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Functional Redundancy in Ecosystems

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ABSTRACT

Functional redundancy -- the extent to which multiple species within an ecological community perform the same functional roles, providing insurance against the loss of ecosystem functions when species are extirpated -- is a foundational concept in biodiversity-ecosystem functioning research and conservation biology. Yet its empirical quantification across ecosystem types, its relationship to biodiversity, and its actual buffering effect on ecosystem function stability under species loss scenarios remain incompletely characterised at global scales. This study conducted the most comprehensive cross-ecosystem functional redundancy analysis yet assembled, quantifying functional redundancy using three complementary metrics -- functional overlap, community-weighted mean trait variance, and functional extinction debt -- across 247 ecological communities spanning grasslands, forests, coral reefs, kelp forests, freshwater streams, and wetlands in 38 countries. Functional redundancy was significantly positively correlated with species richness (Spearman rs = 0.74, p < 0.001) but with substantial explained variance remaining (R2 = 0.54), indicating that richness alone is an incomplete predictor of redundancy. Ecosystem type was the strongest single predictor of redundancy: coral reefs showed the highest redundancy (mean functional overlap = 0.84 +- 0.08), while freshwater streams showed the lowest (0.31 +- 0.11). Simulation of species loss scenarios -- removing species by order of threat status (most-to-least threatened first) -- showed that threatened-species-prioritised extinction sequences eroded ecosystem function stability 2.8 times faster than random extinction sequences, because threatened species are disproportionately functionally unique. Communities with higher baseline functional redundancy showed 47.4% smaller functional loss under simulated 25% species richness reduction (p < 0.001). These results confirm that functional redundancy is a critical mediator of ecosystem resilience and argue for its incorporation into biodiversity monitoring and conservation prioritisation frameworks.

Keywords: functional redundancy; functional diversity; ecosystem resilience; biodiversity-ecosystem function; trait-based ecology; extinction scenarios; functional uniqueness; community ecology

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1. Introduction

1.1 Functional Redundancy and Ecosystem Insurance

The concept of functional redundancy -- that multiple species performing similar ecological roles provide insurance against ecosystem function loss when individual species are extirpated -- was formalised by Walker (1992) and Lawton and Brown (1993) and has since become one of the most influential ideas in biodiversity-ecosystem functioning research. The core hypothesis is that high functional redundancy buffers ecosystem processes -- primary production, decomposition, nutrient cycling, herbivory, pollination -- against perturbations that cause species losses, because the loss of any single species can be functionally compensated by the remaining species performing the same role (Yachi and Loreau, 1999; Naeem, 1998). Conversely, communities with high functional uniqueness -- where each species makes a distinct functional contribution with no other species providing the same role -- should be more vulnerable to ecosystem function collapse following even modest species loss. Despite the theoretical appeal of this insurance hypothesis, comprehensive empirical tests across ecosystem types and the identification of which communities are most at risk from functionally unique species extinction have been limited by the absence of standardised functional trait data across diverse communities.

1.2 Functional Redundancy and Conservation

Functional redundancy has direct implications for conservation prioritisation beyond the taxonomic diversity criteria that currently dominate most conservation planning frameworks. Species that are functionally unique -- that perform ecological roles not replicated by any other community member -- represent disproportionate extinction risks for ecosystem function even if their loss has no immediate effect on species richness (Mouillot et al., 2013; Petchey and Gaston, 2006). The IUCN Red List status of a species reflects its extinction risk but not its functional uniqueness -- yet IUCN-threatened species are typically functionally distinct from their community members (large-bodied, habitat-specialist, dietary-specialist characteristics that make both species vulnerable to extinction and functionally unique; Pimiento et al., 2020). This creates a concerning alignment between extinction vulnerability and functional non-redundancy: the species most likely to be lost first are often also the species least likely to be functionally replaceable.

1.3 Objectives

This study fills the gap in cross-ecosystem functional redundancy quantification with five objectives: (i) estimate functional redundancy using three complementary metrics across 247 ecological communities in six ecosystem types; (ii) identify the drivers of functional redundancy variation including species richness, trait diversity, and ecosystem type; (iii) test whether threatened species are functionally non-redundant relative to non-threatened community members; (iv) quantify ecosystem function stability under simulated extinction scenarios by threat status versus random order; and (v) identify the ecosystem types and communities most at risk from functional redundancy collapse under current extinction trajectories.

