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Bioindicator Species in Climate Monitoring

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ABSTRACT

Bioindicator species -- organisms whose abundance, distribution, physiology, or phenology respond sensitively and predictably to specific environmental stressors -- are increasingly recognised as essential complements to physical climate sensors for monitoring the biological consequences of climate change at spatial resolutions and ecological timescales that instrument networks cannot achieve. This study systematically evaluated 247 candidate bioindicator species across six taxonomic groups (mammals, birds, reptiles, amphibians, fish, and invertebrates) for their effectiveness as climate change indicators across 38 long-term monitoring datasets from 24 countries spanning 1985-2023. Bioindicator effectiveness was quantified using five criteria: climate sensitivity (strength of correlation between species metric and climate variable), response lag (years between climate shift and detectable biological response), spatial resolution (area represented by a single monitoring point), monitoring cost-effectiveness (cost per unit of climate information), and multiple stressor confounding (degree to which non-climate stressors confound climate signal). Amphibians were the highest-scoring taxonomic group overall (mean composite bioindicator score = 7.84 +- 0.84 on a 1-10 scale), followed by freshwater invertebrates (7.24 +- 0.94) and breeding birds (6.84 +- 1.14). Phenological indicators -- breeding date, first appearance, and migration timing -- showed the fastest response lags (mean 0.8 +- 0.4 years) and highest climate sensitivity (mean r = 0.84 +- 0.08 with temperature) across taxonomic groups. A standardised bioindicator network design -- combining 14 priority species across six taxonomic groups with standardised monitoring protocols -- is proposed as a cost-effective complement to existing national climate monitoring systems, providing biological climate change fingerprinting at EUR 47,000 per monitoring site per year.

Keywords: bioindicators; climate monitoring; phenology; species sensitivity; long-term datasets; essential biodiversity variables; biological climate change fingerprinting; monitoring cost-effectiveness

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1. Introduction

1.1 The Case for Biological Climate Indicators

The global physical climate monitoring infrastructure -- comprising surface weather stations, ocean buoys, radiosondes, and satellite remote sensing -- provides comprehensive, high-frequency data on atmospheric and oceanic climate variables including temperature, precipitation, sea level, and sea ice extent. However, physical sensors cannot directly measure the biological consequences of climate change -- the phenological shifts, range movements, population dynamics changes, and community reorganisations that determine whether climate change is affecting biodiversity and ecosystem services in the ways that models project (Parmesan, 2006; Thackeray et al., 2016). Bioindicator species -- whose biological responses track specific climate variables with documented sensitivity and predictable lag times -- bridge this gap by translating physical climate signals into biological reality (Siddig et al., 2016; Niemi and McDonald, 2004). Long-term biological monitoring datasets that document species responses over decades also constitute independent evidence of climate change impact that is complementary to, and in some respects more policy-persuasive than, physical sensor records -- because biological responses integrate climate effects through ecological mechanisms that directly connect to human concerns about food security, nature, and health (Parmesan and Yohe, 2003).

1.2 Bioindicator Selection Criteria and Challenges

The selection of effective bioindicator species requires balancing multiple criteria that are often in tension: high climate sensitivity (ensuring the indicator responds to climate rather than other stressors) versus low multiple-stressor confounding (species affected by land-use change, pollution, and hunting cannot unambiguously attribute observed changes to climate); fast response lags (providing early warning) versus long biological memory (enabling retrospective reconstruction of past climate); wide spatial coverage (reducing monitoring network requirements) versus fine-scale resolution (detecting local climate effects); and low monitoring cost versus high taxonomic expertise requirements for accurate identification (Niemi and McDonald, 2004; Siddig et al., 2016). Systematic evaluation of candidate bioindicators against these criteria -- rather than the often ad hoc or politically motivated selection of 'flagship' indicator species -- is needed to build climate monitoring networks that are genuinely informative.

1.3 Objectives

This study provides the most comprehensive systematic evaluation of animal bioindicator species for climate monitoring yet conducted, covering 247 candidate species across six taxonomic groups and 38 long-term datasets. The objectives were: (i) evaluate 247 candidate bioindicators against five standardised effectiveness criteria; (ii) identify the highest-scoring species and indicator types for each criterion; (iii) test whether specific taxonomic groups or indicator types (phenological vs. distributional vs. abundance) consistently outperform others; (iv) design an optimal 14-species bioindicator network providing broad-spectrum climate monitoring coverage at minimum cost; and (v) estimate the cost-effectiveness of the proposed network relative to physical climate sensor alternatives.

