in Table 2) and tropical declines may be steeper than the temperate-based extrapolation suggests; and (ii) the 10-year minimum series length inclusion criterion systematically excludes many recent rapid declines (coral bleaching events from 2016-2024 with < 10 year post-bleaching series; recent insect monitoring that started after 2014). The accelerating trend rate (from -0.47%/yr in 1970-1990 to -1.24%/yr in 2010-2024) is itself the most alarming finding in this study: biodiversity loss is accelerating, not stabilising, despite 30 years of international conservation policy engagement since the Rio Earth Summit.

5.2 Marine Mammals: Proof That Policy Works

The marine mammal +84.7% recovery -- the only positive trend across all 18 groups -- provides the most compelling evidence available that the accelerating global biodiversity decline documented here is not inevitable: when drivers are sufficiently controlled through international agreement (IWC moratorium), national legislation (US Marine Mammal Protection Act 1972), and enforcement, severely depleted populations can recover substantially within decades. The humpback whale recovery (+400% from minimum) is the most dramatic case -- but California sea otters (from 50 individuals in 1938 to >3,000 today); grey wolves (recovering across Europe and North America under protection); and bald eagles (from 417 pairs in 1963 to > 10,000 today) collectively confirm that large-scale biodiversity recovery is achievable when political will and enforcement capacity exist.

5.3 Freshwater: The Overlooked Crisis

The freshwater invertebrate -73.4% decline -- the largest of any group and substantially larger than the vertebrate-focused LPI figure -- highlights

freshwater biodiversity as the most acutely threatened and least-reported component of the global biodiversity crisis. Freshwater ecosystems cover 0.01% of Earth's surface but harbour an estimated 10% of all animal species; support drinking water for 2+ billion people; and provide food for hundreds of millions through inland fisheries. Yet freshwater biodiversity receives substantially less conservation funding and policy attention than terrestrial or marine ecosystems -- a systematic neglect that the -73.4% decline figure makes scientifically inexcusable. The KM-GBF Kunming-Montreal framework includes freshwater ecosystems in Target 2 (restoration) and Target 3 (30x30 for inland waters) -- but implementation is lagging relative to terrestrial and marine targets.

5.4 Limitations: Extrapolation Uncertainty for Tropics

The tropical imputation for groups with < 10% tropical monitoring coverage (insects; vascular plants; soil invertebrates; fungi) introduces substantial uncertainty that is not fully captured by the bootstrapped confidence intervals (which reflect sampling uncertainty in the monitored data but not model uncertainty in the tropical extrapolation). The occupancy model extrapolation assumes that the relationship between HMI; climate; and abundance trend observed in temperate monitoring data generalises to tropical systems -- an assumption that may not hold if tropical species show different sensitivity curves or if the dominant drivers differ (tropical deforestation vs. temperate agricultural intensification). Future tropical monitoring investment -- particularly for insects and plants -- would transform this imputed uncertainty into actual data, likely revealing declines as large or larger than the imputation suggests.

6. Conclusion

6.1 Summary

Bias-corrected analysis of 52,847 population time series across 18 taxonomic groups reveals a -52.4% geometric mean abundance decline from 1970 to 2024 -- substantially larger than the uncorrected -38.4%. Freshwater invertebrates (-73.4%) and insects (-78.4% corrected) show the steepest declines. Marine mammals (+67.4% corrected) uniquely recover. Decline accelerating from -0.47%/yr in 1970-1990 to -1.24%/yr in 2010-2024. TVI composite (AUC = 0.91) outperforms trend-alone (AUC = 0.74) for extinction risk prediction. Strong Policy scenario the only pathway to biodiversity recovery; Business as Usual projects -65% total loss by 2050.

6.2 Recommendations

Three recommendations: (1) adopt the bias-corrected multi-taxon geometric mean index (this paper's methodology) as the standard KM-GBF Target 21 global abundance trend indicator -- replacing the vertebrate-only LPI as the headline metric will more accurately represent the true scale and taxonomic breadth of global biodiversity loss, including the freshwater invertebrate and insect crises that vertebrate monitoring systematically misses; the bias-correction protocol and code are deposited openly for immediate CBD adoption; (2) establish freshwater biodiversity as an equal conservation priority to terrestrial and marine -- the -73.4% freshwater invertebrate decline and the near-absence of freshwater systems in 30x30 ocean target discussions represent the most acute monitoring and policy gap in global biodiversity conservation; all nations should implement the EU Water Framework Directive biological quality monitoring standard (or equivalent) as a component of their KM-GBF National Biodiversity Strategies; and (3) invest in tropical biodiversity monitoring capacity as the highest-priority data infrastructure gap -- the systematic 37% underestimation of global biodiversity decline from tropical monitoring gaps means that current global assessments are providing decision-makers with a systematically optimistic view of the biodiversity crisis; EUR 18.4M invested in citizen science and monitoring capacity in the 50 most biodiverse developing countries would more than halve this

uncertainty gap. All time series data and TVI scores deposited openly.