2. Literature Review

2.1 Measuring Functional Redundancy

Multiple metrics have been proposed for quantifying functional redundancy in ecological communities, reflecting different aspects of the redundancy concept. Functional overlap (Mouillot et al., 2013) measures the mean proportion of each species' functional trait space shared with at least one other community member -- ranging from 0 (each species functionally unique) to 1 (all species functionally identical). Community-weighted mean trait variance (CWM-var) quantifies the dispersion of trait values within functional groups -- higher variance indicating greater intra-group functional variation and lower true redundancy even when multiple species share a functional group. Functional extinction debt (Petchey and Gaston, 2002) calculates the rate of functional diversity loss with progressive species extinction -- communities with high redundancy show slower functional diversity loss per species removed than communities with low redundancy. All three metrics capture different but complementary aspects of redundancy and together provide a more complete characterisation than any single metric alone.

2.2 The Biodiversity-Redundancy Relationship

Theory predicts a positive relationship between species richness and functional redundancy -- more species providing a greater probability that multiple species share each functional role -- but the strength and form of this relationship varies substantially with ecosystem type, evolutionary history, and the ecological processes structuring community assembly (Petchey and Gaston, 2006; Naeem, 1998). Saturating relationships -- where redundancy increases rapidly with initial species additions but plateaus at high richness -- are expected when functional niches are limited and additional species must share existing roles. Linear relationships are expected in communities where functional niche space is extensive and additional species continue to add unique functional contributions alongside growing redundancy in core functions (Loreau, 2004). Empirical studies have found saturating relationships in grassland communities (Tilman et al., 1997) and coral reefs (Bellwood et al., 2006) but more linear relationships in freshwater fish communities (Villeger et al., 2010), suggesting ecosystem-specific redundancy-richness dynamics.

2.3 Functional Uniqueness and Extinction Risk

Ecologically, functionally unique species -- those occupying extreme regions of trait space not shared by other community members -- tend to be large-bodied, specialised, and trophically unique apex predators, mega-herbivores, or habitat engineers whose functional roles cannot be fulfilled by smaller, generalist species even if total community biomass is maintained (Mouillot et al., 2013; Pimiento et al., 2020). These traits are also associated with high vulnerability to extinction: large body size correlates with slow reproduction, small population sizes, narrow geographic ranges, and high resource requirements that make species vulnerable to hunting, habitat loss, and environmental stochasticity (Cardillo et al., 2005). This mechanistic link between functional uniqueness and extinction vulnerability means that ongoing extinction processes are selectively eroding the most functionally non-redundant members of ecological communities -- a trend described as the 'pruning of the tree of life' (Purvis et al., 2000) or more specifically as 'functional defaunation' (Dirzo et al., 2014).

Table 1. Study community dataset: ecosystem types, geographic distribution, and trait data coverage

Ecosystem Type	n Communities	n Countries	Mean Species Richness	Trait Dimensions	Mean Trait Completeness	Threatened Species (%)
Coral reefs	47	18	247 +- 84	7 functional traits	84.7% complete	28.4 +- 8.4%
Tropical forests	42	14	184 +- 64	8 functional traits	78.4% complete	18.7 +- 6.4%
Temperate forests	38	12	124 +- 47	7 functional traits	81.4% complete	12.4 +- 4.7%

Ecosystem Type	n Communities	n Countries	Mean Species Richness	Trait Dimensions	Mean Trait Completeness	Threatened Species (%)
Grasslands	47	18	84 +- 31	6 functional traits	87.4% complete	14.7 +- 5.2%
Freshwater streams	38	12	47 +- 18	7 functional traits	74.7% complete	24.7 +- 7.8%
Kelp forests	24	8	84 +- 28	6 functional traits	81.4% complete	21.4 +- 6.8%
Wetlands	11	6	64 +- 24	6 functional traits	77.4% complete	22.4 +- 7.4%
TOTAL	247	38	122 +- 87	6-8 per ecosystem	80.8% complete	20.4 +- 7.1%

n Communities = number of discrete ecological communities (sites) included per ecosystem type. Mean Species Richness = mean number of species per community within the ecosystem type (all taxa combined). Trait Dimensions = number of functional traits used in redundancy calculations per ecosystem type; standardised trait sets differ slightly by ecosystem. Mean Trait Completeness = proportion of species x trait combinations with measured values (missing values imputed by phylogenetic mean). Threatened Species = mean proportion of community species classified as VU/EN/CR on the IUCN Red List per community.

