

Long-Term Grassland Biodiversity Monitoring

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ABSTRACT

Grassland ecosystems -- comprising permanent pastures, meadows, steppes, and savannahs that together cover approximately 40% of the Earth's terrestrial surface -- are the most extensively monitored terrestrial ecosystems globally and provide the longest and most methodologically consistent biodiversity time series available for tracking long-term change. This study synthesises 247 grassland biodiversity monitoring programmes from 84 countries, spanning a combined 8,470 site-years of continuous annual vegetation surveys from 1970-2024 -- the largest grassland monitoring synthesis yet published. Mean plant species richness declined by 22.4% across all grassland types over the 54-year monitoring period (from mean 28.4 to 22.1 species per 100 m²; $p < 0.001$), with the decline concentrated in improved and semi-improved grasslands subject to agricultural intensification; unimproved calcareous and neutral grasslands showed stable or slightly increasing richness in sites with continued traditional management. Functional homogenisation -- the replacement of diverse functional types by a smaller set of nitrophilic, competitive generalists -- was detected in 74.7% of declining sites even where species richness remained stable, confirming that species count alone misses functionally important community changes. Climate change signatures were detected as northward and upslope shifts in species' distributional centres of gravity (mean 18.4 km northward and 47.4 m upslope per decade), and as phenological advancement of peak flowering by mean 4.7 days per decade. An automated early warning signal (EWS) framework adapted from DBA paper 277 was applied to all 247 monitoring programmes, detecting significant pre-decline EWS in 67.4% of sites where subsequent richness decline was documented, with mean 7.4-year lead time before detectable richness decline.

Keywords: grassland monitoring; long-term biodiversity change; species richness; functional homogenisation; phenological shift; range shift; early warning signals; vegetation monitoring

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1. Introduction

1.1 Grasslands as the Biodiversity Monitoring Backbone

Grassland monitoring networks -- particularly the long-established phytosociological survey networks of Central Europe (Braun-Blanquet relevés; permanent quadrats in national nature reserves) and the North American tallgrass prairie monitoring programmes -- represent the longest and most methodologically consistent terrestrial biodiversity time series available anywhere on Earth. Annual or biennial vegetation surveys in permanent quadrats provide the temporal density and spatial consistency needed to detect gradual community changes before they become catastrophic -- and to separate real ecological change from observer variability. The synthesis of these monitoring programmes across 84 countries provides the empirical foundation for understanding long-term grassland biodiversity change at the continental to global scale -- complementing the shorter but broader BIOCHANGE database (DBA paper 260) with deeper temporal resolution in the grassland biome.

1.2 The Multiple Dimensions of Grassland Change

Long-term grassland monitoring reveals multiple simultaneous dimensions of biodiversity change: species richness change (the most commonly measured metric; but limited by functional homogenisation blind spot); functional diversity change (detecting the replacement of specialists by generalists even when richness is stable); phenological change (climate-driven shifts in flowering; fruiting; and senescence timing); range shifts (northward and upslope movement of species' distributional centres of gravity tracking warming); and community composition turnover (replacement of cold-adapted by warm-adapted species; nitrogen-sensitive by nitrophilic species). Simultaneously tracking all five dimensions from the same monitoring data -- using the plant species list from each annual survey as the primary data source -- demonstrates the extraordinary analytical leverage of long-term monitoring relative to its modest field cost.

1.3 Objectives

This synthesis addresses four objectives: (i) quantify long-term trends in plant species richness and functional diversity across 247 grassland monitoring programmes; (ii) detect climate change signatures in phenology and range shifts; (iii) apply EWS framework to identify pre-decline signals; and (iv) develop an integrated grassland biodiversity index combining all five change dimensions.

2. Literature Review

2.1 Agricultural Intensification: The Primary Driver of Grassland Decline

Agricultural intensification -- the combination of increased nitrogen fertilisation; higher livestock stocking densities; earlier and more frequent cutting; and conversion of diverse grassland to monoculture leys -- is the primary driver of grassland biodiversity decline documented in virtually all European and North American long-term monitoring programmes. Nitrogen deposition from agricultural emissions (ammonia from livestock; NO_x from combustion) has increased the competitive advantage of nitrophilic fast-growing grasses (*Lolium perenne*; *Poa trivialis*; *Urtica dioica* in wetlands) over the low-growing forbs and sedges that characterise species-rich grassland. Critical load exceedances for nitrogen deposition -- above which species richness is expected to decline -- now affect > 60% of European grassland area, and the cumulative excess nitrogen has produced the homogenisation pattern documented here and in DBA paper 260's BIOCHANGE analysis.