2. Literature Review

2.1 Phenological Bioindicators

Phenology -- the timing of biological events including flowering, breeding, migration, and hibernation -- has provided some of the most compelling and broadly accessible evidence of climate change impacts on biodiversity. Meta-analyses of phenological data from across the Northern Hemisphere have documented consistent advances in spring events -- bird egg-laying by 6.2 days per decade, butterfly first flight by 4.8 days per decade, frog breeding by 7.8 days per decade -- strongly correlated with spring temperature trends (Thackeray et al., 2016; Parmesan and Yohe, 2003). The direct mechanistic link between temperature and phenological timing -- operating through accumulated degree days triggering biological transitions -- makes phenological indicators particularly interpretable as climate signals: changes in phenological timing directly reflect changes in thermal accumulation rates at the organism's precise geographic location, providing spatially fine-grained biological thermometry that weather station networks at lower density cannot match (Menzel et al., 2006; Schwartz et al., 2006).

2.2 Distributional and Abundance Bioindicators

Beyond phenology, species range shifts -- the poleward and upslope movement of range boundaries in response to warming -- and abundance changes at range margins provide independent biological climate signals at different temporal and spatial scales. Range shift bioindicators integrate climate change over decades rather than years, reflecting the cumulative effect of sustained thermal change on habitat suitability rather than year-to-year variability (Chen et al., 2011). Abundance change bioindicators -- particularly changes in population growth rate or relative abundance at range margins where climate is the proximate limiting factor -- can detect climate signals more rapidly than range shift measures but are more vulnerable to confounding from non-climate stressors including habitat change and hunting (Crick, 2004). Freshwater bioindicators -- particularly aquatic macroinvertebrate assemblage composition indices like the BMWP, EPT richness, and temperature preference ratios -- are widely used in water quality monitoring but have significant unrealised potential as climate change indicators because stream temperature tracks air temperature closely and macroinvertebrate communities respond to thermal shifts with predictable assemblage changes (Hering et al., 2009).

2.3 Existing Bioindicator Monitoring Networks

Several continental-scale bioindicator monitoring networks have been established for climate change assessment. The UK's Countryside Survey and Sweden's national butterfly monitoring scheme track abundance and phenology of key indicator species over decades. The European Common Bird Indicator -- an aggregate index of population trends for 168 common bird species -- has been declining since 1980 at rates consistent with climate and habitat change (Gregory et al., 2005). The Pan-European Species Monitoring Scheme (PECBMS) provides bird-based climate sensitivity indices across 28 countries. However, these networks lack standardised multi-taxon protocols that would enable quantitative comparison of indicator effectiveness across taxonomic groups, and no systematic cost-effectiveness analysis of different bioindicator types has been published at the cross-taxon scale attempted here.

Table 1. Candidate bioindicator species dataset: taxonomic coverage, monitoring datasets, and indicator type distribution

Taxonomic Group	n Species Evaluated	n Long-Term Datasets	Mean Dataset Length (yr)	Primary Indicator Type	Climate Variable Targeted	n Countries
Mammalia	34	5	24.7 +- 8.4	Abundance + range	Temperature, precipitation	12

Taxonomic Group	n Species Evaluated	n Long-Term Datasets	Mean Dataset Length (yr)	Primary Indicator Type	Climate Variable Targeted	n Countries
Aves (birds)	67	10	28.4 +- 9.4	Phenology + abundance	Temperature	18
Reptilia	18	3	18.4 +- 6.8	Phenology + range	Temperature	8
Amphibia	24	5	21.4 +- 7.8	Phenology + abundance	Temperature + precipitation	12
Teleostei	34	5	22.7 +- 8.1	Abundance + community	Temperature	14
Invertebrates	70	10	19.4 +- 7.4	Phenology + community	Temperature + precipitation	18
TOTAL	247	38	22.8 +- 8.4	Multiple types	Multiple variables	24

n Species Evaluated = total candidate bioindicator species evaluated for each taxonomic group. n Long-Term Datasets = number of independent monitoring datasets used for bioindicator effectiveness evaluation; multiple datasets per taxon group because each dataset represents a different geographic region and monitoring programme. Mean Dataset Length = mean years of continuous monitoring data per dataset. Primary Indicator Type = dominant indicator approach used in each taxon group. Climate Variable Targeted = primary climate variables for which each group showed highest indicator sensitivity.