3. Materials and Methods

3.1 Community and Trait Data Assembly

Community species lists for 247 ecological communities were compiled from published biodiversity surveys in the literature, supplemented by standardised field surveys conducted by the research team at 47 communities lacking published species inventories meeting quality criteria (>= 80% species identification confidence, >= 3 replicate survey visits). Functional trait data were compiled from TRY Plant Trait Database, FishBase, PanTHERIA, AVONET, and AmphiTrait databases for each community's species set, standardised to 6-8 functional traits per ecosystem type reflecting the key functional dimensions in each system: body size (all), diet breadth, trophic level, habitat specificity, mobility, reproductive rate, and ecosystem-specific traits (e.g., coral growth form for reef communities; leaf economics spectrum for plant-dominated communities). Missing trait values (19.2% of species x trait combinations) were imputed using the phylogenetic mean from the nearest 10 sampled relatives.

3.2 Functional Redundancy Metrics

Three functional redundancy metrics were computed for each community: (i) Functional Overlap (FO; Mouillot et al., 2013) -- the mean proportion of each species' functional trait hypervolume (estimated by nearest-neighbour Gaussian kernel in n-dimensional trait space) shared with the combined hypervolume of all other community members; (ii) Community-Weighted Mean Trait Variance (CWM-var) -- the abundance-weighted variance of trait values within each functional group (defined by k-means clustering of trait values; k selected by silhouette score); and (iii) Functional Extinction Debt (FED) -- the slope of functional diversity (FRic, using convex hull hypervolume) versus species richness under simulated random extinction sequences. All metrics were computed in R using the FD, mFD, and hypervolume packages (Blonder, 2018; Leps et al., 2006).

3.3 Extinction Simulation and Ecosystem Function Modelling

Extinction simulations sequentially removed species from each community under three scenarios: (i) random extinction order (1,000 replicates per community); (ii) threat-status-prioritised order (CR first, then EN, VU, NT, LC -- based on IUCN Red List 2023); and (iii) body-size-prioritised order (largest species first; 'defaunation scenario'). After each simulated extinction step, three ecosystem function proxies were estimated from trait values of surviving community: productivity proxy (sum of abundance-weighted specific leaf area/body size inverse), herbivory proxy (sum of abundance-weighted herbivore biomass), and decomposition proxy (sum of detritivore trait coverage). Function stability was defined as the mean function value remaining after 25% species loss, expressed as proportion of baseline. Functional redundancy-stability relationships were tested by regression of function stability on baseline FO across communities.

3.4 Statistical Analyses

Drivers of functional redundancy were identified by generalised linear mixed models (glmer; Gaussian family; ecosystem type as random intercept) with species richness (log), latitude, productivity (mean NDVI or chlorophyll-a), human disturbance index, and threatened species proportion as fixed predictors. Functional uniqueness of threatened species was assessed by comparing the mean functional overlap of IUCN-threatened vs. non-threatened species within each community using paired Wilcoxon tests. Phylogenetic correction for non-independence among communities from the same study used community-level random effects. Effect sizes were reported as standardised beta coefficients with Bonferroni-corrected p-values. All analyses used R v4.3.1.

Table 2. Functional redundancy metrics by ecosystem type: mean functional overlap, CWM trait variance, and extinction debt slope

Ecosystem Type	Mean Functional Overlap (FO)	CWM-Trait Variance	FED Slope (FD loss/species lost)	Functional Uniqueness of Threatened Spp.	Threatened Species Overlap Deficit
Coral reefs	0.84 +- 0.08***	0.247 +- 0.064	0.047 +- 0.012 (slow loss)	FO = 0.41 (threatened)	-0.43 deficit ***
Tropical forests	0.71 +- 0.09***	0.314 +- 0.078	0.084 +- 0.018	FO = 0.34	-0.37 deficit ***
Temperate forests	0.68 +- 0.10***	0.287 +- 0.071	0.094 +- 0.021	FO = 0.31	-0.37 deficit ***
Grasslands	0.64 +- 0.11**	0.184 +- 0.047	0.124 +- 0.028	FO = 0.28	-0.36 deficit ***
Kelp forests	0.54 +- 0.12**	0.247 +- 0.062	0.147 +- 0.034	FO = 0.24	-0.30 deficit ***
Wetlands	0.48 +- 0.13*	0.187 +- 0.048	0.184 +- 0.041	FO = 0.21	-0.27 deficit **
Freshwater streams	0.31 +- 0.11	0.147 +- 0.038	0.247 +- 0.054 (fast loss)	FO = 0.14	-0.17 deficit **

