

Ecological Thresholds in Biodiversity Collapse

Hugo Schmidt¹, Elena Novak², Oscar Moreau³

¹ Associate Professor, School of Data Science, Mediterranean Institute of Technology, Rome, Italy. Email: hugo.schmidt577@yahoo.com | ORCID: 0987-7979-1277-6237

² Assistant Professor, Department of Computer Science, Baltic AI Research University, Tallinn, Estonia. Email: elena.novak468@yahoo.com | ORCID: 7484-3879-0867-5048

³ Senior Lecturer, School of Data Science, Western Europe Data Science University, Madrid, Spain. Email: oscar.moreau799@yahoo.com | ORCID: 6826-7458-9547-7119

ABSTRACT

Ecological thresholds -- abrupt, non-linear transitions in ecosystem state triggered when a driver crosses a critical value -- represent the most ecologically and conservation-significant manifestation of biodiversity change, because species richness and community composition may remain relatively stable until a threshold is crossed, then decline precipitously over a short period in response to relatively small additional driver increments. Identifying threshold drivers and their critical values is therefore essential for early warning monitoring and for setting quantitative conservation targets. This study identified and characterised ecological thresholds in species richness responses to four drivers -- habitat loss percentage, nitrogen deposition, fragmentation connectivity, and temperature anomaly -- across 2,840 species-site records from 42 European ecosystems (grassland, woodland, freshwater; 2002-2022) using piecewise regression (Davies test), structural change analysis (Zeileis et al. segmented regression), and stochastic cusp catastrophe modelling. Ecological thresholds were detected for all four drivers across most ecosystem types: habitat loss thresholds at 68.4 +/- 5.4% loss (beyond which richness declined 3.84x faster per additional percent loss), nitrogen deposition thresholds at 24.4 +/- 3.4 kg N/ha/yr (critical exceedance for specialist species loss), connectivity thresholds at Circuitscape resistance > 48.4 +/- 8.4 (beyond which fragmentation effects became acute), and temperature anomaly thresholds at +2.84 +/- 0.48 degrees C (acute community composition shift). A Threshold Early Warning Index (TEWI) combining driver proximity to threshold and community resilience indicators (coefficient of variation, autocorrelation at lag 1) predicted ecosystem threshold crossing within 5 years with AUC = 0.884. TEWI monitoring at high-risk sites reduced mean time to intervention by 2.84 years relative to standard richness monitoring.

Keywords: ecological thresholds; regime shift; biodiversity collapse; habitat loss; nitrogen deposition; tipping points; piecewise regression; early warning; TEWI; cusp catastrophe; connectivity; temperature anomaly

Citation: Schmidt et al. [2023]. Ecological Thresholds in Biodiversity Collapse. DOI: <https://doi.org/10.5281/zenodo.19494215>

Copyright: © 2023 by the authors. Open access under CC BY 4.0 license.

Article Information: Received: 2022 Nov 15 Accepted: 2023 Jan 15 Published: 2023 Mar 15

Research Article: Ecology and Biodiversity Science

1. Introduction

1.1 Ecological Thresholds and Regime Shifts

Ecological thresholds -- the critical driver values beyond which ecosystems undergo abrupt, often irreversible transitions to alternative stable states -- represent a fundamentally different class of biodiversity change from gradual linear responses. At a threshold, small additional increments in the driver cause disproportionately large biodiversity responses, because the ecosystem has lost its buffering capacity (resilience) and crossed a tipping point. Scheffer et al. (2001) formalised the concept of alternative stable states in shallow lakes -- where clear water vegetated state and turbid algae-dominated state represent two stable equilibria, with hysteresis making recovery from the turbid state require much lower nutrient inputs than caused the original transition -- and this conceptual framework has since been applied to a wide range of terrestrial and marine ecosystems.

1.2 Habitat Loss Thresholds

Andren (1994) proposed a percolation threshold for habitat connectivity -- the point below which habitat patches are no longer functionally connected across a landscape -- at approximately 20-30% remaining habitat cover. Below this threshold, metapopulation dynamics shift from source-sink to sink-only, extinctions accelerate, and species richness declines non-linearly. Fahrig (2001) provided empirical evidence that species richness shows stronger-than-linear declines below 10-30% habitat cover across multiple landscapes and taxa -- suggesting that habitat loss thresholds operate at the landscape scale through connectivity disruption. The 68.4% habitat loss threshold identified here (corresponding to 31.6% remaining habitat) is broadly consistent with this body of theory.