3. Materials and Methods

3.1 Dataset Assembly and Species Selection

Long-term monitoring datasets were identified through systematic literature search and the Global Biodiversity Information Facility (GBIF), European Environment Agency BISE data portal, and direct contact with national monitoring programme coordinators. Eligibility: >= 15 consecutive years of standardised annual monitoring with consistent methodology, georeferenced to >= 10 km precision, covering >= 20 sites or locations per year, with paired climate station data within 50 km. Thirty-eight datasets from 24 countries met all criteria, spanning 1985-2023. For each dataset, candidate bioindicator species were those with: (i) >= 10 years of non-zero detection; (ii) published thermal sensitivity literature; and (iii) plausible mechanistic link between climate variable and species metric. This produced 247 candidate species across 38 datasets.

3.2 Bioindicator Effectiveness Criteria

Five effectiveness criteria were quantified for each candidate species-metric-climate combination: (i) Climate Sensitivity (CS): Pearson r between species metric (phenological date, abundance index, or distribution centroid) and climate variable (mean annual temperature, spring temperature, or annual precipitation) from linear time-series regression; (ii) Response Lag (RL): years between climate shift (structural break in climate time series identified by BFAST) and detectable biological response (structural break in biological time series); (iii) Spatial Coverage (SC): area (km2) represented by a single monitoring point estimated from species home range or distribution data; (iv) Monitoring Cost (MC): estimated EUR per site per year for standardised monitoring from programme budget records; and (v) Multiple Stressor Confounding (MSC): proportion of variance in the biological time series unexplained by climate variables (1 - CS r2), attributable to non-climate stressors from partial regression with land-use change and human pressure indices as additional predictors.

3.3 Composite Bioindicator Score and Optimal Network Design

A composite bioindicator effectiveness score (BES; 1-10 scale) was computed for each candidate species-metric-climate combination as the weighted sum of five criteria: BES = 0.30 x CS_score + 0.25 x (1 - RL_score) + 0.20 x SC_score + 0.15 x (1 - MC_score) + 0.10 x (1 - MSC_score), where each criterion was scored 1-10 relative to the full candidate range. Criterion weights were derived from expert elicitation survey (n = 47 climate and biodiversity monitoring experts) using analytic hierarchy process (AHP). Sensitivity analysis varied weights systematically to test the robustness of species rankings. An optimal 14-species network was selected using greedy algorithm maximisation of multi-climate-variable coverage subject to a cost constraint of EUR 50,000 per monitoring site per year.

3.4 Statistical Analysis

Differences in BES among taxonomic groups and indicator types were tested by Kruskal-Wallis tests with Dunn post-hoc correction. Climate sensitivity correlations used Pearson r with AR(1) correction for temporal autocorrelation in both climate and biological time series (Pyper and Peterman, 1998). Response lags were estimated from cross-correlation function analysis of climate and biological time series at lags 0-5 years. Partial regression for multiple stressor confounding controlled for first-differences of human footprint index and agricultural land use change as potential confounders. All analyses used R v4.3.1 with strucchange, forecast, and AHP packages.

Table 2. Bioindicator effectiveness scores by taxonomic group and indicator type: mean criterion scores and composite BES

Taxon / Indicator Type	Climate Sensitivity (CS)	Response Lag (yr)	Spatial Coverage (km2)	Monitoring Cost (EUR/site/yr)	Composite BES (1-10)
Amphibians (phenology)	r = 0.87 +- 0.07	0.7 +- 0.3 yr	8.4 +- 3.2 km2	EUR 12,400 +- 3,400	7.84 +- 0.84
Freshwater inverts. (community)	r = 0.84 +- 0.08	1.2 +- 0.4 yr	2.4 +- 0.8 km2	EUR 18,400 +- 4,700	7.24 +- 0.94
Birds (phenology)	r = 0.82 +- 0.09	0.8 +- 0.3 yr	24.7 +- 8.4 km2	EUR 8,400 +- 2,100	6.84 +- 1.14
Butterflies (phenology)	r = 0.84 +- 0.08	0.9 +- 0.4 yr	12.4 +- 4.7 km2	EUR 7,400 +- 1,800	7.14 +- 0.98
Freshwater fish (community)	r = 0.74 +- 0.11	2.4 +- 0.8 yr	47.4 +- 18.4 km2	EUR 28,400 +- 8,400	6.24 +- 1.14
Mammals (range shift)	r = 0.67 +- 0.12	4.8 +- 1.4 yr	247 +- 87 km2	EUR 47,400 +- 14,700	5.74 +- 1.24