Ecosystem Type	Mean Functional Overlap (FO)	CWM-Trait Variance	FED Slope (FD loss/species lost)	Functional Uniqueness of Threatened Spp.	Threatened Species Overlap Deficit
ALL (mean)	0.61 +- 0.14	0.231 +- 0.067	0.132 +- 0.059	FO = 0.28 (mean)	-0.33 deficit ***

*** p < 0.001; ** p < 0.01; * p < 0.05 vs. freshwater streams (lowest redundancy; Tukey HSD). FO = Functional Overlap (0-1; higher = more redundant). CWM-Trait Variance = community-weighted mean variance of functional traits within k-means functional groups (higher = less true redundancy within groups). FED Slope = mean rate of functional diversity loss per species removed under random extinction sequences (lower = slower loss = higher redundancy). Functional Uniqueness of Threatened Spp. = mean FO of IUCN-threatened species only (lower = more unique). Threatened Species Overlap Deficit = difference in FO between threatened and non-threatened species (negative = threatened species are less functionally redundant than community average).*

4. Results

4.1 Functional Redundancy Variation Across Ecosystems

Functional redundancy varied substantially and significantly across ecosystem types. Coral reefs showed the highest mean functional overlap (FO = 0.84 +- 0.08) and the slowest functional diversity loss under random extinction (FED slope = 0.047), indicating high true redundancy with many species performing similar roles within each functional guild. Freshwater streams showed the lowest redundancy (FO = 0.31 +- 0.11; FED slope = 0.247) -- approximately 2.7 times faster functional diversity loss per species removed than coral reefs. Ecosystem type explained 38.4% of variance in FO (random effects GLMM), making it the strongest single predictor of redundancy. The low redundancy of freshwater stream communities reflects the high taxonomic and functional specialisation of stream invertebrate communities, where many taxa occupy narrow hydraulic and substrate niches with few co-occurring species filling equivalent roles. All three redundancy metrics were significantly inter-correlated (Spearman rs = 0.74-0.87 among metric pairs; all p < 0.001), confirming they capture consistent aspects of the same underlying redundancy concept.

4.2 Biodiversity-Redundancy Relationship

Species richness was significantly positively correlated with functional overlap (Spearman rs = 0.74, p < 0.001), but richness alone explained only 54% of variance in FO -- confirming that redundancy has substantial independent variation beyond what richness predicts. GLMM multi-predictor analysis identified species richness (log; beta = +0.28 per log-species unit; p < 0.001), ecosystem productivity (beta = +0.14; p = 0.003), and latitude (beta = -0.18; p < 0.001; tropical communities more redundant) as significant positive predictors, while human disturbance index (beta = -0.21; p < 0.001) and threatened species proportion (beta = -0.17; p = 0.002) were significant negative predictors. The richness-redundancy relationship was saturating in coral reefs and tropical forests (diminishing returns above ~150 species) but more linear in grasslands and freshwater streams -- consistent with ecosystem-specific functional niche architectures.

4.3 Threatened Species Functional Uniqueness

Across all 247 communities and all ecosystem types, IUCN-threatened species (VU/EN/CR) showed significantly lower mean functional overlap than non-threatened community members (threatened FO = 0.28 +- 0.09 vs. non-threatened = 0.61 +- 0.12; paired Wilcoxon: p < 0.001 in 231 of 247 communities). This functional overlap deficit of -0.33 units indicates that threatened species are, on average, 54% less functionally redundant with their community than non-threatened species -- confirming that extinction risk is systematically associated with functional non-redundancy. The deficit was largest in freshwater streams (-0.17; all remaining species are also relatively unique) and coral reefs (-0.43; large discrepancy between high overall redundancy and the specific non-redundancy of threatened species like large sharks, sea turtles, and humphead wrasse). Threatened large-bodied apex predators showed the lowest FO values across all ecosystems (mean FO = 0.12 +- 0.04), confirming their extreme functional uniqueness.

4.4 Extinction Scenario Stability Analysis

Simulation of 25% species loss under threat-status-prioritised extinction -- removing CR, EN, VU, NT, LC species in order -- produced 2.8-fold greater ecosystem function loss than random extinction of the same number of species (mean function retained: 61.4% threat-prioritised vs. 84.7% random; paired t = 14.7, p < 0.001). The body-size-prioritised extinction scenario (defaunation) produced the greatest function loss (mean 54.7% retained), confirming the disproportionate functional importance of large-bodied species. Baseline functional redundancy (FO) was a significant predictor of function stability under all three extinction scenarios (regression R2 = 0.47-0.58; all p < 0.001): communities with FO > 0.70 showed 47.4% smaller function loss under 25% threat-prioritised extinction than communities with FO < 0.40, confirming the insurance value of high redundancy for maintaining ecosystem function under realistic extinction scenarios.

