Supplementary Information

Title: Biodiversity buffers forest ecosystems from compound climate extremes

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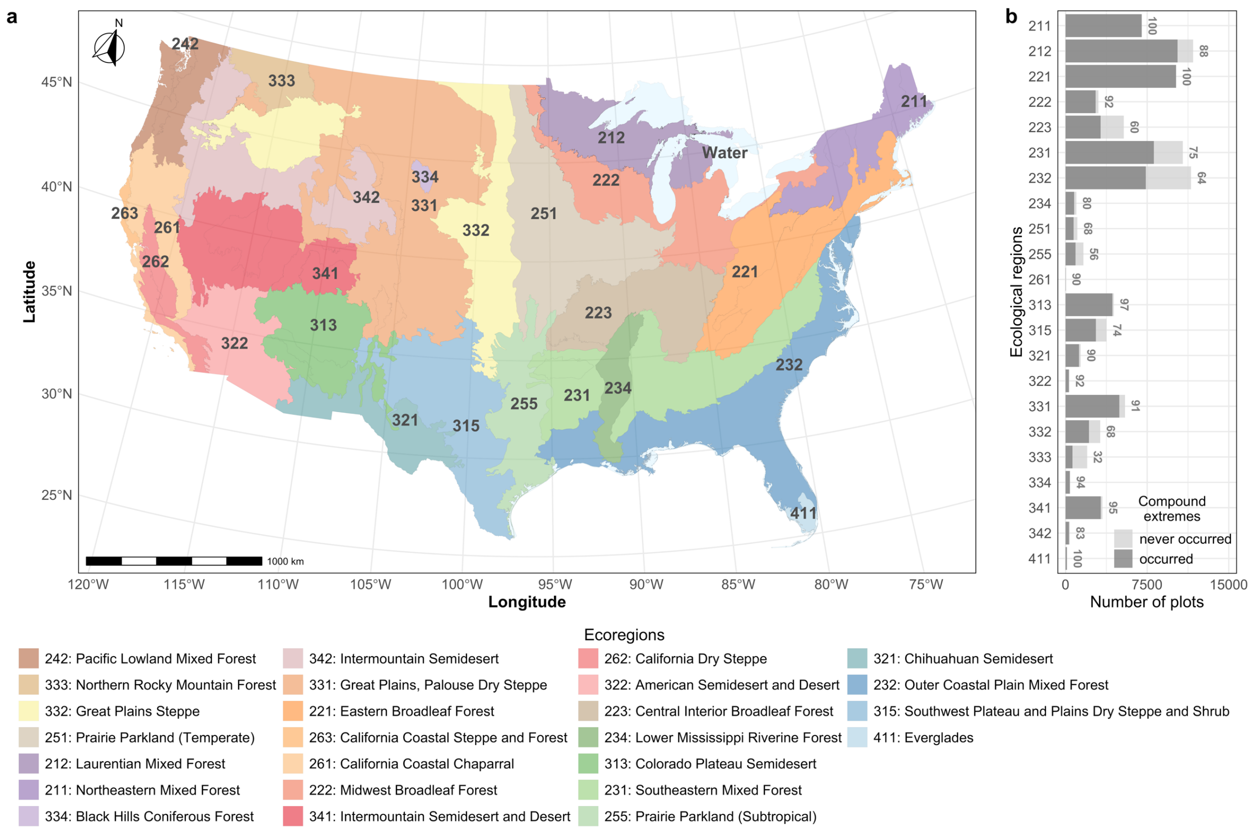
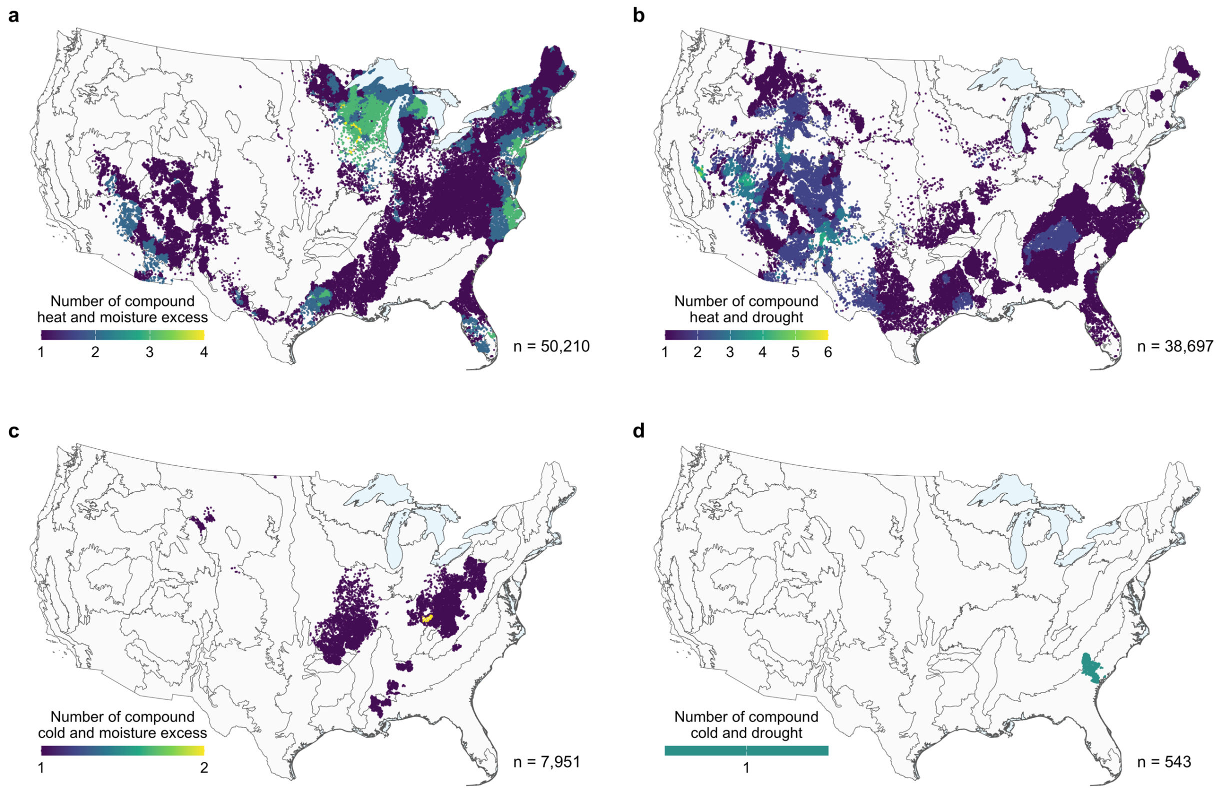
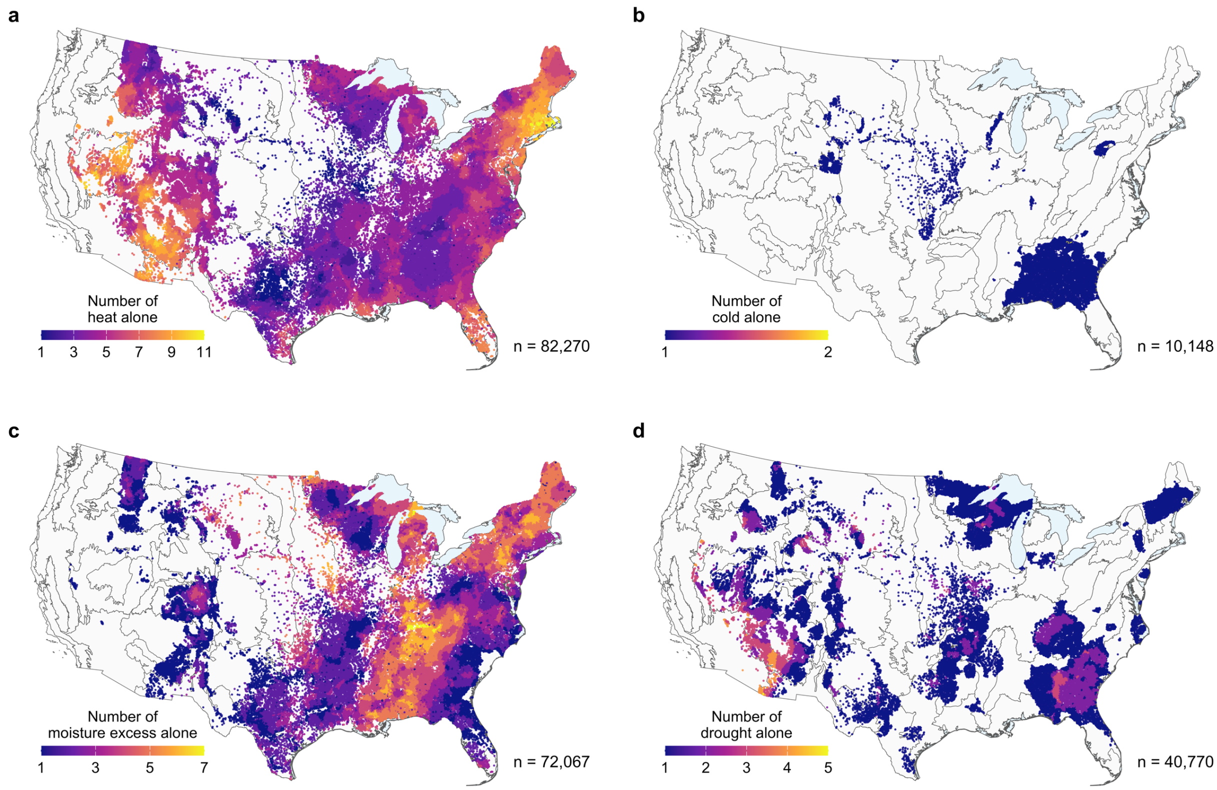


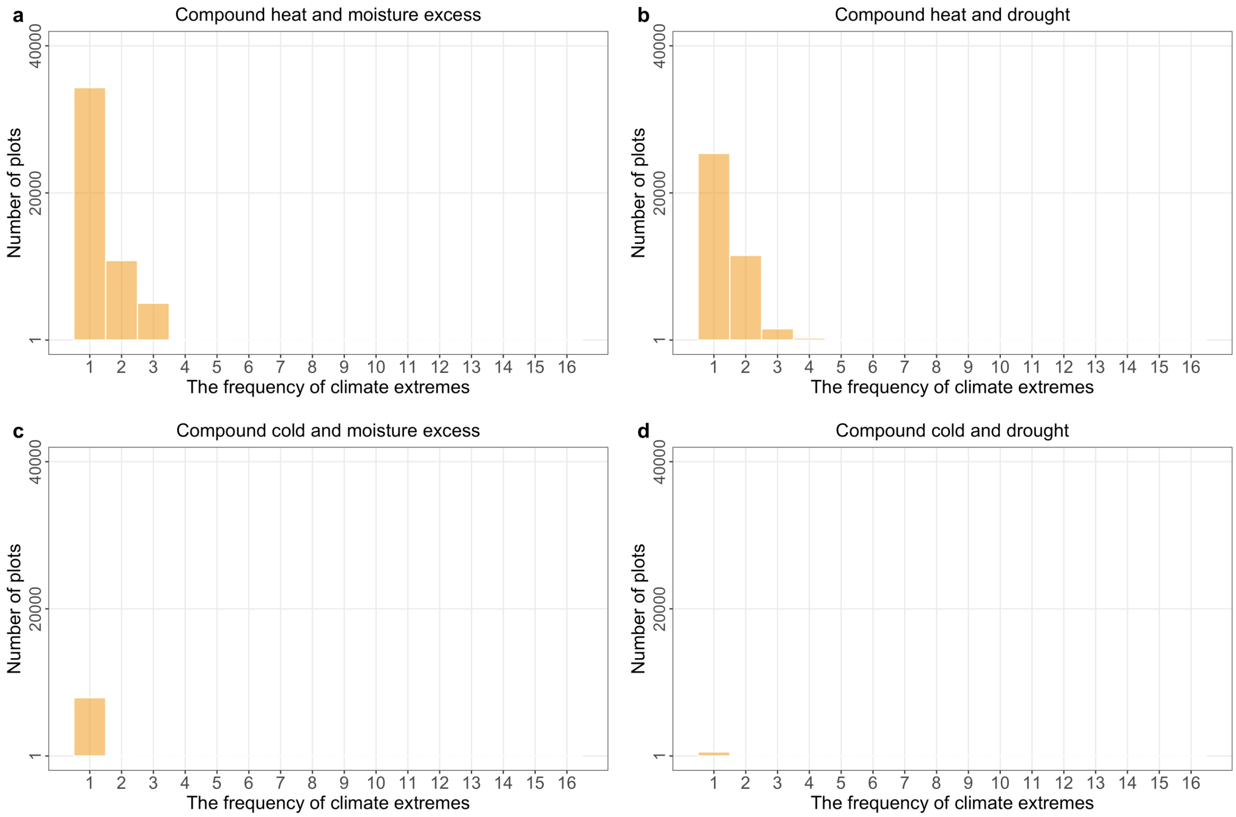
Supplementary Figure 1. Ecoregions of the selected forest plots. (a) Distribution of the ecoregions to which all selected plots belong, according to Cleland et al. (2007). Colours denote individual ecoregions, as listed in the key. (b) Number of