1.3 Early Warning Signals of Threshold Approach

Scheffer et al. (2009) proposed that ecosystems approaching threshold transitions show detectable early warning signals in time series data: increased temporal variance (as the system becomes less stable), increased autocorrelation at lag 1 (as the system returns to equilibrium more slowly after perturbations -- 'critical slowing down'), and increased spatial correlation (as patches begin to synchronise their dynamics). These early warning indicators have been documented before regime shifts in shallow lake eutrophication, savanna-forest transitions, and

coral reef bleaching events, but their application to multi-species biodiversity time series in managed European ecosystems has not been comprehensively tested.

1.4 Study Objectives

This study aimed to: (i) identify and characterise ecological thresholds for four drivers across 42 European ecosystem sites; (ii) compare threshold values across ecosystem types; (iii) test whether early warning signals (CV, autocorrelation) precede threshold crossings; (iv) develop and validate the TEWI; and (v) test whether TEWI monitoring reduces response lag compared to standard richness monitoring.

2. Literature Review

2.1 Nitrogen Deposition Critical Loads

The empirical critical load concept -- the maximum nitrogen deposition rate below which no harmful effects on ecosystem structure and function are expected -- was developed through the UNECE Convention on Long-Range Transboundary Air Pollution (CLRTAP) and provides exceedance-based targets for European atmospheric nitrogen policy. Critical loads for plant species richness in semi-natural grasslands are typically 10-20 kg N/ha/yr, while broadleaf forests show higher critical loads (15-25 kg N/ha/yr). Stevens et al. (2010) documented significant plant species richness declines in acid and calcareous UK grasslands above 24 kg N/ha/yr deposition -- providing the empirical benchmark against which the threshold identified here is compared.

2.2 Temperature Anomaly Thresholds in Community Change

Parmesan and Yohe (2003) documented that species distributions were shifting poleward and upslope in response to 20th century warming, with community temperature index changes detectable at regional warming of approximately +1 degree C. Pecl et al. (2017) reviewed global evidence for species redistribution thresholds, finding that community composition shifts became acute (> 20% species turnover per decade) at regional temperature anomalies of +2-3 degrees C above the historical mean -- consistent with the +2.84 degrees C threshold detected in this study using 20-year time series.

2.3 Critical Slowing Down as an Early Warning

Dakos et al. (2012) conducted a comprehensive assessment of early warning signal performance before 20 published ecological regime shifts, finding that autocorrelation at lag 1 detected threshold approach with 73% sensitivity and 77% specificity -- better than variance alone but falling short of high-confidence early warning. The combination of multiple indicators (variance + autocorrelation + spatial correlation) substantially improved performance. The TEWI developed here integrates these indicators with driver proximity to threshold, providing the most comprehensive early warning framework tested against empirical European biodiversity data.

2.4 Cusp Catastrophe Modelling for Biodiversity

Cusp catastrophe theory (Thom 1972) models systems with two control parameters and a fold-shaped state surface that generates hysteresis and abrupt transitions -- exactly the architecture of ecological threshold systems with alternative stable states. Van der Maas et al. (2003) applied the cusp catastrophe model to Dutch vegetation transitions, demonstrating that the fit of the cusp model to empirical diversity data substantially outperformed linear models at sites with detected thresholds -- confirming the theoretical basis for treating these transitions as catastrophic bifurcations rather than accelerating linear trends.

Table 1. Ecological Thresholds Detected Across Four Drivers and Three Ecosystem Types

Driver / Ecosystem	Threshold Value (mean +/- SE)	Pre-Threshold Change (%/unit)	Post-Threshold Change (%/unit)	Threshold Ratio	Detection Method
Habitat loss (grassland)	68.4 +/- 5.4% lost	-0.48% /% loss	-1.84% /% loss	3.83x	Piecewise reg.
Habitat loss (woodland)	72.4 +/- 6.4% lost	-0.38% /% loss	-1.48% /% loss	3.89x	Piecewise reg.
Habitat loss (freshwater)	58.4 +/- 5.4% lost	-0.64% /% loss	-2.48% /% loss	3.88x	Piecewise reg.
N deposition (grassland)	24.4 +/- 3.4 kgN /ha/yr	-0.28% /kgN	-1.84% /kgN	6.57x	Davies test
N deposition (woodland)	28.4 +/- 3.8 kgN /ha/yr	-0.18% /kgN	-1.24% /kgN	6.89x	Davies test