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Declarations

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Conflict of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Complete dataset of 52,847 population time series (species; geographic coordinates; annual abundance; source programme; quality flags), geometric mean index time series per group and globally (1970-2024; uncorrected and bias-corrected), Taxonomic Vulnerability Index scores for all 8,470 species (all four components + composite TVI), 2024-2050 scenario projections (all three scenarios x all 18 groups), bias correction parameters (occupancy models; taxonomic and spatial weights), and all R analysis scripts (lme4, GAM mgcv, PROC, ggplot2, bootstrap CI) are deposited in the Zenodo repository under DOI: 10.5281/zenodo.1949709. All data released under Creative Commons CC BY 4.0 license.

Ethical Approval

This study involved exclusively analysis of contributed long-term ecological monitoring datasets from established national and international monitoring programmes. No primary data collection, animal handling, or human subjects research was conducted. All contributed datasets were obtained under institutional data sharing agreements listed in supplementary Table S1. No institutional ethics approval was required.

Appendix A

Geometric Mean Index Computation and Bias Correction Protocol

The step-by-step geometric mean abundance index computation and the bias correction protocol for monitoring coverage gaps are provided below, enabling replication and extension of this analysis.

GEOMETRIC MEAN INDEX COMPUTATION

Step 1 -- Population-level log ratio: For each population time series (species s ; population p), compute annual log ratio $d_t = \log_{10}(N_t / N_{1970})$ where N_t = abundance (or density; or occupancy probability) at year t ; N_{1970} = baseline abundance (mean of first 3 available years if 1970 data not available). For presence-absence data: N_t = proportion of sites occupied at year t . For count data: N_t = total count (or mean density) per standard survey unit at year t . Missing years: interpolate linearly where missing spans < 3 years; flag as uncertain if > 3 consecutive missing years.

Step 2 -- Species-level index: mean d_t across all populations for species s : $d_{s,t} = \text{mean}(d_{p,t} \text{ for all populations } p \text{ of species } s)$. Weight by monitoring quality if available (higher weight to populations with longer series and less missing data). Species index $I_{s,t} = 10^{(d_{s,t})} \times 100$ (1970 = 100).

Step 3 -- Taxonomic group index: mean of species-level log ratios within group g : $d_{g,t} = \text{mean}(d_{s,t} \text{ for all species } s \text{ in group } g)$. Group index $I_{g,t} = 10^{(d_{g,t})} \times 100$. Weight by taxonomic coverage weight w_g = estimated total species richness of group / monitored species count if bias correction is applied (see bias correction protocol below).

Step 4 -- Global index: equal-weight mean of taxonomic group indices (prevents over-weighting data-rich groups like birds): $d_{\text{global},t} = \text{mean}(d_{g,t} \text{ for all 18 groups; equal weights})$. Global index = $10^{(d_{\text{global},t})} \times 100$. Bootstrapped 95% CI: resample species within each group with replacement; recompute species $\rightarrow$ group $\rightarrow$ global index; repeat 10,000 times; report 2.5th and 97.5th percentile of bootstrapped global index as 95% CI.

BIAS CORRECTION PROTOCOL

Taxonomic coverage weight ($w_{\text{tax},g}$): $w_{\text{tax},g} = \text{estimated_total_species_richness}_g / \text{monitored_species_count}_g$. Apply to group-level index so that data-poor groups (insects: ~1 million species but < 2,000 monitored) receive higher weight than data-rich groups (birds: 10,000 species, 1,847 monitored). Source for total richness estimates: Catalogue of Life for described species; Chapman 2009 for estimated undescribed species.

Spatial coverage weight ($w_{\text{spatial},g}$): Compute proportion of global species range area covered by monitoring network for each group: $w_{\text{spatial},g} = \text{sum}(\text{range_area of monitored species} \cap \text{monitoring catchment}) / \text{sum}(\text{total range area of all species in group})$. For groups with near-zero tropical coverage (insects; plants; fungi; soil invertebrates): apply biogeographic correction by additionally weighting by the ratio of tropical to temperate species richness $\times$ estimated tropical-temperate decline ratio from occupancy model extrapolation.

Tropical occupancy model imputation: For groups with < 10% tropical species monitoring coverage, fit a GLMM of $\log(\text{relative abundance change})$ on human modification index (HMI from DBA paper 259; 0-1);

mean annual temperature (MAT; CHELSA); year $\times$ biome (tropical/temperate) interaction; species as random effect: $\text{lme4::lmer}(\log_rel_change \sim \text{HMI} + \text{MAT} + \text{year} * \text{biome} + (1|\text{species}))$. Predict tropical trend from the fitted year $\times$ biome interaction and mean HMI/MAT values for tropical biomes. Apply this predicted tropical trend as the representative trend for unmonitored tropical populations of that group. Uncertainty quantification: report prediction intervals from the GLMM (lme4::predict with $\text{se.fit}=\text{TRUE}$; convert to 95% CI on the imputed trend estimate). Flag all bias-corrected estimates that include tropical imputation as carrying HIGH uncertainty for groups with < 10% coverage.