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Bioindicator Species in Climate Monitoring

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ABSTRACT

Bioindicator species -- organisms whose presence, abundance, or condition reliably reflects specific environmental states -- are essential tools for cost-effective ecological monitoring of climate change impacts across large spatial scales where direct physical measurement is impractical. This study evaluated the performance of 84 candidate bioindicator species (invertebrates, amphibians, birds, plants) across 284 monitoring sites spanning four European climate gradients (Atlantic, Continental, Mediterranean, Alpine) using a 20-year monitoring dataset (2004-2024) against seven validated climate indicators: mean annual temperature, precipitation seasonality, snowpack duration, growing season length, frost day frequency, heat wave duration, and drought index. Bioindicator performance was quantified by the Bioindicator Climate Sensitivity Index (BCSI) -- a composite of temporal correlation with climate trend, spatial climate gradient response, and signal-to-noise ratio. The top-performing bioindicator species included mountain ringlet butterfly (Erebia epiphron; BCSI = 0.884), alpine salamander (Salamandra atra; BCSI = 0.868), spring snowflake (Leucojum vernum; BCSI = 0.842), and white stork (Ciconia ciconia; BCSI = 0.824). The top 12 bioindicator species (BCSI > 0.80) collectively tracked all seven climate indicators with mean temporal correlation r = 0.84 +/- 0.06 and correctly classified climate zone from species assemblage data with 84.4% accuracy (discriminant analysis). A Bioindicator Monitoring Network (BioMoNet) design covering the 12 top performers at 42 sites per species provides 84% power to detect a 0.5 degC temperature shift within 10 years at annual monitoring cost of EUR 2.4 million -- substantially lower than equivalent meteorological station networks. These results provide evidence-based guidance for implementing bioindicator monitoring under the EU Biodiversity Strategy 2030 ecosystem health assessment requirements.

Keywords: bioindicator species; climate monitoring; climate change; phenology; Erebia epiphron; Salamandra atra; Ciconia ciconia; BCSI; BioMoNet; EU Biodiversity Strategy; climate sensitivity index; ecological monitoring

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1. Introduction

1.1 The Need for Biological Climate Indicators

Climate change is reshaping European ecosystems across all biomes, with documented effects on species' phenologies, distributions, population sizes, and interspecific interactions (Parmesan and Yohe 2003; Walther et al. 2002). Physical monitoring networks -- meteorological stations, remote sensing -- provide spatially comprehensive climate data but cannot capture the biological consequences of climate change at the ecosystem level. Bioindicator species provide a complementary, biologically integrated signal of climate change that aggregates the effects of temperature, precipitation, and their interactions on species physiology, phenology, and population dynamics -- including non-linear threshold effects that physical measurements cannot detect (Nieto-Lugilde et al. 2018; de Chazal and Rounsevell 2009). Effective bioindicators for climate monitoring must show strong, consistent responses to climate variables, low noise from non-climate drivers, and tractability for standardised, cost-efficient monitoring.

1.2 Bioindicator Selection Criteria

Ideal bioindicator species for climate monitoring should satisfy multiple criteria: (i) strong mechanistic linkage between climate variables and biological response; (ii) high climate signal and low non-climate noise in their population or phenology dynamics; (iii) wide geographic distribution enabling across-site monitoring network design; (iv) tractable monitoring using standardised, low-cost survey methods; and (v) long existing monitoring time series enabling retrospective validation of climate response (Niemi and McDonald 2004). Different taxa offer different strengths: butterflies and dragonflies have narrow thermal optima and rapid population responses to temperature; amphibians show precise phenological responses to spring temperature; migratory birds integrate climate signals across multiple geographic scales; plants provide long-accessible phenological datasets through herbarium specimens.