forest plots within each ecoregion and the occurrence or non-occurrence of compound extremes in the plots during the study period. Dark grey bars indicate plots in which compound extremes occurred, whereas light grey bars indicate plots in which compound extremes did not occur. Dark grey numbers (%) indicate the percentage of the total number of plots within each ecoregion that experienced compound extremes. Base map from United States Forest Service Ecological Subregions of the U.S.A, USDA - Forest Service ECOMAP Team. ref. 1 published under CC BY 3.0: https://creativecommons.org/licenses/by/3.0/.



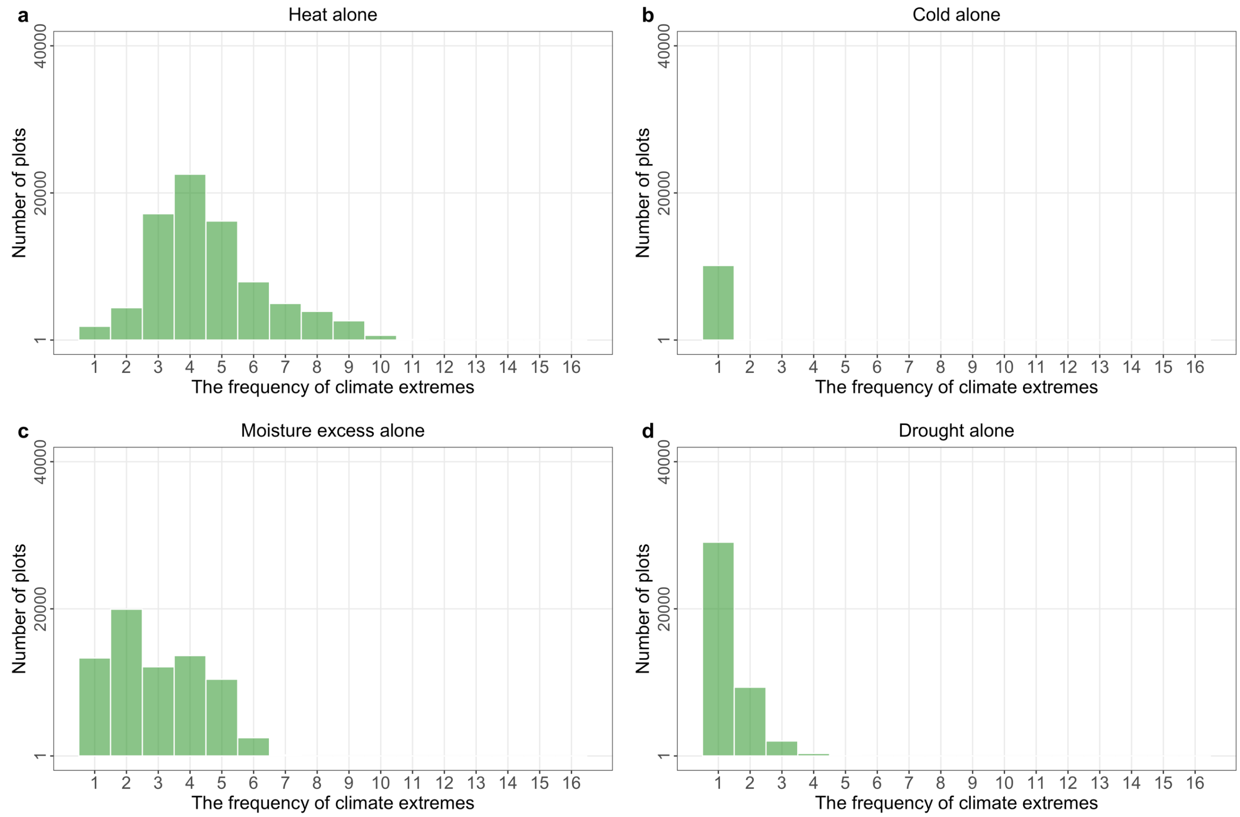
Supplementary Figure 2. The extent and frequency of each type of compound heat and moisture extremes. (a) Compound heat and moisture excess; (b) Compound heat and drought; (c) Compound cold and moisture excess; (d) Compound cold and drought. The occurrence of compound heat and moisture extremes in the plots during the study period (2001-2020). For each compound extreme type, the colour scale indicates the number of occurrences recorded at each plot during the study period (2001–2020). The