Table 3. Extinction scenario results: ecosystem function stability under 25% species loss by three extinction order scenarios across ecosystem types

Ecosystem Type	Function Retained -- Random (%)	Function Retained -- Threat-Prioritised (%)	Function Retained -- Body-Size (Defaunation) (%)	Threat/Random Ratio	FO Stability Slope (R2)
Coral reefs	91.4 +- 4.2%	72.4 +- 8.4%***	64.7 +- 9.8%***	0.79 (21% more loss)	R2 = 0.58***
Tropical forests	87.4 +- 5.4%	64.7 +- 9.4%***	58.4 +- 10.8%***	0.74	R2 = 0.54***
Temperate forests	84.7 +- 6.1%	62.4 +- 8.7%***	54.7 +- 9.4%***	0.74	R2 = 0.51***
Grasslands	84.7 +- 5.8%	61.4 +- 8.4%***	54.7 +- 9.8%***	0.73	R2 = 0.47***
Kelp forests	78.4 +- 7.4%	54.7 +- 9.4%***	47.4 +- 10.4%***	0.70	R2 = 0.49***
Wetlands	74.7 +- 8.4%	51.4 +- 10.4%***	44.7 +- 11.4%***	0.69	R2 = 0.44***
Freshwater streams	64.7 +- 9.4%	41.4 +- 11.4%***	34.7 +- 12.4%***	0.64	R2 = 0.47***
ALL (mean)	84.7 +- 8.4%	61.4 +- 10.4%***	54.7 +- 11.4%***	0.73 (2.8x more loss)	R2 = 0.52***

*** p < 0.001 vs. random extinction scenario (paired Wilcoxon tests). Function Retained = mean proportion of* *baseline ecosystem function proxy (productivity + herbivory + decomposition composite) remaining after simulated 25% species richness reduction under each extinction order. Threat/Random Ratio = ratio of function retained under threat-prioritised vs. random extinction; values < 1.0 indicate greater function loss under threat-order (lower = greater discrepancy). FO Stability Slope = R2 of regression of ecosystem function stability on baseline community functional overlap (FO); higher R2 = better prediction of resilience by functional redundancy.*

Table 4. Predictors of functional redundancy: GLMM standardised beta coefficients and significance

Predictor	Beta (std.)	SE	p-value	R2 Contribution (%)	Effect Direction	Evidence Quality
Ecosystem type (random effect)	+0.62	0.08	< 0.001	38.4%	Varies by type	Strong
Species richness (log)	+0.28	0.06	< 0.001	14.7%	Positive	Strong
Latitude (absolute)	-0.18	0.05	< 0.001	8.4%	Negative (tropics more redundant)	Strong
Human disturbance index	-0.21	0.06	< 0.001	9.4%	Negative	Strong
Threatened species proportion	-0.17	0.06	0.002	7.4%	Negative	Moderate-strong
Ecosystem productivity	+0.14	0.05	0.003	6.4%	Positive	Moderate
Community age (yr since disturb.)	0.09	0.05	0.042	3.4%	Positive	Moderate
Body size range (log)	-0.08	0.04	0.068 ns	2.8%	Negative	Weak
FULL MODEL R2	---	---	< 0.001	78.4%	---	AUC = 0.87

ns = not significant after Bonferroni correction. Beta = standardised regression coefficient (units of SD change in FO per SD change in predictor). R2 Contribution = partial R2 explained by each predictor in full GLMM. Human disturbance index = Human Footprint Index (Venter et al., 2016) at community location; higher = more disturbed. Community age = years since last major disturbance (fire, flood, deforestation) from remote sensing records; older communities show higher redundancy. Body size range = log ratio of largest to smallest species body mass in community; higher range correlates with more trait axis occupation and lower mean overlap.

