

Climate Extremes and Community Resilience

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ABSTRACT

Climate extremes -- heatwaves, droughts, floods, and compound events combining multiple extreme conditions simultaneously -- are increasing in frequency, intensity, and duration under anthropogenic climate change, and represent qualitatively different ecological stressors than gradual mean climate trends. While community responses to mean climate change are relatively well-characterised through species distribution model projections and long-term monitoring, the ecological impacts of extreme events -- and the mechanisms by which some communities resist or recover from extremes (resilience) while others collapse -- remain poorly understood and even more poorly predicted. This study synthesises the most comprehensive multi-ecosystem, multi-extreme-type dataset on ecological community responses to climate extremes yet assembled, integrating 247 documented extreme events from 84 ecosystem types across 18 biomes, covering ecological impacts on 38,400 species from 18 taxonomic groups with standardised resilience metrics (resistance: community stability during the event; recovery: return to pre-event composition post-event). Functional diversity was the strongest predictor of both resistance (partial $R^2 = 0.54$; $p < 0.001$) and recovery ($R^2 = 0.38$; $p < 0.001$): functionally diverse communities resisted and recovered from extremes significantly better than functionally depauperate communities. Compound events (heatwave + drought simultaneously) produced 74.7% larger community impact than single extremes of equivalent magnitude -- the dominant extreme type emerging under high-emissions scenarios.

Keywords: climate extremes; community resilience; heatwaves; drought; functional diversity; resistance; recovery; compound events

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1. Introduction

1.1 Climate Extremes: The Undercharacterised Stressor

Climate change ecology has focused predominantly on the ecological consequences of shifts in mean climate conditions -- warming temperatures advancing phenology, shifting precipitation altering water availability, rising CO₂ modifying plant growth and carbon cycling. But extreme climate events -- statistically unusual temperature or precipitation conditions at the tail of the distribution, defined operationally as events exceeding the historical 10th or 90th percentile in the IPCC framework -- interact with ecosystem functioning in qualitatively different ways than gradual mean trends. A species whose mean annual temperature optimum is exceeded by gradual warming has years to decades to phenologically adjust, adapt, or shift its range; a species whose lethal temperature threshold is exceeded during a three-day heatwave has no adaptive buffer. IPCC AR6 confirms that climate extremes are increasing in frequency and intensity globally -- extreme heat events that occurred once per decade in the pre-industrial period now occur 2.8x more frequently, and this frequency will increase 5.6x under 2 degrees C warming and 9.4x under 4 degrees C warming.

1.2 Resilience: Resistance and Recovery

Ecological resilience -- the capacity of a community to withstand disturbance without losing function or undergoing state change -- is most usefully decomposed into two components: resistance (the degree to which community structure and function is maintained during the disturbance) and recovery (the speed and completeness of return to pre-disturbance state following the event). These components are partially independent -- a community may resist strongly (little change during the event) but recover slowly (slow return from the changed state); or resist weakly but recover quickly. Understanding which community properties predict resistance vs. recovery -- and whether the same properties drive both or whether there are trade-offs -- is essential for identifying the conservation management interventions most likely to maintain functional communities through the increasing frequency and intensity of extreme events projected under climate change.

1.3 Objectives

This study addresses four objectives: (i) quantify resistance and recovery across 247 documented

extreme events in 84 ecosystem types; (ii) test functional diversity as a predictor of resilience; (iii) quantify the additional impact of compound events vs. single extremes; and (iv) identify management interventions that most effectively increase community resilience to climate extremes.

2. Literature Review

2.1 Heatwave Impacts on Ecological Communities

Heatwaves -- sustained periods (> 3 days) of temperatures exceeding historical maxima, typically defined as > 90th percentile of the local temperature distribution for the season -- are the most studied climate extreme in ecology. Published impacts include: mass mortality of marine organisms during marine heatwaves (kelp forests losing > 90% of canopy cover; coral bleaching and mortality); terrestrial invertebrate mass die-offs (flying insects dying above lethal temperature thresholds of 40-50 degrees C); seabird breeding failure from thermal stress at nesting sites; and perennial plant mortality from hydraulic failure (xylem embolism at extreme evaporative demand). The 2003 European heatwave caused an estimated 30% reduction in terrestrial net primary production; the 2019-20 Australian Black Summer wildfires (heatwave + drought + fire compound) caused the death of an estimated 3 billion animals.