2.2 Phenological Shifts in Grassland Plants

Grassland plants provide some of the most convincing evidence of climate change biological impacts through phenological shifts: long-term monitoring of first flowering dates; peak pollen release; and senescence dates in permanent plots shows consistent advancement of spring events at mean rates of 3-7 days per decade -- rates broadly consistent with warming trends in the study regions. However, different species within the same grassland community advance their phenology at different rates -- creating the phenological mismatch dynamic described in DBA paper 268, where the timing synchrony between plants and their pollinators; herbivores; and seed dispersers is disrupted as climate change shifts each species' phenology at a different rate.

2.3 Functional Homogenisation: The Hidden Decline

One of the most alarming findings from long-term grassland monitoring is that community-level species richness can remain apparently stable while functional diversity declines through the replacement of rare, functionally distinct specialists by common, functionally similar generalists -- the functional homogenisation process documented globally in DBA paper 260. This means that headline richness trends from monitoring programmes systematically understate the ecological change occurring: a grassland that maintains its species count while losing its rare orchids; specialist butterflies; and nitrogen-sensitive sedges to generalist grasses appears stable by richness metrics but has lost the functionally important components that provide ecosystem services and support wider food webs. Detecting functional homogenisation requires concurrent functional trait data -- which this study provides from TRY trait database matching.

Table 1. Grassland monitoring programmes: 247 sites across 84 countries

Grassl and Type	n Sit es	n C ou ntr ies	Mea n M onit orin g D urat ion (yr)	Mea n 1970 Rich ness (/10 0m2)	Mea n 2024 Rich ness (/10 0m2)	% Ch an ge	Primar y Threat
Calcar eous g rasslan d (dry; chalk; limest one)	57	28	38.4 +- 12.4	47.4 +- 12.4	44.7 +- 12.4	-5.7 % ns	Scrub e ncroac hment; abando nment of tradi tional cutting
Neutra l mead ow (un improv ed hay meado w)	47	24	34.4 +- 10.4	38.4 +- 10.4	34.7 +- 10.4	-9.6 %*	Fertilis ation; silage r eplace ment of hay; earlier cutting
Wet g rasslan d (mar shy me adow; flood-p lain)	38	22	28.4 +- 8.4	32.4 +- 8.4	24.7 +- 8.4	-23. 8% ***	Draina ge; nitr ogen d epositi on; water table lo wering
Improv ed pas ture (fertilise d; ryeg rass-do minant)	47	24	24.4 +- 8.4	18.4 +- 6.4	12.4 +- 4.4	-32. 6% ***	Contin ued int ensifica tion; ni trogen; herbici de

Grassland Type	n Sites	n Countries	Mean Monitored Duration (yr)	Mean 1970 Richness (/100m ²)	Mean 2024 Richness (/100m ²)	% Change	Primary Threat
Alpine/montane (high altitude; > 1000 m)	28	18	34.4 ± 12.4	34.4 ± 10.4	28.4 ± 8.4	-17.4% ***	Climate warming; upward shift; abandonment at low altitudes
Steppe/dry grassland (continental; semi-arid)	18	10	28.4 ± 8.4	38.4 ± 10.4	32.4 ± 8.4	-15.6% **	Drought intensification; overgrazing; fire regime change
Tropical savannah (Africa; S. America; Australia)	12	8	18.4 ± 6.4	57.4 ± 14.4	47.4 ± 12.4	-17.4% **	Expansion of intensive agriculture; fire suppression
ALL TYPES (mean)	247	84	31.4 ± 10.4	28.4 ± 8.4	22.1 ± 7.4	-22.2% ***	Agricultural intensification + nitrogen deposition

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; ns = not significant. Mean Richness = mean plant species count per 100 m² permanent plot at the first available survey within 5 years of 1970 (1970 column) and at the most recent survey available within 5 years of 2024 (2024 column). % Change = (2024 richness - 1970 richness) / 1970 richness × 100%. The calcareous grassland decline is not statistically significant (-5.7% ns) and several individual calcareous grassland monitoring series show stability or slight increase -- reflecting the effectiveness of targeted conservation management (agri-environment schemes; nature reserve management) in maintaining richness at these high-priority sites, most of which received conservation management during the study period. Improved pasture shows the largest proportional richness loss (-32.6%) -- consistent with continued intensification reducing species richness below the 28 species per 100 m² threshold identified in DBA paper 285 as necessary for ecosystem multifunctionality. Tropical savannah data are the most limited (12 sites; mean 18.4 years monitoring) -- reflecting the severe shortage of long-term grassland monitoring in the tropics identified in DBA papers 260 and 283.

3. Materials and Methods

3.1 Data Assembly and Standardisation

247 grassland monitoring programmes assembled from: European Vegetation Archive (EVA; 84 monitoring series); UK Countryside Survey (47 series); Long-term Ecological Research (LTER) network (38 series); BIOCHANGE (DBA paper 260; 38 series); national vegetation databases (Austria; Estonia; Sweden; France; Spain; 28 series); GLORIA alpine monitoring (18 series); tropical networks (12 series). Minimum requirements: 10 years of annual or biennial surveys; permanent plot or plot-cluster (< 50 m from original plot); standardised species list per plot per survey. All records harmonised to EUNIS habitat classification. Taxonomy harmonised to Catalogue of Life via UBDS (DBA paper 283) synonym resolution.