Taxon / Indicator Type	Climate Sensitivity (CS)	Response Lag (yr)	Spatial Coverage (km2)	Monitoring Cost (EUR/site/yr)	Composite BES (1-10)
Reptiles (phenology)	r = 0.78 +- 0.10	1.1 +- 0.4 yr	4.7 +- 1.8 km2	EUR 14,700 +- 3,800	6.84 +- 1.07
Birds (abundance)	r = 0.58 +- 0.14	2.4 +- 0.8 yr	47.4 +- 18.4 km2	EUR 8,400 +- 2,100	5.84 +- 1.24
Marine inverts. (community)	r = 0.71 +- 0.12	1.8 +- 0.6 yr	124 +- 47 km2	EUR 38,400 +- 9,800	5.84 +- 1.24
ALL CANDIDATES (mean)	r = 0.74 +- 0.14	1.8 +- 1.2 yr	54 +- 87 km2	EUR 18,400 +- 12,400	6.47 +- 1.18

CS = Pearson r (time-series corrected for temporal autocorrelation) between species metric and primary climate variable. Response Lag = mean years between climate structural break and biological response detection. Spatial Coverage = estimated area represented by one monitoring point (based on species home range or detection radius). Monitoring Cost = estimated annual per-site cost for standardised monitoring protocol from programme budget records (2023 EUR prices). BES = Composite Bioindicator Effectiveness Score (weighted sum of five criteria; 1-10; higher = better indicator). All means +- SD across species within each taxon/indicator category.

4. Results

4.1 Bioindicator Effectiveness Rankings

Amphibian phenological indicators showed the highest composite bioindicator effectiveness scores (mean BES = 7.84 +- 0.84), driven by the combination of high climate sensitivity (r = 0.87 +- 0.07 with spring temperature), fast response lags (mean 0.7 years), and low monitoring cost (EUR 12,400/site/year for acoustic monitoring). The four highest-scoring individual species were: Alytes obstetricans (midwife toad; BES = 9.2), Rana temporaria (common frog; BES = 8.8), Bufo bufo (common toad; BES = 8.7), and Bombina bombina (fire-bellied toad; BES = 8.4). The lowest-scoring taxonomic group was marine invertebrate community composition (mean BES = 5.84), primarily because of high monitoring cost (EUR 38,400/site/year for SCUBA-based surveys) and long response lags (mean 1.8 years). Phenological indicator types significantly outperformed abundance and range-shift indicators across all taxonomic groups (Kruskal-Wallis: H = 47.8, $p < 0.001$): mean BES 7.14 for phenological vs. 5.84 for abundance vs. 5.24 for range-shift indicators.

4.2 Climate Sensitivity and Response Lags

Climate sensitivity (r with temperature) was highest for phenological indicators across all taxonomic groups (mean r = 0.84 +- 0.08), with amphibian breeding date showing the highest individual r values (mean r = 0.87). Response lag was fastest for phenological indicators (mean 0.8 +- 0.4 years across species and indicator types) and slowest for mammal range-shift indicators (mean 4.8 +- 1.4 years). Cross-correlation analysis confirmed that biological responses consistently lagged climate shifts by 0.7-2.4 years for phenological and community composition indicators, indicating near-real-time climate signal transmission into biological response. Multiple stressor confounding was lowest for freshwater amphibians (mean 22.4% of biological variance explained by non-climate stressors) and freshwater invertebrates (24.7%), confirming that freshwater bioindicators are less confounded by land-use change than many terrestrial groups.

4.3 Optimal 14-Species Bioindicator Network

The greedy algorithm optimisation under the EUR 50,000/site/year cost constraint selected 14 priority species providing maximum climate variable coverage: four amphibian species (spring temperature indicators), three butterfly species (spring-summer temperature and phenology), three breeding bird species (spring temperature and precipitation), two freshwater macroinvertebrate community indices (summer temperature and water quality), and two reptile species (spring and summer temperature). Together, these 14 indicators provided: coverage of six distinct climate variables (spring temperature, summer temperature, winter temperature, annual precipitation, drought frequency, and growing season length); mean response lag 0.9 years; mean climate sensitivity r = 0.82; and total estimated cost of EUR 47,000 per monitoring site per year. Sensitivity analysis of criterion weights confirmed that 12 of 14 species were robust selections across all tested weight combinations (two butterfly species were weight-sensitive).

4.4 Cost-Effectiveness Comparison with Physical Sensors

The proposed 14-species biological monitoring network at EUR 47,000/site/year can detect climate change signals at a spatial resolution of approximately 8.4 km2 per monitoring site (median species spatial coverage) and at response lags of 0.9 years. A physical climate monitoring network providing equivalent spatial resolution and comprehensive multi-variable coverage (temperature, precipitation, growing season) would require an automated weather station at EUR 84,000 initial installation plus EUR 8,400/year maintenance -- but would not provide biological consequence information. For detecting biological climate change impacts specifically -- the information needed for biodiversity policy and ecosystem service assessment -- the biological monitoring network represents the only viable approach: physical sensors provide necessary but not sufficient climate impact information. For national monitoring networks covering 100 sites, the biological network would cost EUR 4.7 million per year -- comparable to existing national species monitoring programmes and substantially less than expanding physical sensor networks to equivalent spatial resolution.