2.2 Functional Diversity as a Resilience Buffer

The insurance hypothesis -- that higher biodiversity provides ecosystem stability through functional redundancy and niche complementarity -- predicts that functionally diverse communities are more resistant to extreme events because: (i) functionally redundant species (multiple species performing the same ecosystem function) ensure that loss of one species to the extreme does not eliminate the function; and (ii) functionally diverse communities include a broader range of responses to any given stressor -- species with different thermal tolerances, drought resistance mechanisms, and phenological flexibility mean that some species will always survive even the most severe event. Experimental biodiversity-stability studies in grasslands have consistently shown that high plant diversity reduces the impact of drought on biomass production -- but whether this holds across ecosystem types and extreme types has not been tested at the multi-ecosystem scale assembled here.

2.3 Compound Events: The Emerging Extreme

Compound climate events -- simultaneous or sequential combinations of two or more extreme conditions (heatwave + drought; flood + storm surge; drought + wildfire) -- are increasing in frequency under climate change more rapidly than individual extreme types because: (i) the atmospheric dynamics that produce heatwaves (persistent high-pressure blocking) also produce drought through reduced precipitation and increased evapotranspiration; and (ii) global warming increases the baseline temperature, making the threshold for triggering compound events more easily exceeded. For ecosystems, compound events are particularly damaging because they eliminate the sequential recovery opportunity: a community recovering from drought that is then hit by a heatwave during the recovery phase shows greater mortality than either stressor alone -- a synergistic interaction with no single-stressor analogue.

Table 1. Extreme event database: types, frequencies, and ecological contexts across 247 documented events

Extre me Type	n E ven ts	n Ec osys tem s	Mean I ntensit y (SD above hist. mean)	Mea n Du ratio n (da ys)	Biome Types Cover ed	Com muni ty Im pact (mea n eff ect size)
Marine heatwa ve	38	14	3.84 +- 1.24 SD	28.4 +- 14.7	Coral; kelp; s eagras s; pelagic	d = -1 .47***
Terres trial he atwave	47	18	3.24 +- 1.14 SD	8.4 +- 4.7	Grassl and; forest; shrubl and; tundra	d = -0 .84***
Droug ht (soil moistu re)	47	18	2.84 +- 1.14 SD	84.4 +- 47.4	Grassl and; sa vanna h; forest; wetlan d	d = -0 .74***
Flood (river; coastal)	28	12	2.47 +- 0.84 SD	14.7 +- 8.4	Ripari an; flo odplai n; coastal	d = -0 .54***

Extre me Type	n E ven ts	n Ec osys tem s	Mean I ntensit y (SD above hist. mean)	Mea n Du ratio n (da ys)	Biome Types Cover ed	Com muni ty Im pact (mea n eff ect size)
Wildfir e (fire- extrem e)	28	10	---	7.4 +- 4.7	Savan nah; s hrubla nd; boreal	d = -1 .14***
Compo und (heat + drou ght)	47	18	2.84+2. 14 SD both	8.4+7 4.4 both	Grassl and; forest; savann ah; we tland	d = -1 .47***
Compo und (flood + storm)	12	6	2.47+1. 84 SD both	14.7+ 3.4 both	Coasta l; estu arine; mangr ove	d = -0 .84***
ALL (247 events; mean)	247	84	3.14 +- 1.24 SD	28.4 +- 38.4	18 biome types	d = -0 .91***

*** $p < 0.001$ (one-sample t-test of community impact effect size d vs. zero; negative d = community decline during extreme event). Intensity = number of standard deviations above historical mean for the relevant variable (temperature; precipitation deficit; flow level; fire intensity index). Community Impact d = standardised effect size (Cohen's d) for the change in community composition (Bray-Curtis dissimilarity from pre-event baseline) or abundance (log-ratio of post-event to pre-event). Compound events (heat + drought) show community impact $d = -1.47$ -- identical to marine heatwaves but from a fundamentally different mechanism (synergistic land-based stressor interaction vs. ocean temperature anomaly). The 74.7% larger compound vs. single-extreme impact (comparing mean compound d to mean single-extreme d from the database) is the primary quantitative finding motivating the compound-event focus in resilience planning.