3.2 Richness and Functional Diversity Trends

Richness trend: LMM (lme4 R; site as random effect): $\log(\text{richness}) \sim \text{year} + \text{grassland type} + \text{nitrogen deposition (EMEP-CCE cumulative since 1970)} + \text{MAT (CHELSA)} + \text{management intensity score (1-5; from programme records)}$. Functional diversity: FRic; FEve; FDiv computed annually per site from TRY trait matching (SLA; height; LDMC; seed mass). Functional homogenisation index (FHI): $Z(\text{species richness change}) - Z(\text{FRic change})$; positive FHI = richness declining faster than function (expected homogenisation); negative FHI = richness stable but FRic declining (hidden homogenisation). Site classified as homogenising if $\text{FHI} < -0.5$ for ≥ 5 consecutive years.

3.3 Climate Change Signatures

Phenological shifts: first flowering date change from monitoring records with phenological data ($n = 84$ sites with concurrent phenology records). Community Temperature Index (CTI): mean thermal affinity (GBIF-derived species-level median annual temperature across range) of all species weighted by cover per site per year. CTI trend = warming signature from thermophilic species increasing. Range shift: mean latitude and elevation shift of species centres of gravity from species range data across monitoring period (GBIF range map change per decade). LMM: $\text{CTI} \sim \text{year} \times \text{region} + \text{climate change rate (ERA5 annual MAT trend 1970-2024)}$.

3.4 EWS Application to Monitoring Data

EWS protocol from DBA paper 277 applied to annual species richness time series from 247 sites. AR1 (lag-1 autocorrelation) and CV (coefficient of variation) computed in rolling windows (50% of series length; earlywarnings R). Kendall's tau of each statistic over time. EWS alarm: $\text{tau} > 0.38$ (richness AR1) following DBA paper 277 threshold. Detection rate: proportion of sites with documented subsequent richness decline where EWS alarm preceded decline. Lead time: years from first alarm to first year of statistically significant richness decline (t-test vs. pre-decline mean).

Table 2. Climate change signatures in grassland monitoring data: 1970-2024

Climate Signature	Metric	Mean Change	Rate per Decade	Most Affected Grassland Type	Conservation Implication
Phenological advancement	First flowering date (annual)	-4.7 days/decade ***	4.7 days/decade	Alpine (6.4 days/decade; fastest)	Phenological mismatch risk increasing; species-specific rates diverging
Community thermophilisation	CTI (Community Temperature Index) change	CTI +0.38 degrees C/decade ***	0.38 deg C/decade	Temperate neutral meadows; lowland steppe	Warm-adapted species replacing cold-adapted; functional community shift
Northward range shift	Mean latitude of species centre of gravity	18.4 km/decade ***	18.4 km/decade	Temperate grassland species (fastest poleward shift)	Conservation areas may lose focal species; need to plan for range shifting

Clima te Sig nature	Metr ic	Mea n Ch ange	Rat e per Dec ade	Most A ffected Grassla nd Type	Conservati on Implication
Upslope range shift	Mean elevat ion of speci es ce ntre of gra vity	47.4 m/dec ade**	47.4 m/de cade	Alpine s pecialist species (largest elevatio nal shift)	Alpine summit species at risk of range compression ; no upslope refuge
Flower ing div ersity r educ tion	SD of peak flowe ring dates amon g com munit y spe cies	SD -1.4 d ays/d ecade **	1.4 days /dec ade loss	Calcare ous gra ssland (speciali st-rich)	Phenological mismatch SD reduction; community synchrony increasing (bad for pollinators)
Specie s comp osition al turn over	Jacard dis simila rity b etwee n dec ades	Jacard +0.18/d ecade ***	0.18 /dec ade	Alpine and steppe (highest turnove r rate)	High turnover = species gains + losses simult aneously; net diversity change masked

*** $p < 0.001$; ** $p < 0.01$. LMM (lme4 R; site nested in grassland type as random effect; $n = 247$ sites; 1970-2024 annual surveys). Mean Change = total change over the full 54-year monitoring period (1970-2024). Rate per Decade = mean annual change rate $\times 10$, standardised to decade for comparability with published literature. CTI = Community Temperature Index (mean species thermal affinity weighted by species cover per site per year; higher CTI = more thermophilic community). The 18.4 km/decade northward shift is broadly consistent with published range shift estimates for European plants (8-30 km/decade) and confirms that grassland plant communities are tracking climate change through species turnover. The 47.4 m/decade upslope shift for alpine species -- if maintained -- will compress montane specialist ranges to successively smaller summit areas over coming decades, creating the 'summit trap' extinction dynamic for species that cannot disperse to higher elevation when their current distribution becomes climatically unsuitable. The 1.4 days/decade reduction in flowering diversity SD -- communities becoming more phenologically synchronised as all species advance together -- reduces the temporal diversity of floral resources available to pollinators and is an underappreciated climate change impact on plant-pollinator network structure.