value of n in each panel denotes the number of plots that experienced the corresponding type of compound extreme among all study plots and thus represents its spatial extent of occurrence. Base map from United States Forest Service Ecological Subregions of the U.S.A, USDA - Forest Service ECOMAP Team. ref. 1 published under CC BY 3.0: https://creativecommons.org/licenses/by/3.0/.



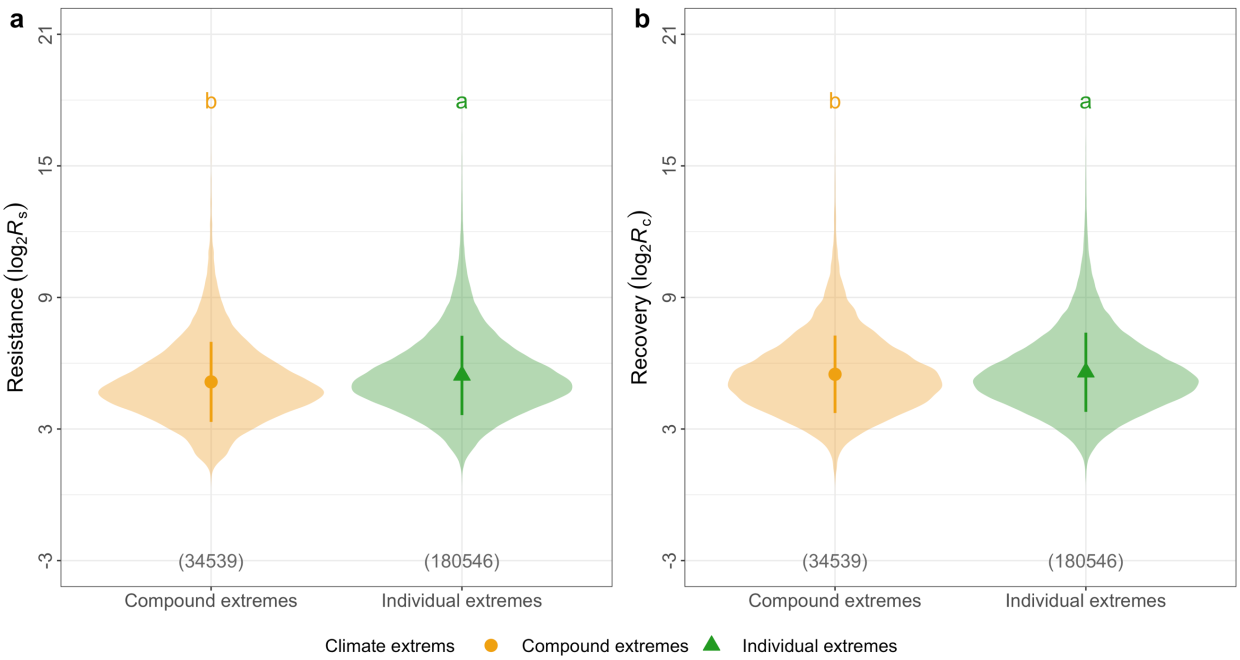
Supplementary Figure 3. The extent and frequency of each type of individual extreme. (a) Heat alone; (b) Cold alone; (c) Moisture excess alone; (d) Drought alone. For each individual ext reme type, the colour scale indicates the number of occurrences recorded at each plot during the study period (2001–2020). The value of n in each panel denotes the number of plots that experie nced the corresponding type of individual extreme among all study plots and thus represents its s patial extent of occurrence. Base map from United States Forest Service Ecological Subregions o f the U.S.A, USDA - Forest Service ECOMAP Team. ref. 1 published under CC BY 3.0: https:// creativecommons.org/licenses/by/3.0/.