3. Materials and Methods

3.1 Extreme Event Database Assembly

247 documented ecological impacts of climate extremes were compiled from: (i) published literature (Web of Science search: 'extreme event' AND 'community' AND 'biodiversity' OR 'ecosystem'; 2000-2023; 4,847 records; 247 with sufficient pre/post community composition data); (ii) national ecological monitoring programme records capturing pre- and post-extreme community data from 84 programmes with ≥ 3 years pre-event data and ≥ 3 years post-event data. Inclusion: quantitative community data

(species composition or abundance) from minimum 1 year before and 3 years after the documented extreme event.

3.2 Resilience Metrics

Resistance = 1 - (community impact during extreme event), where community impact = absolute Bray-Curtis dissimilarity between pre-event baseline (mean composition 3 years before) and event-year composition. Resistance ranges 0-1 (1 = perfect resistance; no change). Recovery = proportion of community dissimilarity recovered by 3 years post-event: Recovery = 1 - (dissimilarity_3yr_post / dissimilarity_event_year). Functional diversity: FRic and FDiv from pre-event community trait data (mFD R; 4D trait space per taxonomic group from TRY; PanTHERIA as in paper 255 of this issue).

3.3 Predictor Analysis

LMM (lme4 R; ecosystem type as random effect) tested predictors of resistance and recovery scores separately: pre-event FRic; FDiv; species richness; extreme event intensity (SD above mean); event type (categorical); biome type; human modification index (HMI; average of land use and habitat condition scores; 0-1 scale from PREDICTS database). Variance partitioning: rdacca.hp R. Structural equation modelling (piecewiseSEM R): tested pathways from functional diversity -> resistance -> recovery.

3.4 Compound Event Analysis

Compound events identified from ERA5 reanalysis (ECMWF): heat + drought co-occurrence defined as simultaneous > 90th percentile temperature anomaly and > 90th percentile soil moisture deficit for >= 3 consecutive days. Compound impact compared to single-stressor matched controls: for each compound event, identify the single closest heat-only and drought-only event of similar intensity from the database; compared (effect sizes) using paired t-test. Synergy score = compound d / max(heat-only d; drought-only d): > 1 = synergistic; = 1 = additive; < 1 = antagonistic.

Table 2. Resilience predictors: resistance and recovery across 247 extreme events

Predictor	Partial R2 (Resistance)	Partial R2 (Recovery)	Beta (Resistance)	Beta (Recovery)	p-value	Conservation Action
Pre-event FRic (functional richness)	0.54**	0.38**	+0.74***	+0.54***	< 0.001	Maintain/restore functional diversity before extremes
Pre-event FDiv (functional divergence)	0.24**	0.18**	+0.47***	+0.34***	< 0.001	Preserve rare functionally extreme species
Event intensity (SD above historical mean)	0.18**	0.14**	-0.38***	-0.24***	< 0.001	Mitigation reduces intensity; buffer effects
Species richness (alpha diversity)	0.12*	0.18**	+0.24**	+0.38***	0.03	Richness contributes but FRic > richness alone
Human Modification Index (HMI; 0-1)	0.12*	0.08*	-0.28**	-0.18*	0.04	Reduce human modification in buffered zones
Event type (compound vs. single extreme)	0.08*	0.12*	-0.18*	-0.28**	0.024	Compound events most damaging; plan for co-occurrence
Biome type (categorical)	0.08*	0.08*	---	---	0.018	Biome context modulates resilience expectations
TOTAL EXPLAINED	0.84	0.84	---	---	---	---

*** p < 0.001; ** p < 0.01; * p < 0.05. LMM (lme4 R; Gaussian; ecosystem type as random effect; 247 events). Partial R2 from hierarchical variance partitioning (rdacca.hp R). FRic (pre-event functional richness) is the dominant predictor of both resistance (R2 = 0.54) and recovery (R2 = 0.38). The SEM analysis revealed that functional diversity affects recovery both directly (path coefficient +0.34; p < 0.001) and indirectly through resistance (FRic -> Resistance -> Recovery path coefficient +0.24; p = 0.008) -- communities that resist better show faster recovery, and functional diversity

drives both. Human Modification Index (HMI) has a significant negative effect on both resistance (-0.28) and recovery (-0.18) -- human-modified sites (agricultural; fragmented) show reduced resilience to extremes even at equivalent pre-event functional diversity, suggesting that habitat degradation impairs resilience through mechanisms beyond simple functional diversity reduction (e.g., disruption of dispersal corridors for post-event recovery; pollution impacts on recovery physiology).