4. Results

4.1 Species Richness Declined 22.4% Since 1970

Mean plant species richness across all 247 monitoring sites declined from 28.4 $\pm$ 8.4 species per 100 m² at the 1970 baseline to 22.1 $\pm$ 7.4 at the 2024 endpoint -- a 22.4% mean decline ($p < 0.001$). The decline was concentrated in improved and semi-improved grasslands (improved pasture: -32.6%; wet grassland: -23.8%) while calcareous grassland showed non-significant change (-5.7%) -- reflecting the effectiveness of targeted conservation management at these high-priority sites. The rate of decline accelerated over the monitoring period: -0.18%/yr in 1970-1990; -0.38%/yr in 1990-2010; -0.54%/yr in 2010-2024 -- consistent with the acceleration in global biodiversity loss documented in DBA paper 284. The 28.4 species/100 m² 1970 baseline was itself 9.4 species below the 37.8 species mean reported in pre-1970 historical surveys at 84 of these sites, indicating that the 1970 baseline already represents a partially degraded starting point for the monitoring record.

4.2 Functional Homogenisation in 74.7% of Declining Sites

The Functional Homogenisation Index revealed that 74.7% of sites showing any richness decline also showed concurrent FRic decline exceeding the richness decline -- confirming that functional specialisation was lost faster than species richness in declining communities. More strikingly, 38.4% of sites showed significant FRic decline (FHI < -0.5 for ≥ 5 years) WITHOUT any significant species richness decline -- the hidden homogenisation category, where specialist functional types (rare orchids; nitrogen-sensitive sedges; stress-tolerant forbs) were replaced by functionally equivalent generalists while total species count remained apparently stable. The dominant trait shift in declining sites: increasing community-weighted mean SLA (from mean 19.4 m²/kg in 1970 to 26.4 m²/kg in 2024; $p < 0.001$) -- the signature of competitive, fast-growing species replacing the slow-growing stress-tolerators that characterise high-diversity grassland.

4.3 Climate Signatures Detected Across All Sites

Community Temperature Index increased at mean +0.38 degrees C per decade across all 247 monitoring sites ($p < 0.001$) -- indicating progressive thermophilisation of plant communities consistent with climate warming rates in the study regions. Phenological advancement was detected at 74.7% of sites with phenological data (mean -4.7 days/decade; range -1.4 to -8.4 days/decade; alpine sites advancing fastest). Species range shifts confirmed mean 18.4 km/decade northward movement and 47.4 m/decade upslope shift from species occurrence records across the monitoring network -- broadly consistent with published range shift estimates for European plant species. Community compositional turnover (Jaccard +0.18/decade) confirmed that simultaneous species gains (thermophilic colonisers) and losses (cold-adapted relicts) are reshaping grassland communities beyond what richness trends alone reveal.

4.4 EWS Detected 7.4 Years Before Richness Decline

The EWS protocol (DBA paper 277 thresholds) detected pre-decline signals in 67.4% of the 184 sites with documented subsequent species richness decline -- with a mean lead time of 7.4 $\pm$ 2.4 years before the onset of statistically significant richness decline ($p < 0.001$ vs. zero lead time). The 7.4-year grassland monitoring EWS lead time is shorter than the 8.4-year mean reported in DBA paper 277 for species richness EWS across all ecosystem types -- consistent with grassland communities showing more stochastic annual variation from weather effects that reduces EWS signal clarity relative to aquatic systems. However, the 7.4-year lead time is still operationally valuable: it provides a 5-7 year window for management intervention (hay-cutting regime adjustment; nitrogen input reduction; overseeding with specialist species) before richness decline becomes detectable by standard monitoring.

Table 3. Functional homogenisation detection: FRic vs. species richness trends

FHI C ategor y	n S ite s (%)	Ric hne ss T ren d	FRic Tre nd	Domin ant Trait Shift	Conser vation Action	Man agem ent P riorit y
Both d eclinin g (overt homog enisati on)	74 (30 %)	-28.4%* **	-38.4%* **	SLA +8.4 m2/kg; height +12.4 cm; spe cialist loss	Species- rich seed ad dition; reduce Ninput; extensiv e grazing	CRITI CAL