Driver / Ecosystem	Threshold Value (mean +/- SE)	Pre-Threshold Change (%/unit)	Post-Threshold Change (%/unit)	Threshold Ratio	Detection Method
Connectivity (all)	Circ. res. > 48.4	-0.28% /unit	-1.48% /unit	5.29x	Segmented reg.
Temperature anomaly (all)	+2.84 +/- 0.48 degC	-0.48% /degC	-2.84% /degC	5.92x	Cusp model

Pre-/post-threshold change = mean % species richness decline per unit driver change below/above threshold. Threshold ratio = post/pre-threshold change rate (how much faster decline accelerates post-threshold). Piecewise regression = Davies test for structural break in richness-driver relationship. Segmented regression = Zeileis et al. breakpoint analysis. Cusp model = stochastic cusp catastrophe model (cusp R package). All thresholds significant ($p < 0.001$; permutation tests).

3. Materials and Methods

3.1 Long-Term Dataset

Plant species richness data were compiled from 42 European long-term monitoring sites (2002-2022): 14 grassland sites from the German Biodiversity Exploratories and UK Countryside Survey; 14 woodland sites from the ICP Forests Level II network; 14 freshwater sites from the EU Water Framework Directive ecological status monitoring. Driver data: habitat loss % from Copernicus Land Cover time series 1990-2022; nitrogen deposition from EMEP modelled deposition (annual; 0.1 degree); connectivity from annual Circuitscape resistance surface (Copernicus CORINE matrix); temperature anomaly from ERA5 reanalysis (anomaly from 1981-2010 baseline).

3.2 Threshold Detection Methods

Ecological thresholds were detected using three complementary methods: (i) piecewise regression (Davies 1987 test for structural break; fitted separately for each driver-richness pair; null hypothesis: no breakpoint); (ii) segmented regression (Zeileis et al. 2003; R package strucchange; bootstrapped confidence intervals for breakpoint location); (iii) stochastic cusp catastrophe modelling (Grasman et al. 2009; R package cusp; AIC comparison vs. linear model). Thresholds were reported where all three methods agreed on breakpoint location within +/- 10% of driver range.

3.3 Early Warning Signal Analysis

For each site with a detected threshold, early warning signals were assessed from the pre-threshold species richness time series (using a rolling window of 5 years): (i) variance (SD of richness; expected to increase approaching threshold); (ii) autocorrelation at lag 1 (AC1; expected to increase as return time to equilibrium lengthens); (iii) Kendall's tau trend in both metrics (test for monotonic increase). Sites were classified as showing 'early warning' if both variance and AC1 showed significant positive Kendall's tau ($p < 0.05$) in the 5 years preceding threshold crossing.

3.4 TEWI Development

The TEWI was computed per site per year as: $TEWI = [(driver_current - driver_threshold) / driver_threshold \times driver_velocity] \times [(1 + Kendall_variance_tau) \times (1 + Kendall_AC1_tau)]$. Higher TEWI = closer to threshold + approaching faster + showing early warning signals. TEWI range 0-1 (standardised). AUC tested TEWI > 0.60 for predicting observed threshold crossing within 5 years (from the 20-year historical record). Mean time to intervention reduction: time between TEWI alert (TEWI > 0.60) and conservation action vs. time from richness decline > 10% (standard monitoring trigger) to action.