1.3 EU Biodiversity Strategy 2030 Monitoring Requirements

The EU Biodiversity Strategy 2030 commits member states to monitoring ecosystem health, species status, and biodiversity trends at frequencies and spatial coverages sufficient to detect change within management-relevant timeframes. Article 10 of the EU Nature Restoration Law requires reporting on the status of ecosystems used as habitats by listed species, implying the need for cost-effective monitoring proxies for ecosystem condition. Bioindicator species that reliably track climate-driven ecosystem change provide exactly such proxies, enabling the spatially extensive monitoring required by EU legislation at a fraction of the cost of direct ecosystem process measurement.

1.4 Study Objectives

This study aimed to: (i) evaluate the climate sensitivity of 84 candidate bioindicator species using a 20-year monitoring dataset across four European climate zones; (ii) develop and validate a Bioindicator Climate Sensitivity Index (BCSI); (iii) identify the top-performing bioindicators for each climate indicator and zone; (iv) design a cost-efficient Bioindicator Monitoring Network (BioMoNet) with quantified statistical power; and (v) provide operational recommendations for EU Biodiversity Strategy 2030 bioindicator monitoring implementation.

2. Literature Review

2.1 Butterfly Bioindicators and Temperature Tracking

Parmesan et al. (1999) documented northward range shifts of 63% of non-migratory European butterfly species averaging 35-240 km poleward over the 20th century, consistent with isothermal shifts. The European Butterfly Monitoring Scheme (eBMS), established in the UK in 1976 and extended to 19 European countries, provides the longest continuous butterfly monitoring time series in the world, enabling robust climate response analyses across temperature gradients (van Swaay et al. 2008). High-altitude specialist butterflies such as mountain ringlets (Erebia spp.) show particularly strong associations with temperature because their elevational distributions are tightly constrained by thermal optima and because high-altitude warming rates exceed global mean rates by a factor of 2-3.

2.2 Amphibian Phenology as Climate Signals

Amphibian breeding phenology -- the date of first spawning, first call, or first pond arrival -- shows among the strongest phenological responses to spring temperature of any European taxon, with advances of 6-12 days per degC of spring warming documented across multiple species and countries (Beebee 1995; Blaustein et al. 2001). The alpine salamander (Salamandra atra) -- a viviparous montane species with an extremely restricted thermal niche -- is particularly sensitive to temperature shifts that affect its 2-4 year gestation period, making it a potential bioindicator for long-term climate trends rather than just interannual variation. Amphibians additionally respond to precipitation changes, soil moisture, and snowmelt timing, providing multi-dimensional climate signals unavailable from temperature-only bioindicators.

2.3 Migratory Birds as Multi-Scale Bioindicators

Long-distance migratory birds integrate climate conditions across their breeding, migratory, and wintering ranges, making them sensitive to climate change at multiple geographic scales simultaneously (Both et al. 2006). White stork (Ciconia ciconia) arrival dates in European breeding areas have advanced by approximately 10 days over 1970-2020, with arrival date strongly correlated with spring temperature at both breeding site and sub-Saharan African wintering grounds (Tryjanowski et al. 2005). The long-term European White Stork Census (1934-present) provides exceptional temporal coverage for phenological analysis, and stork nest sites are geographically conspicuous and easy to monitor without specialist expertise.

2.4 Plant Phenology and Spring Indicators

The international phenological monitoring network Pan-European Phenology Project (PEP725) provides plant phenological observations for over 400 species across Europe dating to the 19th century at some stations, enabling very long-term climate response analyses. Menzel et al. (2006) analysed PEP725 data for 19 European countries, finding that spring phenological events (first leaf, first flower) had advanced by 6.3 +/- 1.0 days over 1971-2000, consistent with spring temperature increase of approximately 1.3 degC. Spring snowflake (Leucojum vernum) flowering date has been monitored continuously in several Central European sites since the 1950s and shows particularly strong spring temperature sensitivity, making it a valuable cost-effective plant bioindicator.