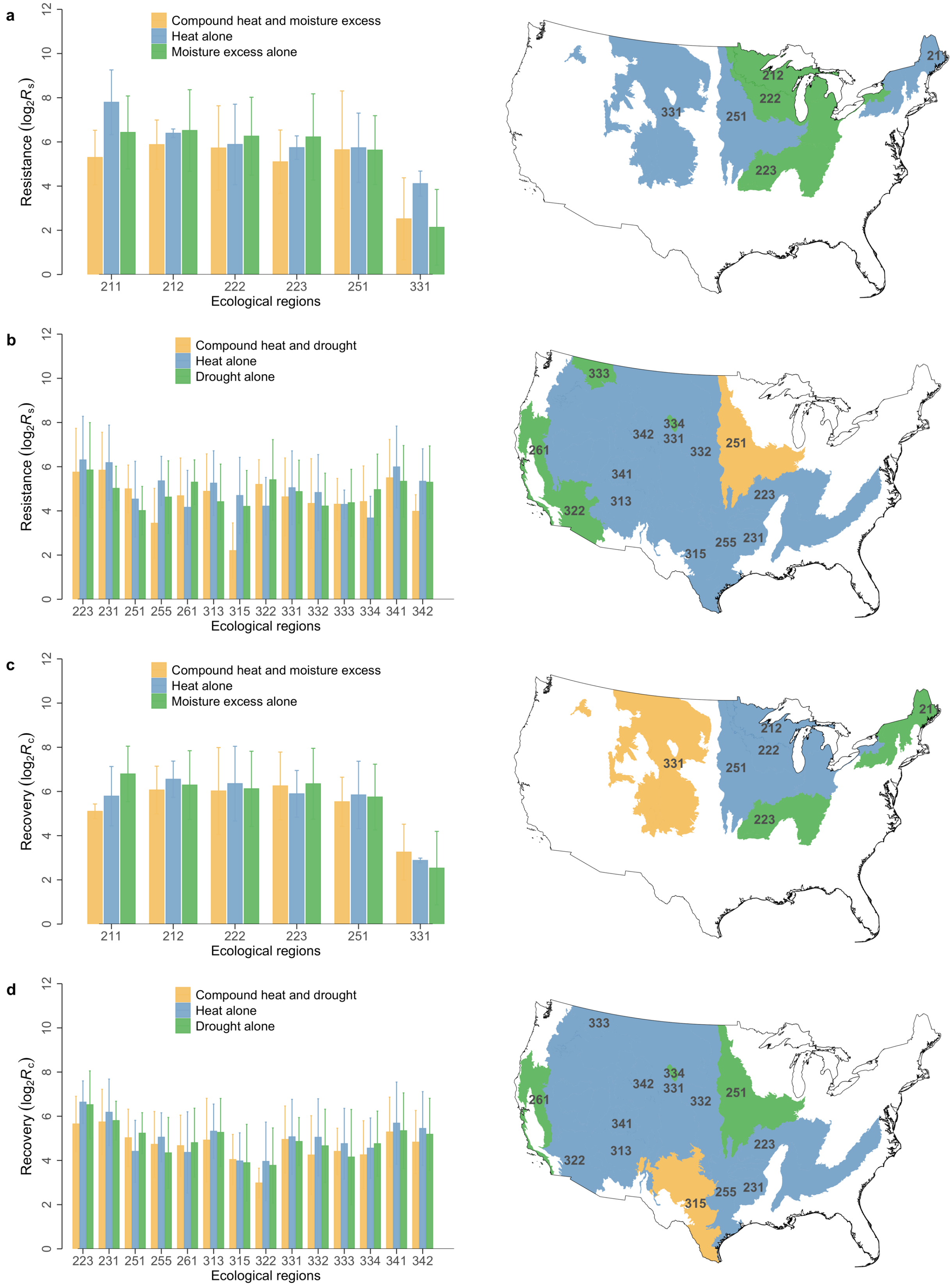
Supplementary Figure 4. The frequency of each type of compound heat and moisture extremes. (a) Compound heat and moisture excess; (b) Compound heat and drought; (c) Compound cold and moisture excess; (d) Compound cold and drought. For each compound extreme type, the colour scale indicates the number of occurrences recorded at each plot during the study period (2001–2020), representing the occurrence frequency of that extreme.