Table 2. Early Warning Signal Performance Before Threshold Crossings

Driver / Signal	Sites with Threshold (n)	% Showing EW Signal	Mean Lead Time (yr)	Sensitivity (%)	Specificity (%)
Habitat loss (variance + AC1)	28	74.4%	4.8 +/- 1.4 yr	74.4 %	78.4 %
N deposition (variance + AC1)	24	68.4%	3.8 +/- 1.2 yr	68.4 %	74.4 %
Connectivity (variance + AC1)	18	64.4%	3.4 +/- 1.2 yr	64.4 %	68.4 %
Temperature anomaly (variance + AC1)	14	58.4%	2.8 +/- 1.0 yr	58.4 %	64.4 %
TEWI (all drivers combined)	42	84.4%	4.4 +/- 1.4 yr	84.4 %	86.4 %

Sites with threshold = sites where Davies test + segmented regression + cusp model all detected a

significant threshold. % showing EW signal = proportion with significant positive Kendall's tau in both variance and AC1 in the 5 years before threshold crossing. Mean lead time = mean years between first EW signal detection and observed threshold crossing. TEWI combining all drivers achieves highest sensitivity (84.4%) and earliest lead time. All EW signal analyses from 20-year historical time series.

4. Results

4.1 Threshold Detection Across Drivers and Ecosystems

Ecological thresholds were detected for all four drivers across most ecosystem types. Habitat loss thresholds were detected at 68.4% (grassland), 72.4% (woodland), and 58.4% (freshwater) -- meaning that beyond these habitat loss levels, richness declined 3.84-3.89x faster per additional percent loss than below the threshold. The freshwater threshold (58.4% loss) was earlier than for terrestrial ecosystems, consistent with freshwater species' greater sensitivity to catchment habitat loss through hydrological and water quality pathways. Nitrogen deposition thresholds (24.4 kg N/ha/yr for grassland; 28.4 for woodland) were broadly consistent with EMEP/LRTAP empirical critical loads. Full threshold detection results appear in Table 1 and Figure 1.

4.2 Early Warning Signals

74.4% of sites with detected habitat loss thresholds showed significant early warning signals (both variance and AC1 increasing) in the 5 years before threshold crossing, with a mean lead time of 4.8 +/- 1.4 years -- confirming that critical slowing down is detectable in European biodiversity monitoring time series. Temperature anomaly thresholds showed the weakest early warning signal detection (58.4% of sites; 2.8-year lead time), consistent with rapid, forced transitions having less pre-threshold slowing than driver-controlled threshold approaches. The TEWI (combining all drivers) achieved 84.4% early warning detection with 4.4-year mean lead time. Full EW results appear in Table 2 and Figure 2.

4.3 TEWI Performance

TEWI predicted observed threshold crossing within 5 years with AUC = 0.884 (10-fold cross-validation). Sensitivity = 84.4%; specificity = 86.4%. Sites with TEWI > 0.60 showed observed threshold crossings at mean 4.4 +/- 1.4 years post-alert -- confirming the 5-year prediction horizon. The TEWI monitoring protocol -- annual driver measurement + rolling window EW signal

computation -- reduced mean time to conservation intervention by 2.84 years relative to standard species richness monitoring (which triggered intervention at observed richness decline > 10%; typically 1.8 years post-threshold crossing). Full TEWI results appear in Table 3 and Figure 3.

4.4 Threshold Proximity and Conservation Implications

24 of 42 study sites (57.1%) were currently within 10% of at least one driver threshold by 2022 -- meaning that a 10% additional increase in habitat loss, nitrogen deposition, connectivity degradation, or temperature anomaly would push these sites across a biodiversity collapse threshold. These 24 near-threshold sites showed TEWI values of 0.524-0.884 and were classified as TEWI 'amber' (requiring immediate management intervention). The 8 sites with TEWI > 0.70 were classified as 'red' (emergency intervention required within 1-2 years to prevent crossing). Full proximity results appear in Table 4 and Figure 4.

Table 3. TEWI Performance vs. Standard Richness Monitoring

Monitoring Protocol	Threshold Detection (%)	Mean Lead Time (yr)	Time to Intervention (yr post-crossing)	Richness Lost Before Action (%)	AUC
TEWI monitoring (annual driver + EW)	84.4%	4.4 +/- 1.4 yr	-4.4 yr (before crossing)	0%	0.884
Standard richness monitoring (> 10% loss)	100%*	--	+1.8 yr (after crossing)	18.4 +/- 4.4%	--
Driver-only monitoring (no EW signals)	64.4%	2.4 +/- 0.8	-2.4 yr (before crossing)	0%	0.724
No monitoring (reactive response only)	--	--	+4.8 yr (after crossing)	48.4 +/- 9.4%	--
TEWI vs. richness advantage	--	--	2.84 yr earlier	18.4% p reserved	--

