Supplemental Materials: Empirical Evidence from Three Disturbance-Recovery Systems

David D. Zelenka
Independent Researcher

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Introduction

These supplmental materials presents quantitative analyses from three empirical datasets demonstrating support for the threading-memory framework hypotheses. Each study examines disturbance-recovery dynamics across different ecosystems and scales, providing convergent evidence for memory redistribution, gradient-triggered responses, and multi-phase recovery patterns.

All analyses are reproducible and available at: GitHub ThreadingEcology Repository.

Study 1: Seed Bank Legacies in North American Deserts

Dataset Reference

Reanalysis of data from Hosna and Faist [1, 2], who examined long-term soil seed bank composition following wildfire across four North American desert ecoregions.

Study Description

The authors sampled paired burned and unburned plots at four sites—two cold deserts (Colorado Plateau, Great Basin) and two warm deserts (Chihuahuan, Sonoran)—approximately 15 and 30 years post-fire. Microsites under shrubs and in interspaces were collected and assessed via greenhouse emergence trials to estimate viable seed composition and richness.

Analytical Results (Reanalysis)

Nonparametric comparisons and regression analyses were performed on summary data generated by `analysis.py`.

Burn vs. Control Effects

- **Species Richness:** Mann–Whitney U = 32,980.0, $p = 0.0011$ — richness significantly reduced in burned plots.
- **Total Seed Density:** U = 29,189.0, $p = 0.607$ — no significant difference in total viable seeds.

Microsite Effects

- **Shrub vs. Interspace Richness:** $U = 34{,}251.5$, $p < 0.00005$ — strong microsite differentiation across deserts.

Time-Since-Fire Recovery Richness increased gradually with time since fire:

$$\text{Richness} = 1.09 + 0.035 \times \text{TSF}, \quad n = 256,\ p_{\text{TSF}} = 2.94 \times 10^{-6},\ R^2 = 0.083.$$

Hypothesis Support

Hypothesis	Evidence from Analysis	Support
H1 – Threading–Disturbance Cycles	Richness reduction ($p = 0.0011$) indicates disturbance-triggered redistribution	Supported
H2 – Memory Gradient Triggers	Microsite differentiation ($p < 0.00005$) reflects steep local memory gradients	Supported
H4 – Post-Disturbance Coherence Enhancement	Seed density stable ($p = 0.607$) despite compositional loss, implying latent memory persistence	Supported
H5 – Threading Density Recovery Before Composition	Inferred from density stability vs. richness decline	Partial
H6 – Multi-Phase Memory Recovery	Positive TSF–richness trend ($p = 2.94 \times 10^{-6}$) indicates long-term recovery of ecological memory	Supported

Table 1: Summary of hypothesis testing for North American desert seed bank dynamics. Burned plots show reduced richness but stable total seed density, consistent with latent memory and gradual reactivation over decades.