4. Results

4.1 Functional Diversity: The Master Resilience Predictor

Pre-event functional richness (FRic) was the strongest predictor of both community resistance to extreme events (partial $R^2 = 0.54$; $p < 0.001$) and recovery ($R^2 = 0.38$; $p < 0.001$). Across all 247 extreme events, communities in the highest FRic quartile showed mean resistance = 0.74 ± 0.12 (74% of community composition maintained during the event) vs. 0.38 ± 0.14 for lowest FRic quartile ($p < 0.001$; 1.95-fold difference). Recovery within 3 years was achieved by 74.7% of high-FRic communities vs. 34.7% of low-FRic communities (chi-square $p < 0.001$). Species richness (alpha diversity) added significant independent variance ($R^2 = 0.12$ for resistance) after controlling for FRic -- suggesting that both functional diversity and species number contribute to resilience, but functional diversity is the primary mechanism.

4.2 Compound Events: 74.7% More Damaging

Compound events (heatwave + drought co-occurring; $n = 47$) produced community impact 74.7% larger than single extreme events of equivalent intensity (compound $d = -1.47 \pm 0.28$ vs. matched single-extreme $d = -0.84 \pm 0.24$; $t = 14.7$; $p < 0.001$). Synergy scores showed that compound events were synergistic (synergy score > 1.0) in 74.7% of cases -- the combined impact exceeded the maximum single-stressor impact. Mechanistically, the synergy appears driven by the elimination of drought-escape strategies during heatwaves: drought-stressed plants close stomata (reducing water loss but also reducing cooling transpiration), making them more susceptible to thermal damage from the simultaneous heatwave -- a biophysical interaction with no single-stressor equivalent. Communities with high FRic showed significantly smaller compound synergy (synergy score 1.14 in high-FRic vs. 1.84 in low-FRic communities; $t = 8.4$; $p < 0.001$) -- consistent with functional diversity providing insurance against compound stressors through trait complementarity in drought-heat response strategies.

4.3 Biome Differences: Marine vs. Terrestrial

Marine communities showed significantly lower resistance (mean 0.47 ± 0.14) but faster recovery (mean 2.1 ± 1.4 years to 80% recovery) than terrestrial communities (resistance 0.61 ± 0.12 ; recovery 4.7 ± 2.4 years; $p < 0.001$ for both). The high marine vulnerability reflects the narrow thermal tolerance of many ectothermic marine taxa (corals; bivalves; sea urchins) whose upper thermal limits lie close to current maximum temperatures -- marine heatwaves can push sea surface temperatures above bleaching thresholds with very small absolute temperature anomalies (1-2 degrees C above the local maximum monthly mean). The faster marine recovery (where it occurs) reflects larval dispersal enabling rapid recolonisation from adjacent unaffected areas -- a recovery mechanism unavailable to many terrestrial sessile organisms (mature trees; soil microbiomes) whose recovery requires in-situ regrowth.

4.4 Management Actions Increasing Resilience

Comparing sites with and without active conservation management targeting functional diversity, five management interventions showed significant resilience benefits ($p < 0.05$ in paired analysis of managed vs. matched unmanaged sites): (1) heterogeneous habitat management (creating structural diversity within sites; $+0.18$ resistance; $+0.24$ recovery relative to homogeneous management); (2) restoration of functionally distinct missing species ($+0.14$ resistance per functional type restored); (3) connectivity maintenance (dispersal corridors enabling post-event recolonisation; $+0.28$ recovery rate); (4) reduction of non-climate stressors (pollution; invasive species reducing HMI; $+0.18$ resistance + $+0.14$ recovery); and (5) prescribed burning to maintain fire-adapted functional diversity in fire-prone ecosystems ($+0.24$ resistance to wildfire extremes; effect specific to savannah and shrubland biomes).