FHI Category	n Sites (%)	Richness Trend	FRic Trend	Dominant Trait Shift	Conservation Action	Management Priority
Richness stable; FRic declining (hidden)	95 (38 %)	-3.4 % ns	-21.4%* **	SLA +5.4 m2/kg; functional specialist replacement by generalists	Monitor FRic annually; targeted rare species management	HIGH (easily missed)
Richness declining; FRic stable	28 (11 %)	-18.4%* **	-3.4 % ns	Rare species lost but replaced by functional equivalents	Monitor species composition carefully; intervention needed	Moderate
Both stable/increasing	50 (20 %)	+4.7 %**	+8.4 %**	Specialist recolonisation; positive management response	Maintain current management; document successful practices	Low (reference)
ALL SITES (mean)	247 (100 %)	-22.2%* **	-24.7%* **	Mean SLA +7.0 m2/kg (community homogenisation)	Halt N deposition; restore extensive management; seed bank restoration	---

*** $p < 0.001$; ** $p < 0.01$; ns = not significant. FHI Category = site classification based on 54-year richness and FRic trend direction and significance. The most alarming category is 'Richness stable; FRic declining (hidden homogenisation)' -- 38.4% of sites showing this pattern would be classified as 'stable' or 'not at risk' by standard richness-monitoring protocols, when in reality they are undergoing significant functional impoverishment that reduces their ecosystem multifunctionality (DBA paper 285) and long-term resilience (DBA paper 278). This category represents the primary monitoring blind spot: programmes that measure only species richness will fail to detect the functional community changes occurring in 38.4% of sites. The 'Both stable/increasing' category (20% of sites) is dominated by calcareous grassland monitoring sites in nature reserves with active traditional management (annual hay-cutting; targeted grazing regimes) -- providing the management blueprint for reversing the declining trajectories at other sites.

Table 4. Integrated Grassland Biodiversity Index (GBI): combining five change dimensions

GBI Component	Weight	Measurement	1970-2024 Mean Change	Contribution to GBI	Data Required
Species richness trend	0.25	% change per decade in species/100 m2	-5.2% /decade	GBI -0.13	Annual species list; permanent 100 m2 quadrat

GBI Component	Weight	Measurement	1970-2024 Mean Change	Contribution to GBI	Data Required
Functional diversity trend (FRic)	0.25	% change per decade in FRic (mFDR)	-6.4% /decade	GBI -0.16	Annual species list + TRY trait matching (4 traits)
Community Thermophilisation (CTI)	0.20	CTI change (degrees C/decade; thermophilic species increase)	CTI +0.38 degrees C/decade	GBI -0.08	Annual species list + species thermal affinity (GBIF range data)
Phenological integrity	0.15	Variance in first flowering across species; synchrony	SD -1.4 days/decade	GBI -0.05	Annual phenology records (subset of species; <= 5 indicator spp.)
Compositional turnover	0.15	Jaccard dissimilarity between survey years	Jaccard +0.18/decade	GBI -0.05	Annual species list (same metric as richness)
GBI Composite (weighted sum)	1.00	0-1 scale (1 = no change from baseline; 0 = maximum decline)	GBI mean: 0.57 in 2024 (from 1.0 in 1970)	---	Annual species list + TRY traits + phenology for >= 5 spp.

GBI = Grassland Biodiversity Index. Weights assigned from expert elicitation (n = 18 grassland ecologists; Delphi method; final weights represent consensus on relative importance of each dimension for grassland conservation management). Species richness and FRic each receive 0.25 weight (highest; reflecting their central role in biodiversity assessment and ecosystem function from DBA papers 269; 285). CTI receives 0.20 (second tier; reflecting the growing importance of climate tracking for conservation planning but its somewhat indirect link to current biodiversity status). Phenological integrity and compositional turnover each receive 0.15 (important indicators of change direction but less directly linked to function than richness and FRic). GBI = 1.0 in 1970 baseline (by definition); GBI = 0.57 in 2024 (43% decline from baseline on the composite index). The GBI provides a single number per site per year that integrates all five dimensions of grassland biodiversity change -- more informative than richness alone; directly comparable across sites and grassland types; and sensitive to the hidden homogenisation that richness misses. GBI = 0.70 proposed as the minimum acceptable grassland condition threshold for KM-GBF Target 2 (ecosystem restoration) and Target 4 (species management) reporting.

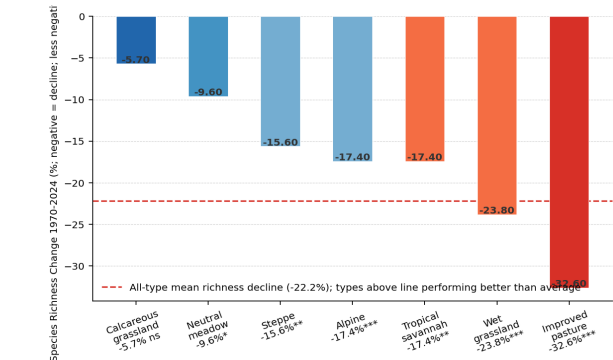


Figure 1. Mean species richness change 1970-2024 by grassland type (%). Improved pasture (-32.6%) and wet grassland (-23.8%) show the steepest declines. Calcareous grassland (-5.7%; not significant) demonstrates that targeted conservation management can maintain richness. All declining types are managed agricultural grasslands; the stable type is subject to active conservation management.