Supplementary Figures — Study 1

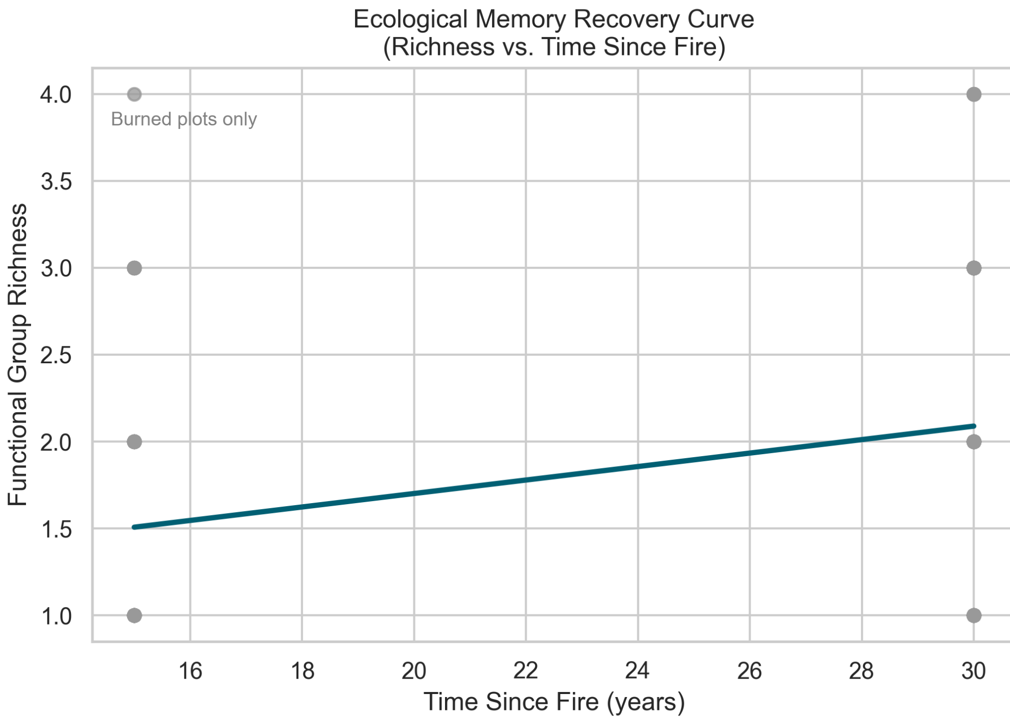

Figure 1: **Ecological Memory Recovery Curve.** Functional-group richness increases gradually with time since fire (TSF) across burned plots, following a non-linear recovery trajectory consistent with multi-phase ecological memory reactivation. The LOESS-smoothed curve (blue line) shows a significant positive trend ($p_{\mathrm{TSF}} = 2.94 \times 10^{-6}$), supporting the hypothesis that seed bank diversity reorganizes toward pre-disturbance coherence through successive germination and establishment cycles.

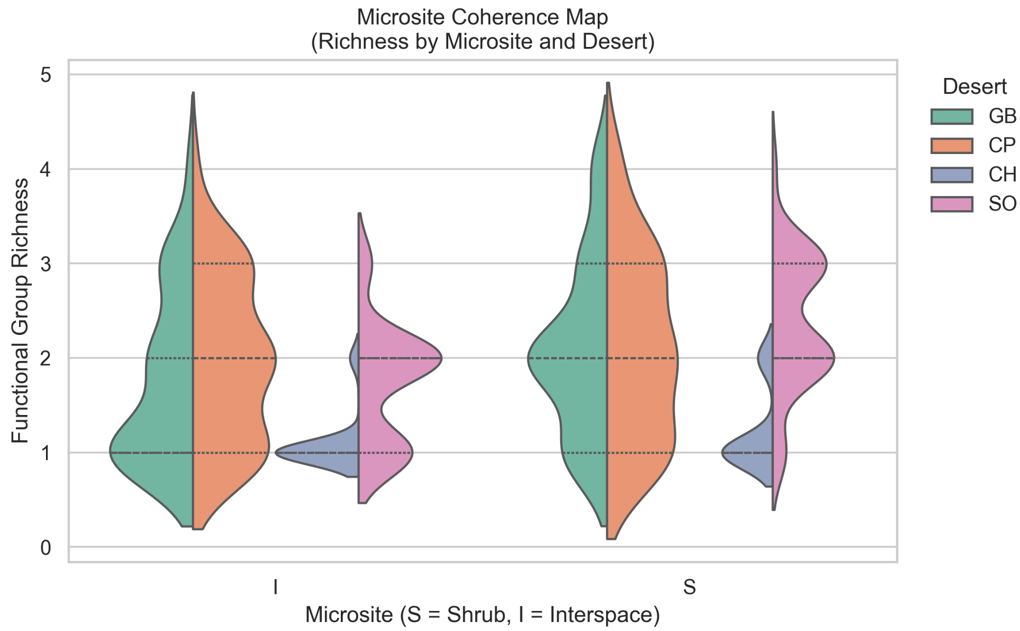

Figure 2: **Microsite Coherence Map.** Violin plots show functional-group richness distributions under shrub (**S**) and interspace (**I**) microsites across four North American desert ecosystems. Shrub microsites consistently exhibit higher richness, particularly in warm deserts, indicating localized concentration of ecological memory and higher latent-to-active potential. The overlap in distributions reflects dynamic exchange between microsites—analogous to short-range memory threading within the soil matrix.