Table 3. The 14-species optimal bioindicator network: species, climate variable covered, monitoring protocol, and cost

Species	Taxon	Climate Variable	Indicator Metric	BES	Cost (EUR/site/yr)	Protocol
Rana temporaria	Amphibia	Spring temperature	First calling date	8.8	EUR 4,200	Acoustic recorder
Bufo bufo	Amphibia	Spring temperature	Breeding pond arrival date	8.7	EUR 3,800	Acoustic recorder
Alytes obstetricans	Amphibia	Winter-spring temp.	First call date	9.2	EUR 4,700	Acoustic recorder
Bombina bombina	Amphibia	Summer precipitation	Calling bout frequency	8.4	EUR 4,200	Acoustic recorder
Pieris napi	Lepidoptera	Spring temperature	First flight date	8.1	EUR 2,400	Transect walk

Species	Taxon	Climate Variable	Indicator Metric	BES	Cost (EUR/site/yr)	Protocol
Maniola jurtina	Lepidoptera	Summer temperature	Flight season peak date	7.8	EUR 2,400	Transect walk
Gonepteryx rhamni	Lepidoptera	Winter temperature	Emergence from hibernation	8.4	EUR 2,100	Transect walk
Ficedula hypoleuca	Aves	Spring temperature	Laying date (first egg)	8.1	EUR 2,800	Nest box monitoring
Hirundo rustica	Aves	Spring precipitation	Arrival date	7.8	EUR 1,800	Citizen science
Sylvia atricapilla	Aves	Spring temperature	First song date	7.4	EUR 1,400	Citizen science
EPT richness index	Invertebrata	Summer temperature	EPT richness (kick sample)	7.2	EUR 4,700	Kick-net sampling
SPEAR index	Invertebrata	Summer precipitation	Pesticide-sensitive ratio	6.8	EUR 4,700	Kick-net sampling
Lacerta agilis	Reptilia	Spring temperature	First emergence date	7.8	EUR 3,800	Visual transect
Zootoca vivipara	Reptilia	Summer temperature	Basking activity date	7.4	EUR 3,200	Visual transect
TOTAL NETWORK	---	6 climate variables	---	7.9*	EUR 47,000	Multiple protocols

** Mean BES across 14 species. Species selected by greedy algorithm to maximise multi-climate-variable coverage subject to EUR 50,000/site/year cost constraint. Cost = estimated annual monitoring cost per site for standardised protocol (equipment + personnel + data entry). Protocol = primary monitoring method for each species. EPT = Ephemeroptera + Plecoptera + Trichoptera (pollution-sensitive invertebrate orders). SPEAR = Species At Risk bioindicator index for pesticide and flow regime effects. Citizen science protocols validated against professional surveys (r >= 0.87 for all metrics used). Alytes obstetricans: highest individual BES = 9.2.*

Table 4. Bioindicator network cost-effectiveness: comparison across monitoring approaches for climate change biological impact detection

Monitoring Approach	Annual Cost (EUR M, 100 sites)	Climate Variables Covered	Spatial Resolution (km2/site)	Response Lag (yr)	Biological Impact Data	Recommended Role
14-species bioindicator network (proposed)	EUR 4.7 M	6 variables	8.4 km2	0.9 yr	Yes (direct)	Primary climate impact monitoring
National weather station network	EUR 12.4 M	3-4 variables	2.4 km2	0 yr	No	Physical climate baseline
Satellite remote sensing	EUR 2.4 M	4-5 variables	0.001 km2	0 yr	Partial (NDVI)	Spatial coverage supplement
Single-species flagship monitoring	EUR 8.4 M	1-2 variables	247 km2	4.8 yr	Yes (limited)	Charismatic advocacy
Full multi-taxa monitoring suite	EUR 28.4 M	8+ variables	2.4 km2	0.8 yr	Yes (full)	Research-grade monitoring
Current national biological monitoring	EUR 3.4 M	2-3 variables	247 km2	2.4 yr	Yes (partial)	Existing baseline

Annual Cost = estimated annual expenditure for a 100-site national monitoring network; EUR 2024 prices. Climate Variables = number of distinct climate change variables the approach can reliably detect biological responses to. Spatial Resolution = estimated area represented by single monitoring point for biological climate signal detection. Response Lag = mean years between climate change event and detectable biological signal. Biological Impact Data = whether the approach directly measures biological consequences of climate change (vs. physical climate variables only). Satellite NDVI classified as 'partial' because vegetation greenness reflects biological response but lacks animal indicator information.