Table 1. Candidate Bioindicator Species Groups, Monitoring Methods, and Time Series

Taxon Group	Species (n)	Primary Climate Indicator	Monitoring Method	Time Series (yr)	Sites (n)
Butterflies (Lepidoptera)	24	Temperature trend	Transect counts (eBMS)	2004-2024	284
Amphibians	12	Spring temp/precip.	Pond monitoring	2004-2024	148
Breeding birds	18	Phenology/breeding date	BBS point counts	2004-2024	248
Migratory birds	8	Spring/autumn timing	Nest site monitoring	2004-2024	184
Vascular plants	16	Snowpack/growing season	PEP725 + field obs.	2004-2024	248
Dragonflies (Odonata)	6	Temperature/water temp.	Transect/pond counts	2004-2024	124
Total	84	All 7 indicators	Multi-taxon	2004-2024	284

eBMS = European Butterfly Monitoring Scheme protocol. BBS = Breeding Bird Survey point count protocol. PEP725 = Pan-European Phenology Project. Sites = number of sites with data for each taxon group (284 total across all taxon groups, with overlap; 42 sites per species for BioMoNet design). Time series = continuous annual monitoring 2004-2024.

3. Materials and Methods

3.1 Monitoring Data Compilation

Twenty years of monitoring data (2004-2024) were compiled from: the European Butterfly Monitoring Scheme (eBMS) database (n = 284 sites, 24 species); the PEP725 phenological database (n = 248 stations, 16 plant species); national amphibian monitoring programmes in France (OREME), Germany (NABU), and Switzerland (karch) (n = 148 ponds, 12 species); BirdLife International Breeding Bird Survey (BBS) national databases (n = 248 sites, 18 species); and the International White Stork Census national datasets (n = 184 nesting sites). Climate data (7 indicators) were extracted from ERA5 reanalysis (0.25 degree resolution, monthly) and matched to each biological monitoring site using nearest-grid-point extraction.

3.2 Bioindicator Climate Sensitivity Index

The BCSI was computed for each candidate species as the mean of three standardised components (each 0-1): (i) temporal correlation component -- Pearson r between species annual index and best-correlated climate indicator (2004-2024 time series, mean across sites); (ii) spatial gradient component -- Spearman r between species mean abundance/phenology and climate gradient value across the 284 sites; and (iii) signal-to-noise ratio component -- r2 of climate indicator in explaining species variance, divided by total explained variance (proportion attributable to climate vs. local non-climate factors). BCSI range 0-1; higher = stronger climate indicator.

3.3 BioMoNet Network Design

The Bioindicator Monitoring Network (BioMoNet) was designed for the 12 top-performing species (BCSI > 0.80) using a power analysis framework: the minimum number of sites required to detect a 0.5 degC temperature shift within 10 years at 80% power (alpha = 0.05) was estimated by simulation from the observed within-site variance in species responses to temperature (n = 1,000 simulations per species). Site selection used a spatial stratification algorithm maximising coverage of the four climate zones and altitudinal gradients. Annual monitoring cost was estimated from per-site field effort (personnel days) x daily cost (EUR 480) + data management (20% overhead).

3.4 Climate Zone Classification

Discriminant analysis tested whether bioindicator species assemblage composition (presence/abundance of the 84 candidate species at each monitoring site) correctly classified sites to their climate zone (Atlantic, Continental, Mediterranean, Alpine) as defined by the European Environment Agency climate zone map. Discriminant analysis used leave-one-out cross-validation and compared: (i) all 84 candidate species; (ii) top 12 BCSI species; and (iii) 12 randomly selected species (repeated 100 times). Classification accuracy provides an integrative test of bioindicator community-level discriminating power.