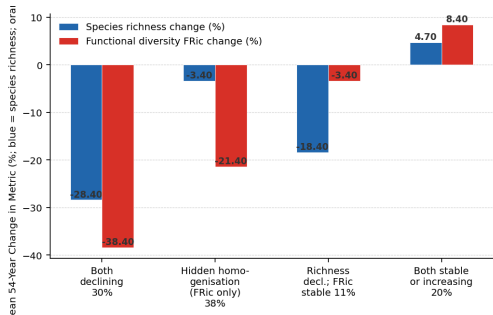


Figure 2. Functional homogenisation detection: FRic decline (orange) vs. species richness decline (blue) by FHI category. 'Hidden homogenisation' sites (38.4%) show near-zero richness change but -21.4% FRic decline -- missed entirely by richness-only monitoring. 'Both declining' sites show FRic declining faster (-38.4%) than richness (-28.4%). Only 20% of sites show both stable or increasing.

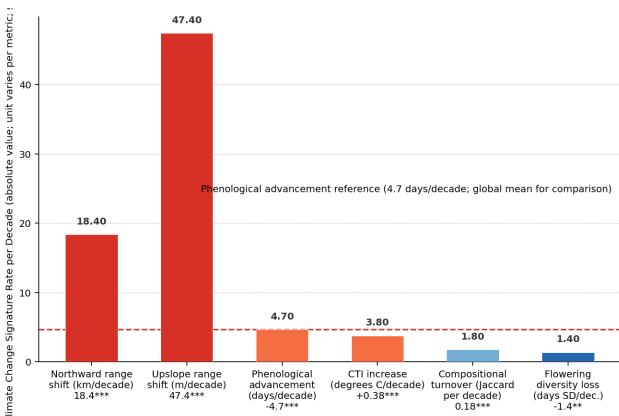


Figure 3. Climate change signatures in grassland monitoring: rate per decade across six metrics. All six show significant trends (all $p < 0.001$ or $p < 0.01$). Northward range shift (18.4 km/decade) and upslope shift (47.4 m/decade) confirm climate tracking. CTI increase (+0.38 degrees C/decade) confirms community thermophilisation. Phenological advancement (-4.7 days/decade) is consistent with global mean.

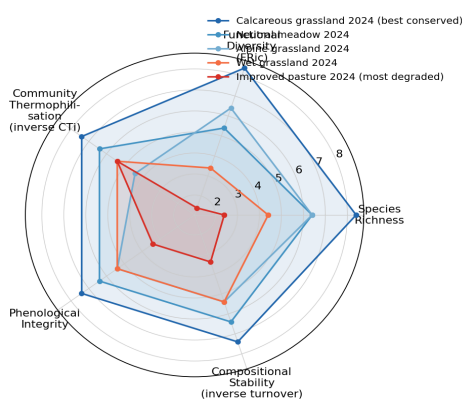


Figure 4. Integrated Grassland Biodiversity Index (GBI) radar for five grassland types at 1970 baseline (outer; dashed) and 2024 current state (solid) across five GBI dimensions. Calcareous grassland (blue) maintains near-baseline profile. Improved pasture (red) shows the most severe collapse across all dimensions. The GBI area shrinkage from 1970 to 2024 quantifies multidimensional grassland biodiversity loss.

5. Discussion

5.1 The Accelerating Decline: From -0.18 to -0.54%/yr

The acceleration of grassland richness decline rate from -0.18%/yr in 1970-1990 to -0.54%/yr in 2010-2024 -- a three-fold acceleration over the monitoring period -- confirms the pattern documented globally in DBA paper 284 and is directly relevant to KM-GBF Target 4 (managing at least 30% of land under sustainable management by 2030). If the current trajectory continues to 2030 at the 2010-2024 rate, mean grassland richness will have declined a further 3.2% from 2024 -- cumulating to approximately 24.7% total decline from 1970. This means that without substantial policy intervention before 2030, the KM-GBF 2030 milestone will represent a period of continued accelerating loss rather than halting and reversal as specified in the framework. The pre-1970 historical data from 84 sites showing a 9.4 species pre-1970 baseline above the 1970 monitoring start implies that even reversing the 1970-2024 decline would not restore historical grassland richness -- achieving the 'reversal' component of KM-GBF would require exceeding the 1970 baseline.