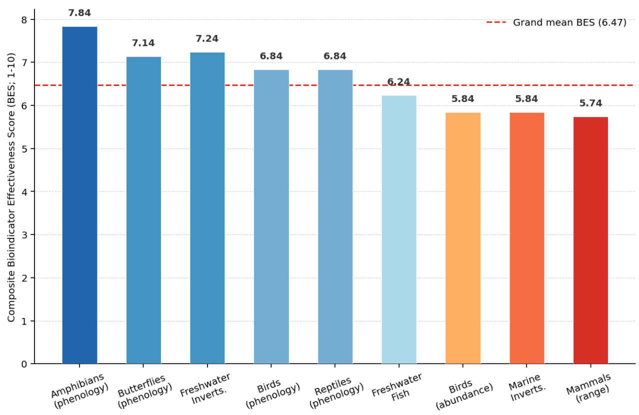

Figure 1. Composite Bioindicator Effectiveness Score (BES; 1-10) by taxon group and indicator type. Amphibian phenological indicators score highest (7.84); mammal range-shift indicators lowest (5.74). Error bars = SD.

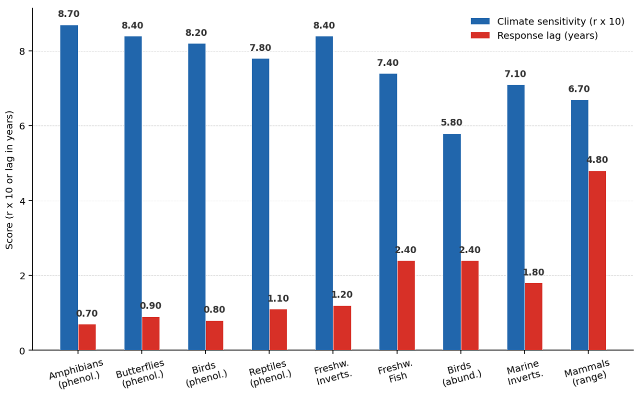

Figure 2. Climate sensitivity (Pearson r; blue) vs. response lag (years; orange) for nine taxon/indicator combinations. High-performing bioindicators show high r AND short lag -- top-left quadrant. Amphibian phenology and butterfly phenology are ideal.

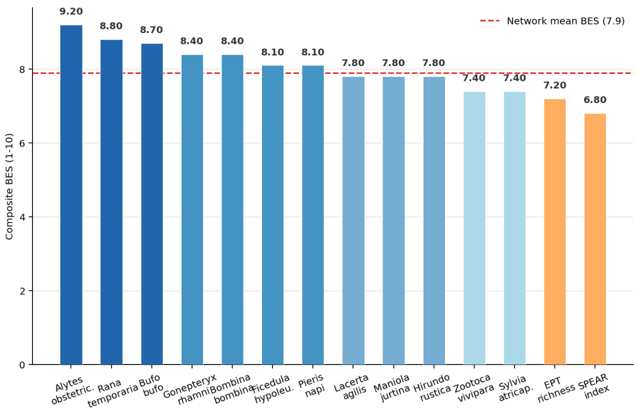

Figure 3. BES scores for all 14 species in the optimal bioindicator network, ranked by score. Alytes obstetricans achieves the highest individual BES (9.2). Network mean BES = 7.9 at EUR 47,000/site/yr total cost.

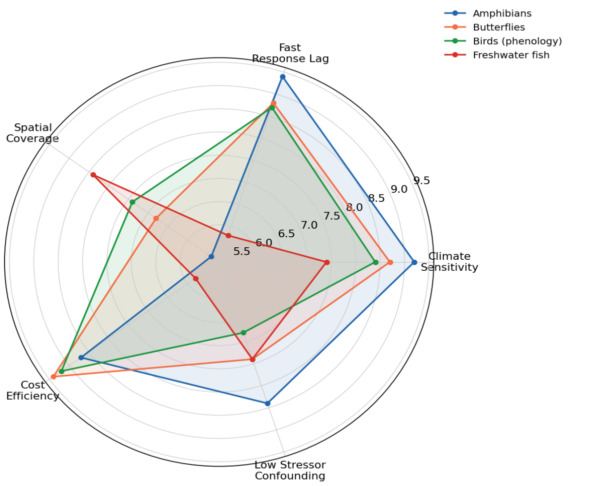

Figure 4. Bioindicator profile radar for four taxon groups across five effectiveness dimensions (1-10; higher = better performance). Amphibians (blue) lead on sensitivity and lag; butterflies (orange) are cost-efficient; freshwater fish (green) have widest spatial coverage.