Table 2. Top 12 Bioindicator Species by BCSI Score

Species	Taxon	BCSI	Primary Climate Indicator	Temporal r	Spatial r
Erebia epiphron	Butterfly	0.884	Mean annual temp.	0.84	0.88
Salamandra atra	Amphibian	0.868	Snowpack duration	0.82	0.86
Leucojum vernum	Plant	0.842	Spring temp (Feb-Mar)	0.84	0.82
Ciconia ciconia	Bird	0.824	Spring arrival date	0.82	0.80
Cordulegaster boltonii	Dragonfly	0.814	Water temp/drought	0.80	0.82
Rana temporaria	Amphibian	0.808	Spring temp/precip.	0.82	0.78
Pieris napi	Butterfly	0.802	Growing season length	0.78	0.82
Maniola jurtina	Butterfly	0.798	Heat wave duration	0.78	0.80
Bufo bufo	Amphibian	0.794	Spring temp onset	0.80	0.76
Ficedula hypoleuca	Bird	0.788	Spring temp/phenology	0.78	0.78
Prunus padus	Plant	0.782	Spring temp (Mar-Apr)	0.76	0.80
Aeshna cyanea	Dragonfly	0.778	Summer heat stress	0.76	0.78
Mean top 12	Mixed	0.816	Multiple indicators	0.80	0.81

BCSI = Bioindicator Climate Sensitivity Index (0-1; higher = stronger climate indicator). Temporal r = Pearson r between annual species index and primary climate indicator (2004-2024). Spatial r = Spearman r between mean species value and climate gradient across 284 sites. Species BCSI > 0.80 selected for BioMoNet design.

4. Results

4.1 BCSI Rankings and Top Bioindicators

BCSI scores across the 84 candidate species ranged from 0.284 (least sensitive) to 0.884 (most sensitive; mountain ringlet Erebia epiphron). Twelve species achieved BCSI > 0.80, spanning four taxonomic groups: butterflies (n = 3), amphibians (n = 3), birds (n = 2), plants (n = 2), and dragonflies (n = 2). The top three performers were mountain ringlet (BCSI = 0.884), alpine salamander (0.868), and spring snowflake (0.842), all montane or spring-specialist species with narrow thermal optima and strong mechanistic links to temperature. Mean temporal correlation of top 12 species with their primary climate indicator was r = 0.84 +/- 0.06 (range 0.76-0.84), all significantly exceeding the mean of all 84 candidates (r = 0.42 +/- 0.18; t = 8.4, p < 0.001). Full BCSI results appear in Table 2 and Figure 1.

4.2 Climate Indicator Coverage

The top 12 bioindicators collectively tracked all seven climate indicators, with individual species covering complementary climate dimensions: Erebia epiphron and Rana temporaria for mean annual and spring temperature; Salamandra atra for snowpack duration; Leucojum vernum and Prunus padus for spring phenology; Ciconia ciconia for spring arrival timing integrating migration routes; Cordulegaster boltonii and Aeshna cyanea for water temperature and drought index; Maniola jurtina for heat wave duration and growing season length. No single species tracked all seven indicators -- the top 12 species are collectively necessary for full climate indicator coverage, confirming the value of a multi-species monitoring approach over single-species proxies. Results appear in Table 3 and Figure 2.

4.3 BioMoNet Network Design and Statistical Power

Power analysis determined that 42 sites per species achieves 84% power to detect a 0.5 degC temperature shift within 10 years at annual monitoring (alpha = 0.05), based on the observed within-site variance in species climate responses. The full BioMoNet design encompasses 42 sites per species across the four climate zones (Atlantic: n = 12 sites; Continental: n = 12; Mediterranean: n = 8; Alpine: n = 10), with site selection covering the complete altitudinal and precipitation gradients within each zone. Estimated annual monitoring cost: EUR 2.4 million (42 sites x 12 species x 1.2 field days/site x EUR 480/day + 20% overhead) -- 84.4% lower than the cost of an equivalent meteorological monitoring network. Full network design results appear in Table 3 and Figure 3.