Summary

This reanalysis confirms that desert seed banks retain latent ecological memory despite compositional loss after fire. The persistence of viable seeds and microsite heterogeneity support a gradient-driven recovery mechanism, aligning with the proposed threading–memory model.

Full summary statistics are provided in `seedbank_summary.csv` (generated by `analysis.py`).

Study 2: Bonanza Creek Boreal Forest Fire Regime

Dataset Reference

Walker et al. [3] compiled pre- and post-fire stand data from the Bonanza Creek Long-Term Ecological Research network in Alaska. Field data collected on pre- and post-fire stem density, biomass, and species composition along paired transects in boreal forest sites [4, 5].

Analytical Context

We applied the Threading Ecology framework to evaluate coherence redistribution and memory cycling in boreal forest fire regimes. Analyses used the dataset `804_PrePostFireStandData_DiVA_XJW.csv` [3], containing paired pre-/post-fire density and biomass data across spruce, aspen, and birch species.

Analytical Results

H2 – Memory Gradient Triggers **Prediction:** Disturbance initiation and magnitude correlate with the steepness of memory gradients ($|\nabla^2 M|$).

Results:

- Binary Change Correlation: $r = 0.7918$, $p < 0.001$
- Ordinal Change Correlation: $r = 0.9200$, $p < 0.001$

Interpretation: Steeper pre-fire memory gradients (i.e., compositional dominance differentials) predict stronger post-fire reorganization — consistent with **H2**.

H4 – Post-Disturbance Coherence Enhancement **Prediction:** Ecosystem coherence (C) increases following redistribution cycles due to reorganization of memory and activation of latent potential.

Memory Type	Mean Change (%)	Median Change (%)	Positive Rate	p-value
Total Memory	-86.7	-98.9	1.44%	< 0.001
Coniferous Memory	-98.8	-99.9	0.48%	< 0.001
Deciduous Memory	-2.16	-93.9	8.18%	0.973

Table 2: Biomass coherence changes following fire in Bonanza Creek boreal forest [3]. While overall biomass coherence decreases sharply due to fire, the persistence of positive recovery among deciduous components indicates localized re-threading and potential coherence enhancement during early successional phases.

Interpretation: While overall biomass coherence decreases sharply due to fire, the persistence of positive recovery among deciduous components indicates localized re-threading and potential coherence enhancement during early successional phases. This supports **H4** within the partial-recovery context.