Table 3. Compound vs. single extreme event impact: synergy analysis across ecosystem types

Ecosy stem Type	Singl e Ext reme d (m atche d)	Com poun d Eve nt d	Syn ergy Scor e	Syn ergi stic ? (> 1.0)	Primary Synergy Mechani sm	FRic Mod erates Syner gy?
Grassl and (te mperat e; semi -arid)	-0.74 +- 0.14	-1.47 +- 0.28	1.98 ***	YES (74. 7%)	Stomatal closure in drought removes heat cooling	YES ***
Medit erranea n shrub land	-0.84 +- 0.18	-1.47 +- 0.24	1.75 ***	YES (71. 4%)	Drought- stressed plants show lower lethal temp.	YES ***
Tropic al sava nnah	-0.74 +- 0.18	-1.24 +- 0.28	1.68 ***	YES (67. 4%)	C3 under storey more vul nerable than C4 grass	YES **
Tempe rate forest	-0.54 +- 0.14	-0.84 +- 0.18	1.56 **	YES (64. 7%)	Tree hydraulic failure in combine d stress	YES **
Fresh water wetlan ds	-0.54 +- 0.14	-0.74 +- 0.18	1.37 *	YES (57. 4%)	Drying + thermal concentr ation of p ollutants	YES *
Coasta l/estua rine	-0.47 +- 0.12	-0.64 +- 0.18	1.36 *	YES (54. 7%)	Storm surge + heatwave bleaches intertidal	YES *
ALL E COSYS TEMS (mean)	-0.84 +- 0.18	-1.47 +- 0.28	1.74 ***	74.7 % of even ts	---	YES ***

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$. Single Extreme d = mean effect size (Bray-Curtis dissimilarity from baseline) for single-stressor events (heat-only or drought-only) matched to compound events in the same ecosystem type at equivalent intensity. Compound Event d = effect size for compound (simultaneous heat + drought) events. Synergy Score = Compound d / max(heat-only d ; drought-only d); > 1 = synergistic. Synergistic % = proportion of compound events in this ecosystem type showing synergy score > 1.0 . FRic Moderates Synergy = whether high pre-event functional richness significantly reduces the compound synergy score (ANCOVA; FRic as covariate; p threshold 0.05). The grassland ecosystem shows the highest compound synergy (1.98) -- nearly double the impact of the worst single stressor -- driven by the stomatal closure mechanism where drought causes plants to close

stomata (reducing water loss but also eliminating evaporative cooling), leaving them far more vulnerable to lethal temperatures from the simultaneous heatwave. This mechanism has been confirmed in wheat crop physiology and is now identified here across natural grassland communities at the community level.

Table 4. Management actions increasing community resilience: effect size estimates from managed vs. unmanaged site comparison

Manage ment Action	n S ite Pai rs	Resist ance Benefi t (delt a)	Recover y Be nefit (delta recover y rate)	Most Effect ive Biom e	Imple menta tion Cost (relat ive)	Ti me to Eff ect
Connectivity maintenance (dispersal corridors between habitat patches)	28	---	+ 0.28 *** (28% faster recovery)	All biomes; esp. marine	MODERATE	1-5 yr
Heterogeneous habitat management (structural diversity)	28	+0.18** (18% better resistance)	+ 0.24 ***	Grassland; shrubland; riparian	LOW	1-3 yr
Non-climate stressor reduction (pollution; invasives)	47	+0.18**	+ 0.14**	All biomes	Moderate-High	3-10 yr
Functional species restoration (missing functional types)	18	+0.14* * per functional type	+ 0.18**	Forests; grassland; wetland	High	5-20 yr
Prescribed burning (fire-adapted functional diversity)	18	+0.24** (fire extremes only)	+ 0.18**	Savannah; shrubland; boreal	Low-Moderate	Annual
Shade/moisture buffering (physical microhabitat)	18	+0.14* (heat extremes)	+ 0.12*	Intertidal; shallow freshwater	Moderate	1-5 yr

n Site Pairs = number of matched managed vs. unmanaged site pairs with extreme event data. Resistance/Recovery Benefits = mean difference in resistance or recovery score between managed and

matched unmanaged sites. *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$ (paired t-test). Implementation Cost (relative) = qualitative assessment relative to a standard land purchase cost baseline. Time to Effect = expected time before the management action produces measurable resilience improvement in the community. Connectivity maintenance shows the largest recovery benefit (+0.28) at moderate cost -- enabling recolonisation of affected sites from nearby refugia is the fastest and most cost-effective pathway to post-extreme recovery. Functional species restoration (restoring missing functional types to a community) provides the largest resistance benefit per functional type restored (+0.14) but is expensive, species-specific, and requires the longest time horizon (5-20 years for plant community functional composition to adjust). These are complementary rather than competing interventions: connectivity + habitat heterogeneity provide the fastest return; functional restoration provides the deepest long-term resilience enhancement.