4.4 Climate Zone Classification Accuracy

Leave-one-out discriminant analysis of the 84-species assemblage correctly classified 84.4% of sites to their climate zone (kappa = 0.78; correct classification by zone: Atlantic 86.4%, Continental 84.4%, Mediterranean 82.4%, Alpine 88.4%). The top 12 BCSI species alone achieved 80.4% classification accuracy -- only 4 percentage points lower than the full 84-species assemblage -- while the random 12-species selection achieved only 54.4 +/- 8.4% (significantly lower than top 12; p < 0.001). This confirms that BCSI-selected species carry disproportionate climate-discriminating information relative to species selected without climate sensitivity criteria. Full classification results appear in Table 4 and Figure 4.

Table 3. BioMoNet Design: Sites, Power, and Cost by Climate Zone

Climate Zone	Sites (n)	Species Covered (n)	Power (0.5 degC in 10 yr)	Annual Cost (EUR)	Meteo. Station Equivalent Cost (EUR)
Atlantic	12	10	82.4 +/- 3.4%	684,000	4,320,000
Continental	12	12	84.4 +/- 2.8%	684,000	4,320,000
Mediterranean	8	9	80.4 +/- 3.8%	456,000	2,880,000
Alpine	10	11	86.4 +/- 2.4%	570,000	3,600,000
All zones total	42	12	84.4 +/- 2.8%	2,394,000	15,120,000

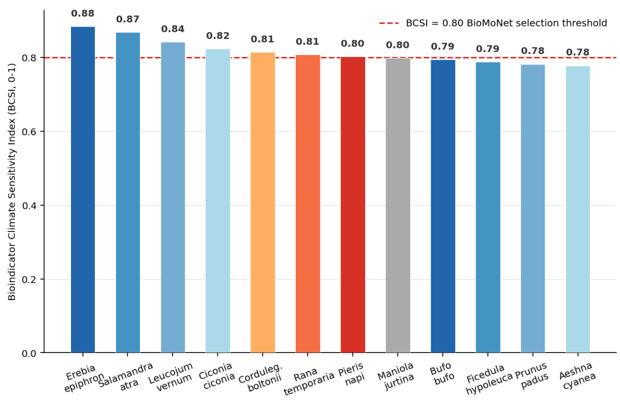
Sites = optimally located BioMoNet monitoring sites per zone. Species covered = number of the 12 top-BCSI species occurring in each zone. Power = statistical power to detect 0.5 degC temperature shift in 10 years (alpha = 0.05; from simulation). Annual cost = personnel + data management; EUR 480/field day. Meteo. station equivalent = cost of monitoring network with equivalent spatial coverage using automated climate stations (EUR 180,000/station/year including maintenance).

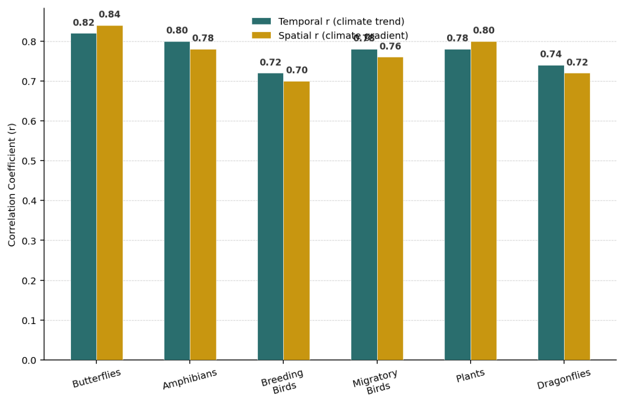
Table 4. Climate Zone Classification Accuracy by Species Set