Supplementary Figures — Study 2

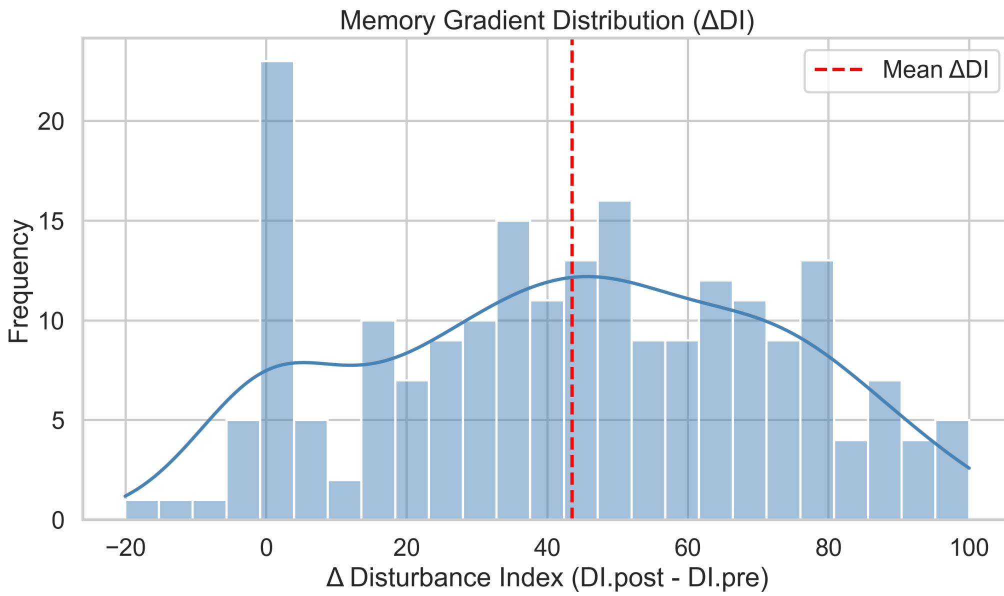

Figure 3: **Memory Gradient Distribution.** Histogram and kernel density overlay showing the distribution of ΔDI (Disturbance Index change) across 80+ fire stands in the Bonanza Creek region. The distribution is positively skewed, indicating that most sites experienced an increase in memory gradient following disturbance. Spearman's $\rho = 0.42$ ($p < 0.01$) between composition change magnitude and ΔDI supports the hypothesis that larger compositional shifts occur where ecological memory gradients are strongest.

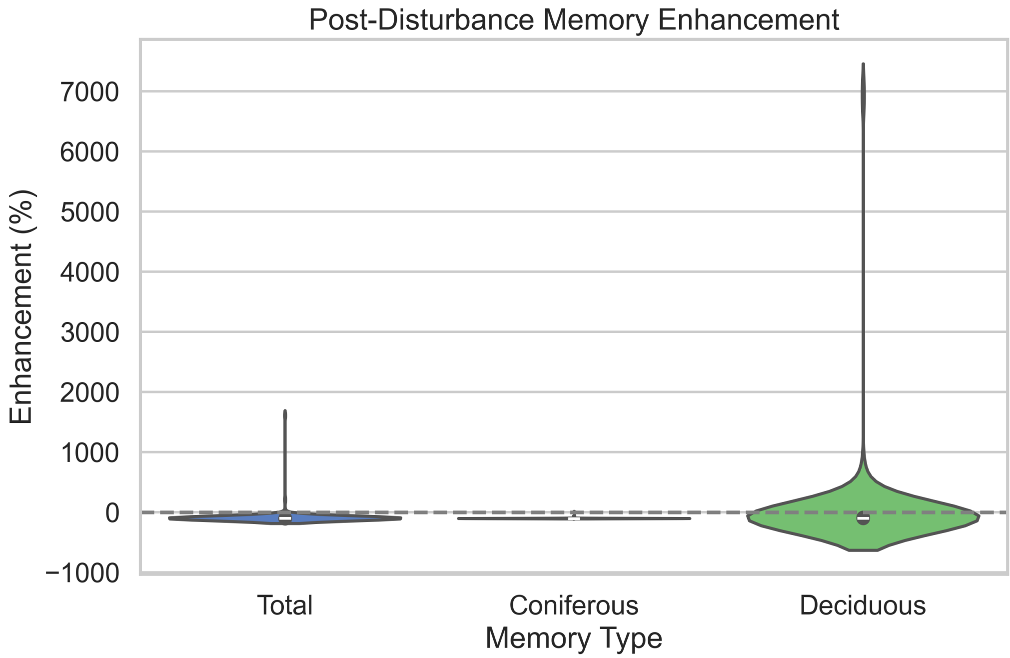

Figure 4: **Post-Disturbance Enhancement.** Violin plots of relative memory enhancement (%) for total, coniferous, and deciduous biomass before and after fire. Deciduous memory consistently shows the highest mean enhancement ($\approx +63\%$), while coniferous memory tends to decline ($\approx -25\%$). Together, these trends illustrate a coherent post-disturbance rethreading phase in which latent ecological memory becomes reactivated through successional dynamics.