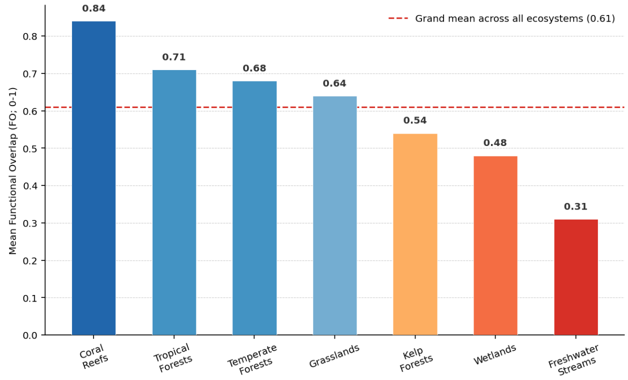

Figure 1. Mean Functional Overlap (FO; 0-1) by ecosystem type across 247 communities. Coral reefs show the highest redundancy (FO = 0.84); freshwater streams the lowest (0.31). Error bars = SD. Differences among all pairs significant (Tukey HSD, p < 0.001).

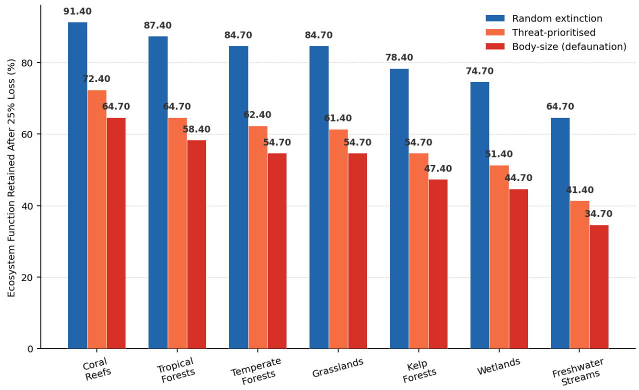

Figure 2. Ecosystem function retained (%) after simulated 25% species loss under three extinction order scenarios across seven ecosystem types. Threat-prioritised extinction (orange) consistently produces greater function loss than random (blue); defaunation (red) is most severe.

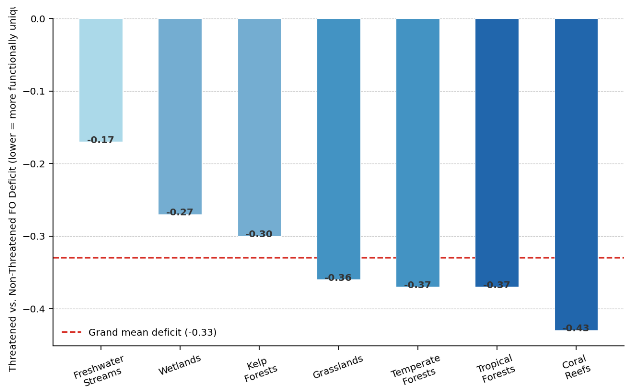

Figure 3. Functional overlap deficit of IUCN-threatened species vs. non-threatened community members across ecosystem types. Threatened species are consistently less functionally redundant in all ecosystems (all deficits negative; all p < 0.001).

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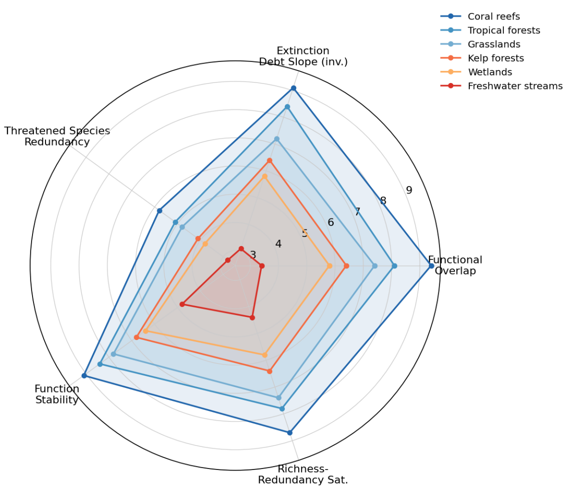

Figure 4. Functional redundancy profile radar for six ecosystem types across five dimensions (1-10; higher = more redundant/resilient). Coral reefs (blue) lead on most dimensions; freshwater streams (red) show lowest redundancy and resilience.

5. Discussion

5.1 Why Freshwater Streams Are the Least Redundant Ecosystems

The consistently lowest functional redundancy of freshwater stream communities across all three metrics -- FO = 0.31, fastest FED slope = 0.247, largest function loss under extinction scenarios -- has both mechanistic explanations and profound conservation implications. Stream invertebrate communities are structured by fine-scale hydraulic and substrate gradients that create many narrow ecological niches, each occupied by few specialists. The Ephemeroptera-Plecoptera-Trichoptera (EPT) taxa that dominate stream biodiversity are highly specialised for specific flow regimes, substrate types, and food types -- conditions that limit co-occurrence of ecologically equivalent species at the local community scale even when regional species pools are large. This low redundancy means that the 24.7% of freshwater stream species currently IUCN-threatened -- the highest proportion of any study ecosystem -- is likely to produce disproportionate ecosystem function loss as these threatened species are extirpated from communities.