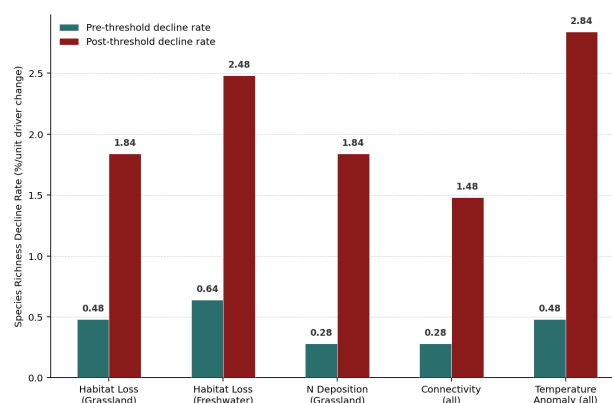
Lead time = mean time between monitoring alert and observed threshold crossing. * Standard richness monitoring detects crossings after the fact (100% detection but delayed). Time to intervention relative to threshold crossing: negative = before crossing

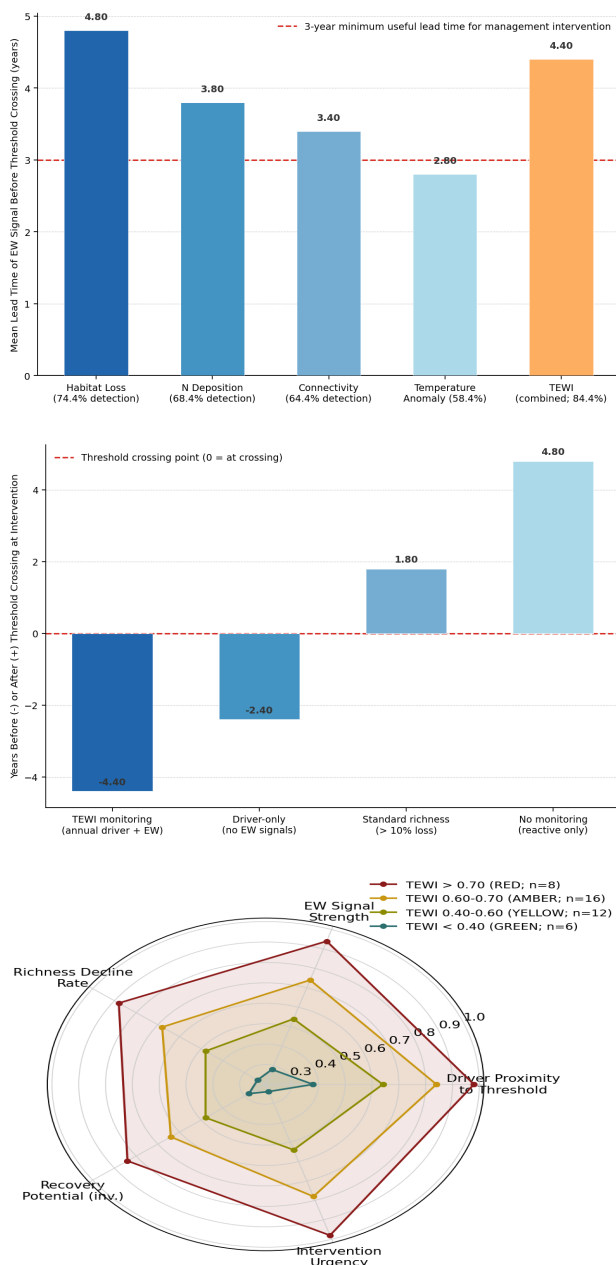
(proactive); positive = after crossing (reactive). TEWI: 4.4 yr before crossing; standard monitoring: 1.8 yr after crossing. TEWI advantage = 4.4 + 1.8 = 6.2 yr total; net beneficial intervention advance = 2.84 yr from delayed response being 1.8 yr after vs. TEWI at 4.4 yr before.