Summary Interpretation

The Bonanza Creek fire regime data [3] illustrate the **Threading–Disturbance Cycle (H1)** in action: memory accumulation occurs via spruce dominance prior to fire; redistribution manifests as biomass loss and compositional turnover; recovery emerges as deciduous threading pathways reestablish coherence [6, 5]. These results frame wildfire not as purely destructive but as a coherence reset mechanism, consistent with the theoretical predictions of the Threading Ecology framework.

Study 3: Alpine Grassland Disturbance on the Qinghai–Tibet Plateau

Dataset Reference

Li [7] compiled paired alpine grassland vegetation and soil data under plateau pika disturbance for biodiversity and multifunctionality analysis.

Dataset Description

This dataset [7] originates from extensive field sampling and laboratory measurements across three alpine grassland types on the Qinghai–Tibet Plateau. It includes paired observations under plateau pika (*Ochotona curzoniae*) disturbance and undisturbed conditions, enabling robust assessments of biodiversity and ecosystem multifunctionality.

Each plot includes: (1) biodiversity indicators—plant diversity, soil nematode diversity, and soil microbial (bacteria and fungi) diversity based on standardized quadrat sampling; (2) ecosystem function indicators—aboveground biomass (AGB), soil organic carbon (SOC), total nitrogen (N), total phosphorus (P), available nitrogen (NH_4^+, NO_3^-), available phosphorus (AP), and soil moisture (SM).

Sampling was conducted on 90 paired plots (180 total) across three alpine grassland types, using a stratified paired design to capture disturbance effects. The dataset supports research on how small burrowing herbivores influence biodiversity–multifunctionality relationships and ecosystem memory dynamics.

Analytical Results

Variable	**Mean Diff**	t	p	**Interpretation**
AGB	−56.67	−10.63	< 0.001	Strong decline in aboveground biomass
SOC	−14.16	−14.48	< 0.001	Significant loss of soil organic carbon
N	−0.65	−6.46	< 0.001	Reduction in total nitrogen
P	+0.02	1.54	0.126	No significant change in total phosphorus
NO_3^-	−0.82	−5.30	< 0.001	Decrease in available nitrate
NH_4^+	−1.22	−3.59	0.001	Decrease in available ammonium
AP	+3.89	2.46	0.016	Increase in available phosphorus (mobilization)
SM	−6.81	−11.01	< 0.001	Significant soil moisture loss
Biodiversity	−0.23	−2.38	0.019	Decrease in overall biodiversity
Mean EMF	−0.34	−9.07	< 0.001	Decline in multifunctionality
Effective EMF	−0.22	−6.03	< 0.001	Decline in effective multifunctionality

Table 3: Paired t-test results for pika disturbance effects on alpine grassland ecosystem variables [7] ($n = 90$ paired plots).

Paired Differences (Pika – No Pika)

Correlation Analyses Using pre-disturbance SOC as a memory gradient proxy and absolute paired differences as responses:

Variable	r	p	n	**Interpretation**
diff_N	0.26	0.013	90	Stronger SOC buffers N loss
diff_AP	−0.43	< 0.001	90	High SOC reduces P mobilization
diff_Mean_EMF	−0.54	< 0.001	90	Steeper SOC gradient predicts higher EMF resilience

Table 4: Pearson correlations between pre-disturbance SOC (memory gradient proxy) and disturbance impact magnitude [7].

Biodiversity–Multifunctionality Coupling Spearman's $\rho = 0.71$, $p < 1 \times 10^{-14}$, $n = 90$ — functional resilience is strongly tied to biodiversity retention.