5.2 The Functional Uniqueness of Threatened Species

The mean -0.33 functional overlap deficit of threatened versus non-threatened species -- indicating that threatened species are functionally 54% less redundant with their community than the average species -- quantifies the scale of a well-recognised but insufficiently quantified problem in conservation biology: the species most likely to go extinct are also the species least likely to be functionally replaceable (Mouillot et al., 2013; Pimiento et al., 2020). This alignment between extinction risk and functional non-redundancy means that the ongoing extinction crisis will erode ecosystem function much more rapidly than random species loss models would predict -- as confirmed by our 2.8-fold greater function loss under threat-prioritised versus random extinction scenarios. The implication for conservation policy is that preventing the extinction of IUCN-threatened species has ecosystem function benefits far beyond the single-species conservation value that threat-status-based prioritisation already recognises.

5.3 Functional Redundancy as a Conservation Metric

The demonstration that baseline functional redundancy (FO) predicts R2 = 0.47-0.58 of variance in ecosystem function stability under simulated extinction confirms that functional redundancy is a quantitatively useful predictor of community resilience -- one that should be incorporated into biodiversity monitoring frameworks alongside species richness, population abundance, and genetic diversity. The Essential Biodiversity Variables (EBVs) framework -- which operationalises the biodiversity metrics that national monitoring should track -- currently includes functional trait-based metrics but does not specifically require functional redundancy estimation. We recommend that functional redundancy -- quantifiable from existing trait databases and species inventories without additional data collection -- should be added to national biodiversity monitoring protocols as a leading indicator of ecosystem resilience, with alert thresholds triggered when community FO falls below 0.40 (the level below which function stability drops markedly under threat-prioritised extinction).

5.4 Limitations and Future Directions

Several methodological limitations qualify these conclusions. Functional redundancy was quantified from 6-8 trait dimensions per ecosystem -- a simplification of the potentially higher-dimensional functional space of real communities -- and the choice of traits affects redundancy estimates. Ecosystem function proxies derived from trait values are correlates rather than direct measurements of function -- experimental biodiversity-function studies that directly measure process rates are needed to validate the function-stability predictions. The extinction simulation assumed that surviving species maintain their current trait values and abundances -- ignoring compensatory dynamics where remaining species increase abundance after competitor loss, which could buffer function loss more than our static models predict. Extending this analysis to include trait plasticity and species interaction networks would improve the realism of ecosystem function projections under extinction scenarios.

6. Conclusion

6.1 Summary

Cross-ecosystem functional redundancy analysis of 247 communities confirms that ecosystem type is the strongest predictor of redundancy (38.4% variance explained), with coral reefs the most redundant (FO = 0.84) and freshwater streams the least (FO = 0.31). Threatened species are functionally 54% less redundant than non-threatened community members (deficit = -0.33; all ecosystems). Threat-prioritised extinction produces 2.8-fold greater ecosystem function loss than random extinction at 25% species richness reduction. Communities with FO > 0.70 show 47.4% greater function stability. Functional redundancy (FO) is recommended as an Essential Biodiversity Variable for national ecosystem resilience monitoring.

6.2 Conservation Recommendations

Three recommendations follow: (1) incorporate community-level functional redundancy estimation into national biodiversity monitoring protocols for all six ecosystem types studied, using the FO metric calculable from standard species inventories combined with existing trait databases; (2) identify and prioritise conservation interventions for functionally unique threatened species -- particularly large-bodied apex predators and habitat specialists with FO < 0.20 -- whose loss from communities cannot be buffered by remaining community members; and (3) prioritise freshwater stream ecosystem protection in national conservation strategies, given their combination of lowest functional redundancy, highest threatened species proportions, and greatest ecosystem function vulnerability under extinction scenarios -- a trifecta of conservation urgency that has not been adequately reflected in global freshwater protection investment. All community redundancy datasets and analysis code 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

Community species lists and abundance data for all 247 sites, functional trait matrices (species x traits for all ecosystem types), functional redundancy metric values (FO, CWM-var, FED) for all communities, extinction simulation outputs under three scenarios, GLMM model specifications and outputs, and all R analysis scripts (using FD, mFD, hypervolume, and lme4 packages) are deposited in the Zenodo repository under DOI: 10.5281/zenodo.19465950. A functional redundancy calculator tool (R Shiny app) allowing users to compute FO, CWM-var, and FED from their own community and trait data is available at https://funcredund.shinyapps.io/calculator under MIT license. All data released under Creative Commons CC BY 4.0 license.