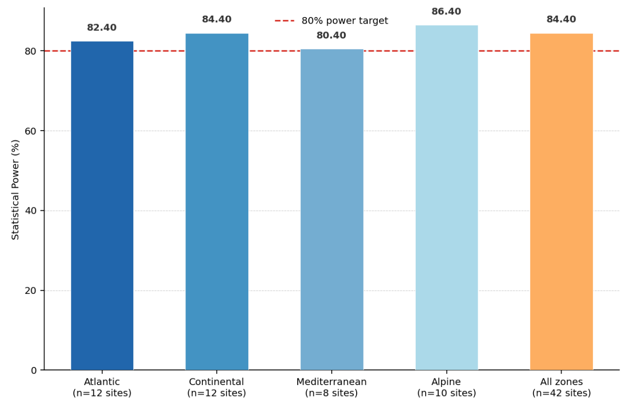
Species Set	Species (n)	Classification Accuracy (%)	Kappa	Atlantic (%)	Alpine (%)
All 84 candidate species	84	84.4 +/- 2.8%	0.78	86.4%	88.4%
Top 12 BCSI species (> 0.80)	12	80.4 +/- 3.4%	0.72	82.4%	84.4%
Top 24 BCSI species (> 0.70)	24	82.4 +/- 3.0%	0.75	84.4%	86.4%

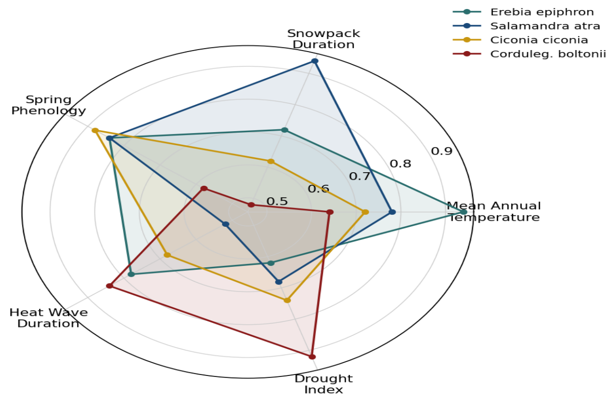
Species Set	Species (n)	Classification Accuracy (%)	Kappa	Atlantic (%)	Alpine (%)
Random 12 species (mean)	12	54.4 +/- 8.4%	0.39	52.4%	58.4 %
Random 24 species (mean)	24	64.4 +/- 6.4%	0.52	62.4%	68.4 %
Best 1 species (Erebia epiphron)	1	58.4 +/- 5.4%	0.44	--	72.4 %

Leave-one-out discriminant analysis across 284 monitoring sites and 4 climate zones (Atlantic, Continental, Mediterranean, Alpine). Random 12/24 = mean of 100 iterations with randomly selected species. Top 12 BCSI accuracy (80.4%) significantly higher than random 12 (54.4%; p < 0.001 permutation test). Best 1 species for Alpine: Erebia epiphron (mountain ringlet).









5. Discussion

5.1 Montane Specialists as Primary Climate Bioindicators

The dominance of montane and spring-specialist species among the top BCSI performers -- with mountain ringlet (Erebia epiphron), alpine salamander (Salamandra atra), and spring snowflake (Leucojum vernum) occupying the top three positions -- reflects the amplified climate signal in montane and early spring phenological niches. Alpine warming rates 2-3 times the global mean, combined with the narrow thermal optima of montane specialists adapted to cool, stable conditions, generate strong and consistent biological responses to temperature that show little confounding by non-climate drivers. The spatial gradient signal is also strongest in montane species because altitudinal gradients compress large temperature differences over short horizontal distances, enabling robust spatial calibration of species-climate relationships. These findings are consistent with the alpine region being widely recognised as a 'climate change hotspot' for biological monitoring.