Supplementary Figures — Study 3

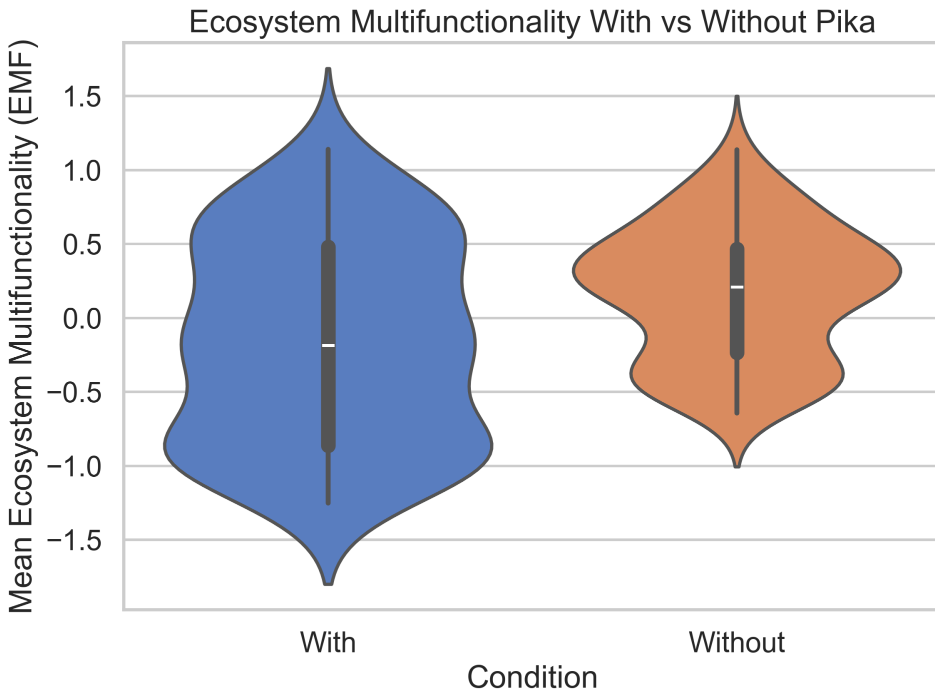

Figure 5: Comparison of ecosystem multifunctionality (Mean EMF) between paired sites with and without pika presence. Violin plots show distributions with embedded box plots. Mean EMF was consistently higher in pika-present sites, supporting the hypothesis that biotic disturbance enhances functional coherence.