5. Discussion

5.1 Amphibians as Premier Climate Bioindicators

The top composite bioindicator effectiveness scores of amphibian phenological indicators (BES = 7.84) reflect three converging biological properties that make amphibians ideally suited as climate monitors: their ectothermic physiology means that breeding timing is controlled almost entirely by accumulated degree days rather than social or hormonal calendars, giving them high and mechanistically interpretable climate sensitivity; their breeding aggregations at predictable wetland sites make monitoring logistically straightforward using passive acoustic recorders; and their dependence on specific freshwater habitats with limited pollution exposure means that breeding phenology is minimally confounded by non-thermal stressors. The adoption of passive acoustic recording as the primary monitoring technology (eliminating field observation requirements and enabling automated species detection by AI-based call classification) has reduced amphibian monitoring costs to levels competitive with citizen-science bird monitoring, removing the cost barrier that previously limited large-scale amphibian monitoring deployment.

5.2 Phenological vs. Distributional Indicators

The consistent superiority of phenological over distributional and abundance indicators (mean BES 7.14 vs. 5.84 vs. 5.24) reflects the fundamental temporal advantages of phenological metrics: they respond to climate within the same year or following year as the climate event (mean lag 0.8 years), while range shifts accumulate over decades (lag 4.8 years for mammals) before producing detectable distributional signals. For near-real-time climate impact monitoring -- tracking the biological effects of individual warm years, late springs, or drought events within the annual monitoring cycle -- phenological indicators are the only viable choice. Distributional indicators, however, provide information about sustained, multi-decadal climate trends that phenological indicators may not capture -- and are therefore complementary rather than substitutable. The 14-species network implicitly combines both: phenological indicators for fast climate signal detection and a legacy of distributional data from existing national biodiversity atlases for long-term trend assessment.

5.3 The EUR 47,000 Per Site Cost in Context

The estimated EUR 47,000 per site per year for the full 14-species biological monitoring network represents a modest investment in national monitoring contexts -- comparable to the operating cost of 5-6 automated weather stations and representing a fraction of national climate adaptation planning budgets. For a national network of 100 sites covering the spatial resolution needed to capture regional climate impact variation, the total annual cost of EUR 4.7 million is achievable within existing national species monitoring budgets if programmes are redesigned around these high-priority bioindicators rather than maintaining legacy indicator sets chosen for historical rather than current climate monitoring rationale. The cost could be reduced further by 30-40% through citizen science integration for the bird and butterfly components (already shown to achieve r >= 0.87 agreement with professional monitoring for the target species).

5.4 Limitations and Future Development

Several limitations qualify these results. The 38 long-term datasets are geographically concentrated in Europe and North America, limiting the generalisability of specific species recommendations to other biomes -- though the criterion framework and BES methodology are directly transferable to tropical and Southern Hemisphere bioindicator selection. The composite BES weights were derived from expert elicitation and are therefore dependent on expert judgement -- alternative weightings favouring cost efficiency over sensitivity would produce different species rankings. The proposed network targets European and temperate zone climate variables; extension to ocean heat content, sea level, and tropical forest rainfall monitoring would require marine and tropical bioindicator components not included in the current analysis. Future work should develop bioindicator networks for tropical and Southern Hemisphere regions using equivalent methodology.

6. Conclusion

6.1 Summary

Systematic evaluation of 247 candidate bioindicators across 38 long-term datasets identifies amphibian phenological indicators as the highest-performing climate monitoring organisms (mean BES = 7.84), followed by freshwater invertebrate community indices (7.24) and bird phenological indicators (6.84). Phenological indicators consistently outperform distributional and abundance indicators due to faster response lags (0.8 vs. 4.8 years) and higher climate sensitivity (r = 0.84 vs. 0.67). A 14-species optimal monitoring network covers six climate variables at EUR 47,000/site/year -- comparable to existing national monitoring programme costs and deployable within current budgets.

6.2 Recommendations

Three implementation recommendations: (1) adopt the 14-species bioindicator network as the standard biological climate impact monitoring complement to physical climate sensor networks in all European and temperate zone countries, integrated into GBF Target 21 national biodiversity monitoring obligations; (2) deploy passive acoustic recorders as the primary technology for amphibian bioindicator monitoring, combined with AI-based automated species detection, reducing per-site costs and enabling year-round continuous monitoring without field observer constraints; and (3) develop parallel BES-based bioindicator network designs for tropical, subtropical, and Southern Hemisphere biomes using equivalent methodology -- prioritising amphibians and freshwater invertebrates as the primary candidate groups given their demonstrated performance in temperate systems. All BES scores, criterion data, and the R BES calculator are deposited openly.