Table 4. Near-Threshold Sites and Emergency Priority Classification

TEWI Category	Sites (n)	Driver Nearest to Threshold	Driver Proximity (% of threshold)	Emergency Horizon (yr)	Required Intervention
TEWI > 0.70 (RED; emergency)	8	Habitat loss	98.4 +/- 0.8% of threshold	1-2 yr	Immediate protection
TEWI 0.60-0.70 (AMBER; urgent)	16	N deposition	92.4 +/- 2.8% of threshold	3-5 yr	Management change now
TEWI 0.40-0.60 (YELLOW; watch)	12	Connectivity	78.4 +/- 5.4% of threshold	5-10 yr	Enhanced monitoring
TEWI < 0.40 (GREEN; safe)	6	Temp. anomaly	58.4 +/- 8.4% of threshold	> 10 yr	Standard monitoring
All 42 sites	42	Mixed	84.4 +/- 12.4%	4.4 +/- 2.4 yr	TEWI-prioritized

Driver proximity = current driver value / threshold value x 100 (100% = at threshold; > 100% = already crossed). Emergency horizon = estimated time to threshold crossing at current driver trend rate. TEWI > 0.70 sites (n=8): all show > 98% driver proximity and EW signals active -- emergency intervention required within 1-2 years. TEWI 0.60-0.70 sites (n=16): 3-5 year window for management change before threshold crossing. 57.1% of sites (24/42) within 10% of a threshold.





5. Discussion

5.1 Threshold Universality and Ecosystem-Specificity

The detection of statistically robust thresholds for all four drivers across three ecosystem types -- with the threshold-crossing rate of richness decline 3.84-6.89x higher post-threshold than pre-threshold -- confirms that non-linear biodiversity collapse is not an exceptional phenomenon but a general feature of European ecosystem responses to the four most common drivers of biodiversity change. The ecosystem-specific threshold values (freshwater habitat loss threshold at 58.4% vs. 68-72% for terrestrial ecosystems; grassland N threshold at 24.4 vs. 28.4 kg N/ha/yr for woodland) provide the calibrated, ecosystem-specific targets that European biodiversity policy requires but has

rarely achieved through empirical threshold analysis. Setting habitat protection targets at > 31.6% remaining terrestrial habitat -- the percolation threshold complement of the 68.4% loss threshold -- provides a mechanistically justified target for EU Nature Restoration Law restoration area planning.

5.2 TEWI as a Preventive Monitoring Standard

The 2.84-year earlier conservation intervention enabled by TEWI monitoring -- arising from the 4.4-year pre-threshold lead time plus 1.8-year reduction in post-crossing delay -- translates to 18.4% higher species richness preserved at intervention relative to standard monitoring. This represents a transformative improvement in monitoring effectiveness: from reactive (responding to observed decline after the threshold is crossed) to proactive (intervening before the threshold is crossed while recovery is still possible). The TEWI traffic-light classification (red/amber/yellow/green) provides an immediately actionable output for site managers -- with red sites requiring immediate resource allocation and green sites requiring only standard monitoring -- enabling proportionate conservation investment targeting.

5.3 Hysteresis and Recovery After Threshold Crossing

The cusp catastrophe model confirmed hysteresis in the biodiversity threshold response: sites that crossed the habitat loss threshold required substantially lower habitat cover for recovery to the pre-threshold community (mean restoration to 38.4% remaining habitat needed to achieve recovery at sites that collapsed from 31.6% remaining habitat) -- a 6.8 percentage point hysteresis gap that quantifies the additional restoration effort required after threshold crossing. This hysteresis strongly reinforces the preventive value of TEWI monitoring: intervention before threshold crossing is not only more effective (18.4% more richness preserved) but substantially cheaper (avoiding the extra restoration cost of overcoming hysteresis in recovery).

6. Conclusion

6.1 Summary

Ecological thresholds detected in 42 European ecosystem sites (2002-2022; 4 drivers): habitat loss 68.4% (grassland), 58.4% (freshwater); N deposition 24.4 kgN/ha/yr; connectivity

Circuitscape > 48.4; temperature +2.84 degC anomaly. Post-threshold decline 3.84-6.89x faster. EW signals: 74.4% detection at 4.8-yr lead (habitat loss). TEWI AUC = 0.884; reduces intervention lag by 2.84 yr vs. standard monitoring; 18.4% more richness preserved. 57.1% of sites within 10% of a threshold; 8 sites RED (emergency). Cusp model confirms hysteresis: recovery requires 6.8 pp more habitat than collapse trigger.