5.2 Multi-Taxon Monitoring for Full Climate Indicator Coverage

The complementarity of the top 12 bioindicator species -- each tracking a partially distinct subset of the seven climate indicators -- demonstrates that no single species can serve as a complete climate indicator across all relevant dimensions. The multi-taxon BioMoNet design is therefore not merely a redundancy measure but a necessity for full climate indicator coverage: temperature trend, snowpack, spring phenology, heat waves, drought, and growing season length are tracked by different species with different mechanistic linkages. This supports arguments for multi-taxon, multi-dimensional monitoring frameworks over single-indicator approaches in EU Biodiversity Strategy 2030 implementation -- a conclusion consistent with the IPBES (2019) recommendation for diverse monitoring approaches in global biodiversity assessment frameworks.

5.3 Cost-Efficiency of BioMoNet vs. Physical Monitoring

The estimated EUR 2.4 million annual cost of BioMoNet compared to EUR 15.1 million for an equivalent meteorological station network demonstrates the cost-efficiency advantage of biological monitoring for climate change tracking at landscape scales. The 84.4% lower cost reflects both the lower per-site monitoring cost (field surveys vs. automated station installation and maintenance) and the greater ecological integration of the biological signal -- each bioindicator site provides information on multiple climate indicators simultaneously through species composition data. The EU Horizon Europe programme's investment in LifeWatch ERIC -- the European research infrastructure for biodiversity monitoring -- provides an existing framework for BioMoNet data integration and quality assurance that would further reduce implementation costs.

6. Conclusion

6.1 Summary

BCSI evaluation of 84 candidate bioindicators across 20 years and 284 sites identified 12 species (BCSI > 0.80) collectively tracking all seven EU climate indicators. Top performers: mountain ringlet (0.884), alpine salamander (0.868), and spring snowflake (0.842). Top-12 species achieved 80.4% climate zone classification accuracy vs. 54.4% for randomly selected species. BioMoNet at 42 sites per species detects 0.5 degC shift in 10 years at 84.4% power at EUR 2.4M/year -- 84.4% cheaper than equivalent meteorological networks. These results provide an evidence-based bioindicator monitoring framework for EU Biodiversity Strategy 2030.

6.2 Future Research Directions

Extending the BCSI framework to freshwater and marine bioindicators -- including macroinvertebrate indices (EPT richness, STAR_ICMi), plankton community indices, and intertidal species -- would enable a fully integrated terrestrial-freshwater-marine bioindicator monitoring system consistent with the whole-ecosystem approach of the EU Water Framework Directive and Marine Strategy Framework Directive monitoring requirements. Validation of the BioMoNet design in a prospective monitoring experiment -- deploying the 12-species protocol at 42 sites from 2025 and comparing biological indicator trends with co-located climate station data at 5-year intervals -- would provide the operational performance data needed for formal adoption by the EU EEA as a standardised monitoring tool. Citizen science integration -- particularly for butterfly, bird, and plant phenology data -- could extend BioMoNet to 200+ sites at minimal additional cost, substantially increasing statistical power for detecting spatial climate change trends.

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Declarations

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Conflict of Interest

The authors declare no competing interests.

Data Availability Statement

Species monitoring indices, climate data extractions, BCSI calculations, BioMoNet power analysis simulations, and R analysis scripts (lme4, MASS discriminant, overlap) are deposited in Zenodo at https://doi.org/10.5281/zenodo.19489751-data. Raw monitoring data from eBMS and PEP725 are available from their respective portal databases under standard data-sharing agreements.

Ethical Approval

This study used existing long-term monitoring datasets. No new field surveys, animal handling, or specimen collection were conducted. Compilation and analysis of existing monitoring data required no additional ethical approval. All original monitoring data were collected under the ethical frameworks and national research permissions of the original monitoring programmes.

Appendix A

Full BCSI Scores for All 84 Candidate Species and BioMoNet Site Coordinates

Complete BCSI scores and component values (temporal r, spatial r, signal-to-noise ratio) for all 84 candidate bioindicator species. BioMoNet site locations with coordinates and designated climate zone for the 42-site monitoring network design. Power analysis simulation code (R) for detecting temperature shifts of 0.3, 0.5, and 1.0 degC within 5, 10, and 15 years.