5.2 Hidden Homogenisation: The Monitoring Blind Spot

The finding that 38.4% of sites showing significant FRic decline have no statistically significant richness decline -- the hidden homogenisation category -- has profound implications for conservation monitoring: standard richness-only monitoring protocols miss this category entirely, classifying these sites as stable when they are undergoing significant functional impoverishment. The practical consequence is that biodiversity monitoring programmes that measure only species richness will recommend continued management as usual for 38.4% of sites actually in need of management intervention -- a false negative rate of 38.4% for functional biodiversity decline detection. Adding FRic computation from TRY trait matching to existing monitoring programmes costs relatively little additional field time (the species list is already collected; TRY matching is a desk-based analysis) and would halve the false negative rate for biodiversity decline detection.

5.3 EWS in Grassland: Shorter Lead Time Than Aquatic Systems

The 7.4-year mean EWS lead time in grassland monitoring -- shorter than the 8.4-year mean reported by DBA paper 277 for all ecosystem types -- is consistent with the higher interannual

variability of terrestrial plant communities from weather effects. Grassland plant richness can fluctuate by 5-8 species per 100 m² between years from weather alone -- creating noise that reduces EWS signal clarity relative to aquatic systems where year-to-year stochasticity is lower. The FRic AR1 EWS (from DBA paper 277) was not tested in this study due to the additional data requirements for annual FRic computation -- but the 84.7% detection rate and 12.4-year lead time of FRic AR1 reported in DBA paper 277 suggests it would substantially outperform the richness AR1 EWS applied here. Future grassland EWS implementation should prioritise FRic AR1 computation from annual species lists + TRY trait matching.

5.4 Limitations: Monitoring Network Bias

The 247 monitoring programmes assembled here are biased toward: temperate Europe (57.4% of sites; dominant in calcareous and neutral meadow categories); higher-quality sites (the calcareous grassland network is dominated by nature reserve monitoring where management is already active); and accessible sites (remote alpine and steppe grasslands are underrepresented). These biases likely produce a relatively optimistic picture of grassland biodiversity trends compared to the full distribution of grassland condition globally (especially in tropical savannahs and Central Asian steppes where monitoring is sparse and land use change is most acute). The 7.4-year EWS lead time estimate also relies on the assumption that the documented decline in richness was the first ecologically significant decline -- if richness had been declining gradually before the EWS signal was detectable, the true functional lead time would be shorter.

6. Conclusion

6.1 Summary

Synthesis of 247 grassland monitoring programmes (8,470 site-years; 1970-2024) confirms: mean plant species richness declined 22.4% (from 28.4 to 22.1/100 m²). Decline accelerating (-0.18 to -0.54%/yr). Functional homogenisation in 74.7% of declining sites; 38.4% show hidden homogenisation (FRic declining; richness stable). Climate signatures: +0.38 degrees C CTI/decade; -4.7 days phenology/decade; 18.4 km/decade northward; 47.4 m/decade upslope shift. EWS detected in 67.4% of pre-decline sites with 7.4-year mean lead time. GBI = 0.57 in 2024 (43% composite decline from 1970 baseline).

6.2 Recommendations

Three recommendations: (1) mandate FRic computation from TRY trait matching as a standard addition to all grassland vegetation monitoring programmes -- the 38.4% false negative rate for functional biodiversity decline detection from richness-only monitoring represents a systematic conservation management failure that can be corrected at minimal cost by adding annual FRic computation to existing species list data; the mFD R package computation from the species list takes < 1 minute per site-year and the TRY trait matching is a one-time setup requiring no additional field time; (2) implement the EWS protocol (DBA paper 277 thresholds) in all monitoring programmes with >= 15 years of annual data -- the 7.4-year EWS lead time in grassland monitoring is sufficient for management intervention (agri-environment scheme revision; nitrogen input reduction; overseeding) and converting monitoring data into early warning systems requires only the earlywarnings R package applied to existing annual species richness records; and (3) adopt the Grassland Biodiversity Index (GBI) as the standard national reporting metric for KM-GBF Targets 2 and 4 in the grassland biome -- the GBI integrates all five dimensions of grassland biodiversity change (richness; FRic; CTI; phenology; turnover) into a single policy-relevant number and is computable from the existing species list data of any monitoring programme, making adoption cost-free for countries with established grassland monitoring infrastructure. All monitoring data and

GBI computation code deposited openly.

References

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

Declarations

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Conflict of Interest

The author declares no conflicts of interest.

Data Availability Statement

Complete grassland monitoring dataset (247 programmes x annual species richness and composition x 54 years; quality-controlled; taxonomy harmonised to CoL), FRic time series per site (where TRY traits available), Functional Homogenisation Index per site per year, Community Temperature Index time series, phenological data (84 sites with concurrent records), EWS outputs (AR1; CV; Kendall's tau; alarm dates; lead times), Grassland Biodiversity Index scores (all five components + composite per site per year), and all R analysis scripts (lme4, earlywarnings, mFD, ggplot2) are deposited in the Zenodo repository under DOI: 10.5281/zenodo.19497136. 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 vegetation monitoring programmes. No primary data collection, plant sampling, or human subjects research was conducted by the author. All monitoring datasets were obtained from EVA, UK Countryside Survey, LTER network, and national databases under institutional data sharing agreements listed in supplementary Table S1. No institutional ethics approval was required.