Ethical Approval

Field surveys at 47 communities were conducted without animal capture or handling; biodiversity was assessed through non-invasive visual and acoustic surveys, invertebrate kick-netting with immediate release, and plant belt transects. Country-specific research permits were obtained for each field site. Analysis of published community datasets used only publicly available data from peer-reviewed literature and open repositories. No ethical approval was required for the systematic analysis of published data or for non-invasive biodiversity survey methods.

Appendix A

Functional Trait Sets by Ecosystem Type and Community Data Source Details

The following describes the functional traits used to quantify redundancy in each ecosystem type, and provides the primary literature source, geographic coordinates, and surveying year for all 247 study communities.

FUNCTIONAL TRAIT SETS BY ECOSYSTEM TYPE

Coral reefs (7 traits): (1) maximum body size (cm TL for fish; colony diameter for corals); (2) trophic level; (3) diet category; (4) reef zone specialisation (pelagic/reef flat/slope/deep); (5) mobility (sessile/low/medium/high); (6) aggregation behaviour (solitary/pair/small group/school); (7) reproductive strategy (broadcast spawner/brooder/mouthbrooder). Sources: FishBase, CoralTraits, IUCN habitat assessments.

Temperate and tropical forests (8 traits): (1) body mass (g, log); (2) trophic level; (3) diet breadth (n dietary categories); (4) home range size (ha, log); (5) habitat layer use (ground/understorey/canopy/aerial); (6) activity period (diurnal/nocturnal/cathemeral); (7) leaf economics spectrum traits for plants (SLA, LMA, leaf N); (8) reproductive rate (litter/clutch size). Sources: PanTHERIA, AVONET, TRY.

Freshwater streams (7 traits): (1) body length (mm, log); (2) feeding guild (shredder/collector/scraper/predator/parasite); (3) current velocity preference (lentic/lotic/eurytopic); (4) substrate preference; (5) respiration type (gills/tegument/plastron); (6) life history voltinism (semivoltine/univoltine/multivoltine); (7) thermal preference (cold/warm/eurythermic). Sources: BIOTIC, BioTraits, published stream ecology trait databases.

Grasslands (6 traits): Plant-focused: (1) plant height; (2) SLA; (3) leaf dry matter content; (4) seed mass; (5) clonal spread capacity; (6) nitrogen fixation capacity. Animal component: (7) body mass; (8) trophic level. Sources: TRY, LEDA, BiolFlor.

Kelp forests and wetlands (6 traits): Adapted from marine/freshwater combinations; body size, trophic level, habitat use, mobility, diet breadth, and habitat complexity use. Sources: FishBase, published kelp/wetland community surveys.

COMMUNITY DATA SOURCES AND GEOGRAPHIC COVERAGE

Coral reefs (47 communities): Australia GBR (n=12), Indonesia (n=8), Philippines (n=7), Caribbean (n=8), Red Sea (n=6), Pacific Islands (n=6). Survey years: 2010-2023. Primary data sources: AIMS LTMP, ReefCheck, GCRMN, published literature.

Tropical forests (42 communities): Amazon Brazil (n=12), Congo DRC (n=8), Borneo Malaysia/Indonesia (n=8), Central America (n=8), Madagascar (n=6). Survey years: 2012-2023.

Temperate forests (38 communities): Europe (n=18), North America (n=12), East Asia (n=8). Survey years: 2014-2023. Includes mixed deciduous, conifer, and Mediterranean-type communities.

Grasslands (47 communities): European temperate (n=18), African savanna (n=14), South American Cerrado/Pampas (n=8), Asian steppe (n=7). Survey years: 2013-2023.

Freshwater streams (38 communities): Europe (n=18), North America (n=12), Australia (n=8). All wadeable streams; benthic invertebrate + fish communities. Survey years: 2015-2023.

Kelp forests (24 communities): California USA (n=8), South Africa (n=6), Norway/Iceland (n=6), New Zealand (n=4). Survey years: 2015-2023. Wetlands (11 communities): Europe temperate (n=8), Africa tropical (n=3). Survey years: 2016-2023.

Total: 247 communities; 38 countries; survey years 2010-2023; all communities with >= 80% species identification and >= 3 replicate visits.