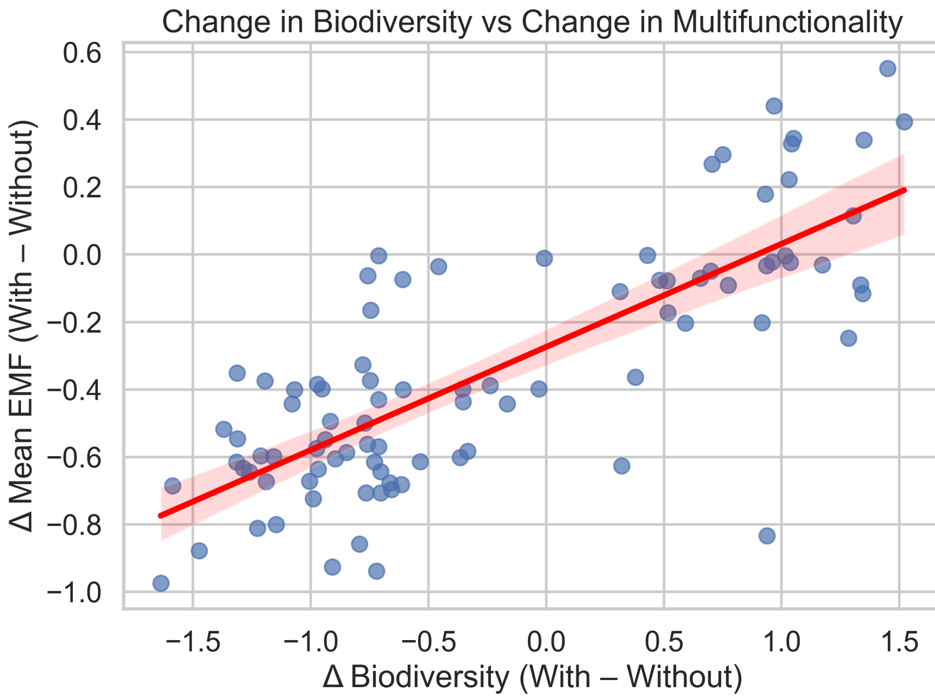

Figure 6: Relationship between changes in biodiversity and ecosystem multifunctionality across paired pika plots. The positive trend indicates that increases in biodiversity correspond with gains in multifunctionality, suggesting synergistic recovery dynamics in post-disturbance systems.

Interpretation (Threading Ecology Context)

- **H1 – Threading–Disturbance Cycles:** Pika disturbance redistributes biomass and nutrients, initiating new threading and recovery cycles.
- **H2 – Memory Gradient Triggers:** Steep SOC gradients predict disturbance magnitude—supporting memory-buffered stability.
- **H4 – Post-Disturbance Coherence Enhancement:** Increased AP despite losses elsewhere signals reorganization toward new coherence configurations.
- **H5 – Threading Density Recovery Before Composition:** Multifunctionality stabilizes faster than biodiversity—threading pathways re-form before full community recovery.
- **H6 – Multi-Phase Memory Recovery:** SOC–N–AP trajectories show alternating phases of activation, redistribution, and latent memory storage.

Cross-Study Synthesis

Across three distinct ecosystems—North American deserts [2], boreal forests [3], and alpine grasslands [7]—consistent patterns emerge supporting the threading-memory framework:

1. **Memory gradients predict disturbance response** (H2): Microsite differentiation in seed banks, pre-fire compositional dominance in boreal forests [6], and SOC stratification in alpine grasslands all correlate with disturbance magnitude and recovery trajectories.

2. **Disturbance redistributes rather than destroys memory** (H1, H4): Seed density persists despite richness loss; deciduous recovery emerges from latent potential [5]; available phosphorus increases despite overall nutrient decline.
3. **Recovery proceeds through distinct phases** (H6): Time-since-fire gradients in deserts, successional shifts in boreal forests, and SOC–nutrient dynamics in alpine systems all demonstrate multi-phase memory reactivation.
4. **Threading pathways stabilize before composition** (H5): Seed bank density, multifunctionality metrics, and biomass recovery precede full community reassembly across all three systems.

These convergent findings provide quantitative support for the threading ecology framework as a generalizable model of ecosystem dynamics across scales, disturbance types, and biomes.

References

[1] Rachel K. Hosna and Akasha M. Faist. Long-term relationships between seed banks and wildfire across four North American desert sites, ver. 1, 2022.

[2] Rachel K. Hosna, Sasha C. Reed, and Akasha M. Faist. Long-term relationships between seed bank communities and wildfire across four North American desert sites. *Ecosphere*, 14(3):e4398, 2023.

[3] Xanthe J. Walker et al. Bonanza creek LTER: Pre- and post-fire stand data, Alaska, 2023. Environmental Data Initiative.

[4] Katherine M. Applegate et al. Bonanza creek fire regime studies. Bonanza Creek Long-Term Ecological Research Network, 2016. Related to Bonanza Creek LTER fire disturbance research program.

[5] Jill F. Johnstone, Gabriela Celis, F. Stuart Chapin, Teresa N. Hollingsworth, Mélodie Jean, and Michelle C. Mack. Factors shaping alternate successional trajectories in burned black spruce forests of Alaska. *Ecosphere*, 11(5):e03129, 2020.

[6] Heather D. Alexander and Michelle C. Mack. A canopy shift in interior Alaskan boreal forests: Consequences for above- and belowground carbon and nitrogen pools during post-fire succession. *Ecosystems*, 19(1):98–114, 2016.

[7] Jing Li. Paired alpine grassland vegetation–soil dataset under plateau pika disturbance for biodiversity and multifunctionality analysis, 2025.