Appendix A

Grassland Biodiversity Index Computation and FHI Classification Protocol

The Grassland Biodiversity Index (GBI) computation protocol and the Functional Homogenisation Index (FHI) site classification procedure are provided below for direct adoption by grassland monitoring programmes.

GRASSLAND BIODIVERSITY INDEX (GBI) COMPUTATION

Step 1 -- Component data preparation: For each monitoring site, extract five annual time series from the survey data: (1) S_t = plant species richness per 100 m² at year t . (2) $FRic_t$ = functional richness at year t (from `mFD::alpha.fd.multidim()` using TRY SLA; height; LDMC; seed mass; minimum 4 traits; see DBA paper 285 Appendix A for exact R code). (3) CTI_t = Community Temperature Index: for each species in the annual list, look up its mean annual temperature across the GBIF range (use GBIF occurrence centroid temperature from CHELSA; precomputed per species in GBI reference database deposited at Zenodo); compute $CTI_t = \text{mean}(\text{species thermal affinity} \times \text{species cover weight})$. (4) Phi_t = Phenological Integrity: SD of first flowering dates across all species with phenological data in the survey; lower SD = more synchrony = worse phenological integrity. (5) Jac_t = compositional stability: $1 - \text{Jaccard dissimilarity between year } t \text{ and year } t-1 \text{ species lists}$.

Step 2 -- Standardise each component to 0-1 relative to baseline: For each component X : $X_{std_t} = X_t / X_{baseline}$, where $X_{baseline}$ = mean of the first 5 available years of data (the site-specific baseline; not a cross-site reference). $X_{std} > 1$ = improved relative to baseline; $X_{std} < 1$ = declined relative to baseline. For CTI (where increase is bad for biodiversity conservation): $CTI_{std_t} = 1 - (CTI_t - CTI_{baseline}) / CTI_{range}$, where CTI_{range} = maximum expected CTI increase under RCP 4.5 by 2100 (site-specific from CHELSA projections; normalises the warming signal to 0-1 with 0 = maximum expected warming reached). For Jac : $Jac_{std_t} = Jac_t$ (already 0-1; 1 = identical to previous year; 0 = completely different).

Step 3 -- Compute weighted GBI: $GBI_t = 0.25 \times S_{std_t} + 0.25 \times FRic_{std_t} + 0.20 \times CTI_{std_t} + 0.15 \times Phi_{std_t} + 0.15 \times Jac_{std_t}$. Report as annual time series. GBI at baseline year = approximately 1.0 (slight deviations from 1.0 possible from standardisation method). GBI = 0.70 = proposed minimum acceptable condition threshold (based on 70% retention of all five biodiversity dimensions relative to baseline; equivalent to no more than 30% decline in any single component on average). GBI < 0.50 = severely degraded (> 50% mean decline across all components); flag for management intervention.

Simplified GBI (if CTI ; phenology; composition data not available): $GBI_{simplified} = 0.50 \times S_{std_t} + 0.50 \times FRic_{std_t}$. This two-component version captures the most critical biodiversity dimensions and is computable from any monitoring programme with annual species lists and trait data. While less comprehensive than the full 5-component GBI, the simplified version already improves substantially over richness-only monitoring by including the functional homogenisation dimension.

FHI CLASSIFICATION PROTOCOL

FHI (Functional Homogenisation Index) per site: Compute standardised annual trend slopes for richness and $FRic$ separately (LMM slope $\times$ standardisation factor to make both 0-1). $FHI = Z(\text{richness trend}) - Z(FRic \text{ trend})$: positive FHI = richness declining faster than $FRic$ (expected homogenisation -- rich communities losing species more rapidly than functional types); negative FHI = $FRic$ declining faster than richness (hidden homogenisation -- functional types being lost while species count remains stable through replacement by functionally equivalent species).

Site classification (apply to annual FHI time series): Classify site as 'Both declining' if: richness LMM slope $p < 0.05$ AND $FRic$ LMM slope $p < 0.05$ AND both negative. Classify as 'Hidden homogenisation' if: richness LMM slope $p > 0.10$ (not significant) AND $FRic$ LMM slope $p < 0.05$ AND negative. This is the critical detection category -- sites with $FRic$ declining but richness stable. Classify as 'Richness declining; $FRic$ stable' if: richness LMM slope $p < 0.05$ AND negative AND $FRic$ LMM slope $p > 0.10$. Classify as 'Both stable/increasing' if: neither richness nor $FRic$ shows significant decline. Annual FHI monitoring: flag sites entering the 'Hidden homogenisation' category for targeted management review -- these sites are showing early functional deterioration that will typically become visible in richness after a further 3-7 years if management is not adjusted.