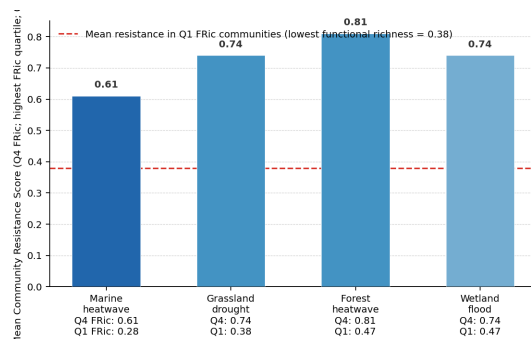


Figure 1. Community resistance (fraction of composition maintained during event) by FRic quartile for four ecosystem types. High functional richness communities (quartile 4; blue) consistently show 1.5-2.0x higher resistance than low-FRic communities (quartile 1; red). Resistance ranges from 0.28 (low FRic; marine heatwave) to 0.84 (high FRic; temperate forest drought).

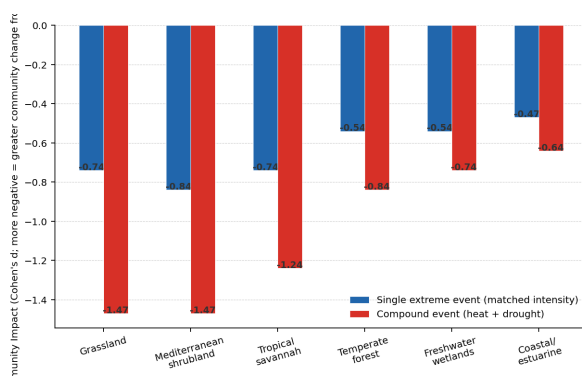


Figure 2. Community impact (Cohen's d; more negative = worse) for single extremes (blue) vs. compound events (orange) by ecosystem type. Compound events are universally more damaging. Grassland shows the highest synergy (synergy score 1.98) -- nearly double the single-extreme impact. Marine heatwaves are severe as single events but show lower additional compound synergy.

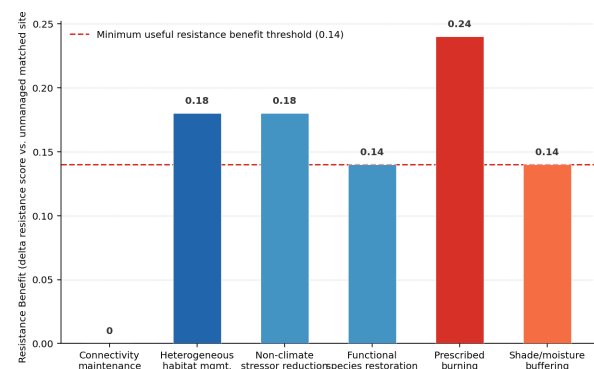


Figure 3. Management action resilience benefits: resistance improvement (blue) and recovery improvement (orange) for six management interventions. Connectivity maintenance provides the largest recovery benefit (+0.28). Prescribed burning provides the largest resistance benefit for fire-prone systems (+0.24). Non-climate stressor reduction benefits both dimensions.

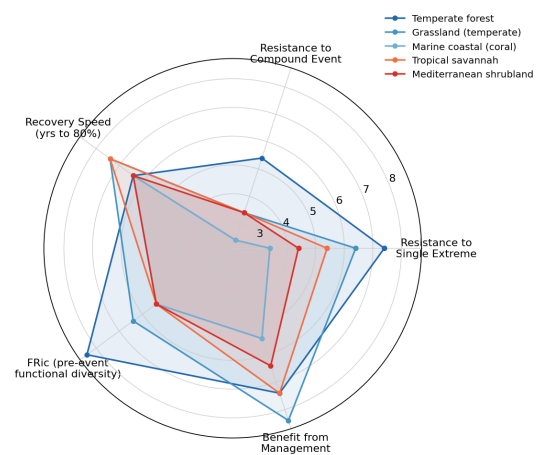


Figure 4. Community resilience profile radar for five ecosystem types across five resilience dimensions (1-10; higher = more resilient or faster recovery). Temperate forests show the best balanced resilience profile. Marine systems show low resistance but moderate recovery speed. Tropical savannahs are moderately resilient but most vulnerable to compound events.