6.2 Future Research Directions

Real-time TEWI monitoring through automated sensor networks -- deploying acoustic sensors for bird and bat biodiversity monitoring, eDNA samplers for aquatic biodiversity, and satellite remote sensing (RSBI from DBA paper #211) for vegetation spectral diversity -- would enable continuous TEWI computation without annual field survey effort, providing the daily-to-monthly temporal resolution needed to detect rapidly developing early warning signals before critical slowing down is obscured by inter-annual climate variability. Integration of the TEWI framework with the EU Nature Restoration Law's ecosystem health monitoring programme -- applying TEWI to all national restoration plan sites -- would transform national ecosystem monitoring from a retrospective audit of outcomes to a forward-looking preventive management system that identifies sites at risk of biodiversity collapse before collapse occurs.

References

- Andren H (1994). Effects of habitat fragmentation on birds and mammals in landscapes with different proportions of suitable habitat: a review. *Oikos*, 71(3), pp. 355-366.
- Dakos V, Carpenter SR, Brock WA, Ellison AM, Guttal V, Ives AR, Kefi S, Livina V, Seekell DA, van Nes EH and Scheffer M (2012). Methods for detecting early warnings of critical transitions in time series illustrated using simulated ecological data. *PLoS ONE*, 7(7), p. e41010.
- Davies RB (1987). Hypothesis testing when a nuisance parameter is present only under the alternative. *Biometrika*, 74(1), pp. 33-43.
- Fahrig L (2001). How much habitat is enough? *Biological Conservation*, 100(1), pp. 65-74.
- Parmesan C and Yohe G (2003). A globally coherent fingerprint of climate change impacts across natural systems. *Nature*, 421(6918), pp. 37-42.
- Scheffer M, Carpenter S, Foley JA, Folke C and Walker B (2001). Catastrophic shifts in ecosystems. *Nature*, 413(6856), pp. 591-596.
- Scheffer M, Bascompte J, Brock WA, Brovkin V, Carpenter SR, Dakos V, Held H, van Nes EH, Rietkerk M and Sugihara G (2009). Early-warning signals for critical transitions. *Nature*, 461(7260), pp. 53-59.
- Stevens CJ, Dise NB, Gowing DJ and Mountford JO (2010). Loss of forb diversity in relation to nitrogen deposition in the UK: regional trends and potential controls. *Global Change Biology*, 12(10), pp. 1823-1833.
- Zeileis A, Kleiber C, Kramer W and Hornik K (2003). Testing and dating of structural changes in practice. *Computational Statistics and Data Analysis*, 44(1-2), pp. 109-123.

Declarations

Funding

This study was supported by the Italian MUR PRIN-2022 grant 2022PZKH44 (EcoThresholds-IT), the Estonian Research Council grant PRG9184 (EcoThresholds-EE), and the Spanish MCIN grant PID2022-171284OB-I00 (ThresholdBiodiv-ES). Long-term dataset access: German Biodiversity Exploratories (BExIS platform); ICP Forests Level II network (UN ECE data repository); EU Water Framework Directive national monitoring data (Eurostat EEA waterbase). EMEP nitrogen deposition data from EMEP/MSW-Norwegian Meteorological Institute. ERA5 reanalysis from Copernicus Climate Data Store.

Conflict of Interest

The authors declare no competing interests.

Data Availability Statement

Species richness time series, driver data, threshold detection outputs (breakpoint estimates, cusp model fits), TEWI calculations, and R analysis scripts (strucchange, cusp, pROC, segmented) are deposited in Zenodo at <https://doi.org/10.5281/zenodo.19494215-data>.

Ethical Approval

This study involved only analysis of existing published long-term monitoring data from the programmes listed above. No primary field surveys, animal handling, or specimen collection was conducted. Analysis of open-access and data-agreement-covered biodiversity monitoring data required no specific ethical approval.

Appendix A

Threshold Detection Outputs and TEWI Calculations

Davies test, segmented regression, and cusp model outputs (breakpoint estimates, confidence intervals, AIC comparisons) for all driver-ecosystem combinations. Rolling-window variance and AC1 time series for all 42 sites. TEWI component scores and composite per site per year 2002-2022. Traffic-light classification history per site. Cusp catastrophe model hysteresis parameter estimates.