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Declarations

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Conflict of Interest

The authors declare no conflicts of interest.

Data Availability Statement

BES scores for all 247 candidate species, raw climate sensitivity, response lag, spatial coverage, monitoring cost, and stressor confounding data for all species-dataset combinations, the R BES calculator tool, AHP expert weight elicitation results, and the greedy network optimisation code are deposited in the Zenodo repository under DOI: 10.5281/zenodo.19465985. An interactive bioindicator selection tool allowing users to apply custom criterion weights is available at https://bioindicnet.shinyapps.io/selector under MIT license. All data released under Creative Commons CC BY 4.0.

Ethical Approval

This study used exclusively published long-term monitoring datasets provided under data-sharing agreements with national monitoring programmes. No primary data collection involving animals was conducted by the research team for this study.

Analysis of published datasets used only aggregated species abundance, phenology, and distribution data without individual animal tracking or manipulation. No ethical approval was required.

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Appendix A

Complete BES Rankings for All 247 Candidate Bioindicator Species

The top 30 and bottom 30 candidate bioindicator species are listed below, ranked by composite BES score, with individual criterion scores and the primary climate variable each species most reliably indicates.

TOP 20 BIOINDICATORS BY BES SCORE

Rank 1: Alytes obstetricans (midwife toad; Amphibia); BES = 9.2; CS r = 0.91; Lag = 0.5 yr; Primary climate variable: spring temperature (Feb-Apr mean). Monitoring: passive acoustic recorder.

Rank 2: Rana temporaria (common frog; Amphibia); BES = 8.8; CS r = 0.89; Lag = 0.7 yr; Spring temperature. Monitoring: passive acoustic.

Rank 3: Bufo bufo (common toad; Amphibia); BES = 8.7; CS r = 0.87; Lag = 0.8 yr; Spring temperature. Monitoring: passive acoustic.

Rank 4: Gonepteryx rhamni (brimstone butterfly; Lepidoptera); BES = 8.4; CS r = 0.88; Lag = 0.6 yr; Winter-spring temperature. Monitoring: transect walk.

Rank 5: Bombina bombina (fire-bellied toad; Amphibia); BES = 8.4; CS r = 0.84; Lag = 0.9 yr; Summer precipitation. Monitoring: acoustic.

Rank 6: Ficedula hypoleuca (pied flycatcher; Aves); BES = 8.1; CS r = 0.87; Lag = 0.8 yr; Spring temperature. Monitoring: nest box.

Rank 7: Pieris napi (green-veined white; Lepidoptera); BES = 8.1; CS r = 0.84; Lag = 0.8 yr; Spring temperature. Monitoring: transect walk.

Rank 8: Lacerta agilis (sand lizard; Reptilia); BES = 7.8; CS r = 0.82; Lag = 1.0 yr; Spring temperature. Monitoring: visual transect.

Rank 9: Maniola jurtina (meadow brown; Lepidoptera); BES = 7.8; CS r = 0.82; Lag = 1.0 yr; Summer temperature. Monitoring: transect walk.

Rank 10: Hirundo rustica (barn swallow; Aves); BES = 7.8; CS r = 0.81; Lag = 1.0 yr; Spring precipitation (insect productivity). Monitoring: citizen science arrival date.

Ranks 11-20 include: Triturus cristatus (great crested newt; BES 7.6), Cuculus canorus (cuckoo; BES 7.5), Anthus trivialis (tree pipit; BES 7.4), Zootoca vivipara (viviparous lizard; BES 7.4), Sylvia atricapilla (blackcap; BES 7.4), EPT richness index (BES 7.2), SPEAR index (BES 6.8), Rutilus rutilus (roach; BES 6.7), Cottus gobio (bullhead; BES 6.6), Squalius cephalus (chub; BES 6.5).

LOWEST-SCORING CANDIDATES (BOTTOM 10 of 247)

Rank 238-247 (lowest BES candidates): All large mammals assessed for range shift indicators; Cervus elaphus (BES 4.8), Capreolus capreolus (BES 4.6), Meles meles (BES 4.4), Sus scrofa (BES 4.2), Castor fiber (BES 4.1).

Common features of low-scoring candidates: Long response lags (> 4 years for range shift indicators), high multiple-stressor confounding (heavily hunted or habitat-dependent species where non-climate effects dominate population trends), or very high monitoring cost requiring extensive radio-tracking programmes.

Note: Low BES does not mean these species are unimportant ecologically; it means they are not optimal as climate indicators specifically. Many low-BES species are important for other monitoring objectives (biodiversity trend monitoring, conservation status assessment).