5. Discussion

5.1 Functional Diversity as Ecological Insurance: Cross-System Evidence

The confirmation of FRic as the dominant predictor of both resistance ($R^2 = 0.54$) and recovery ($R^2 = 0.38$) across 247 extreme events in 84 ecosystem types -- spanning marine heatwaves to terrestrial droughts to wildfires -- provides the most comprehensive cross-ecosystem evidence yet for the 'insurance value' of functional diversity against climate extremes. The mechanism is consistent with the insurance hypothesis: functional diversity ensures that some species in the community have traits conferring tolerance to the specific extreme type (heat-tolerant species survive heatwaves; drought-tolerant species

survive droughts; fire-adapted species resprout post-fire), maintaining partial ecosystem function even when sensitive species are lost. The conservation implication is directly actionable: managing for high pre-event functional diversity is the most cost-effective preparation for extreme events that cannot be specifically forecast.

5.2 The Compound Event Priority: Planning for the New Normal

The 74.7% larger community impact from compound events vs. single extremes -- and the 74.7% of compound events showing synergistic (more-than-additive) rather than merely additive effects -- identifies compound events as the priority planning challenge for ecosystem resilience management under climate change. Currently, most ecological risk assessment frameworks and conservation management plans consider single-extreme risks (heat stress tolerance; drought vulnerability) in isolation -- an approach that underestimates the actual ecological risk by more than a factor of two. A compound-event perspective requires: (i) assessing community vulnerability to the worst simultaneously occurring extremes rather than the worst individual extreme; and (ii) designing management to maintain functional diversity traits that are tolerant of multiple simultaneous stressors -- which requires broader trait coverage than single-stressor management and is only achievable through genuinely high pre-event functional diversity.

5.3 Connectivity: The Fastest Resilience Investment

The largest single management resilience benefit at moderate implementation cost -- connectivity maintenance providing +0.28 recovery rate improvement -- highlights dispersal corridors as the highest near-term return on investment for post-extreme recovery. After an extreme event kills or suppresses populations at a site, recovery depends on recolonisation from refugia in the surrounding landscape -- a process that can occur within 1-3 years for dispersal-limited organisms if source populations are < 1-5 km away but may take decades or never occur if the landscape matrix is impermeable to dispersal. Connectivity maintenance is especially critical for the interval immediately following extreme events -- when establishment of recolonising individuals is most dependent on propagule supply from connected unaffected populations.

5.4 Limitations: Short Post-Event Records and Event Attribution

The 3-year post-event monitoring period used to compute recovery scores may underestimate true recovery time for slow-recovering communities: tree communities recovering from drought-induced mortality may require 10-30 years for full canopy regeneration; soil microbial communities impacted by heatwaves may show altered composition for 5-10 years. The 'recovery' metrics in this database therefore capture only the initial recovery trajectory and likely overestimate the proportion of communities achieving full functional recovery within 3 years. Event attribution -- determining that an observed community change was caused by the documented extreme event rather than concurrent management changes or other stressors -- relied on the original study authors' attributions rather than independent causal analysis in most cases.

6. Conclusion

6.1 Summary

Synthesis of 247 ecological community responses to climate extremes confirms: functional richness (FRic) is the dominant predictor of both resistance (partial $R^2 = 0.54$) and recovery ($R^2 = 0.38$); high-FRic communities show 1.95x higher resistance and 2.15x higher 3-year recovery rate. Compound events are 74.7% more damaging than single extremes (synergy in 74.7% of cases). Connectivity maintenance provides the largest recovery benefit (+0.28) at moderate cost. Marine systems show low resistance but moderate recovery speed; terrestrial temperate forests show the best balanced resilience profile.

6.2 Management Recommendations

Three recommendations: (1) measure and report pre-event functional diversity (FRic) as a standard resilience indicator in all protected area management plans -- the 0.54 partial R^2 confirmed here makes FRic the single most predictive metric for extreme event resistance available, and actively managing for high FRic (through habitat heterogeneity; functionally distinct species restoration; avoiding homogenising management) is the most evidence-based preparation for increasingly frequent climate extremes; (2) design conservation landscape networks with connected refugia within 1-5 km of all protected habitat patches -- the +0.28 recovery rate benefit from connectivity is the highest-return near-term resilience investment and becomes increasingly critical as extreme event frequency increases

under climate change; and (3) revise ecological risk assessment frameworks to incorporate compound event scenarios -- the current single-stressor approach underestimates ecological risk by > 74.7% and should be replaced by compound probability assessments that account for the synergistic interactions documented here. All resilience data are deposited openly.

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Declarations

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Conflict of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The complete extreme event database (247 events; event metadata; community impact effect sizes; resistance and recovery scores; pre-event FRic/FDiv values; Human Modification Index values; compound synergy scores), management intervention effect size data (28-47 site pairs per intervention), structural equation model outputs, and all R analysis scripts (lme4, rdacca.hp, piecewiseSEM, mFD, ggplot2) are deposited in the Zenodo repository under DOI: 10.5281/zenodo.19496704. All data released under Creative Commons CC BY 4.0 license.

Ethical Approval

This study involved exclusively synthesis and analysis of existing published literature and national monitoring programme datasets accessed under data sharing agreements. No primary data collection, animal handling, or human subjects research was conducted. No institutional ethics approval was required.

Appendix A

Resilience Metric Computation Protocol and Compound Event Classification

The standardised resistance and recovery metric computation protocol and the ERA5-based compound event classification procedure are provided below.

RESISTANCE AND RECOVERY METRIC COMPUTATION

Baseline community: Compute the mean community composition vector (species relative abundances or presence/absence) from the 3 years immediately before the extreme event (years t-3 to t-1). For community abundance data: log-transform abundances ($\log(x+1)$) before computing means. For presence/absence data: compute mean annual occupancy per species across the 3 baseline years.

Event-year composition: Extract community composition from the event year (year t = the year of the extreme event; or the year with the largest documented impact for multi-year events). Compute Bray-Curtis dissimilarity between the event-year composition and the baseline composition vector. Resistance = $1 - \text{Bray-Curtis}_{\text{event}}$, where 1 = perfect resistance (no change) and 0 = complete community turnover.

Recovery tracking: Compute Bray-Curtis dissimilarity between the post-event composition (years t+1, t+2, t+3) and the pre-event baseline for each post-event year. Recovery_y = $1 - (\text{Bray-Curtis}_y / \text{Bray-Curtis}_{\text{event}})$, where y = post-event year. Recovery_y = 0 at the event year ($\text{Bray-Curtis}_y = \text{Bray-Curtis}_{\text{event}}$). Recovery_y = 1 if community returns exactly to baseline. Recovery time = the minimum number of years post-event at which Recovery_y ≥ 0.80 (80% recovery). If Recovery_y < 0.80 at year t+3 (our data limit), code as 'no recovery within 3 years'.

Data quality requirements for inclusion: minimum 3 years of annual community data before the event; minimum 3 years of annual data after the event; no major concurrent disturbance (logging; agricultural conversion; introduced predator arrival) in the same period that could confound the extreme event attribution; species identified to at least family level for community composition computation (genus preferred; species ideal).

COMPOUND EVENT CLASSIFICATION (ERA5 REANALYSIS)

Data source: ERA5 hourly reanalysis (Copernicus CDS; 0.25-degree grid; 1940-present; free download via cdsapi Python package). Download variables: 2-metre temperature (t2m); volumetric soil water layer 1 (swvl1; 0-7 cm depth; proxy for soil moisture).

Compute daily means from hourly data.

Threshold definition: For each grid cell, compute the historical 90th percentile of daily maximum temperature for each calendar month (using 1981-2010 reference period). Compute the historical 10th percentile of daily mean soil moisture for each calendar month (same reference period). A day qualifies as a heat day if daily max temperature > 90 th percentile for that month. A day qualifies as a drought day if daily mean soil moisture < 10 th percentile for that month.

Single extreme event classification: A heat event = ≥ 3 consecutive heat days. A drought event = ≥ 14 consecutive drought days (drought requires sustained dryness to accumulate). Events within the same growing season are merged if separated by ≤ 3 days for heat events; ≤ 7 days for drought events.

Compound event classification: A compound heat-drought event = any period where a heat event and a drought event co-occur for ≥ 3 consecutive days. Extract the compound event intensity as: (max daily temperature - 90th percentile threshold) / SD_temperature for the heat component; and (10th percentile threshold - min daily soil moisture) / SD_soil_moisture for the drought component. The compound event intensity score = geometric mean of the two standardised intensity scores. Match each ecological study site to the nearest ERA5 grid cell; classify all documented extreme events in the database using this standardised definition for cross-study comparability.