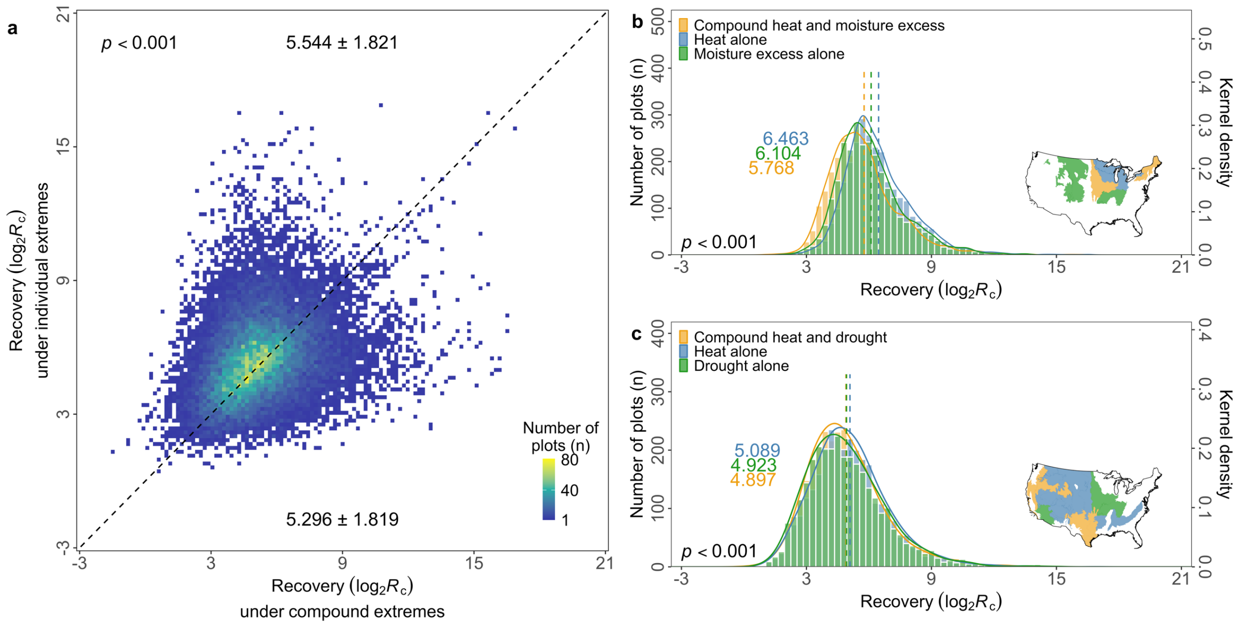
Supplementary Figure 5. The frequency of each type of individual extreme. (a) Heat alone; (b) Cold alone; (c) Moisture excess alone; (d) Drought alone. Occurrence of individual extremes in the plots during the study period (2001-2020). For each individual extreme type, the histogram shows the distribution of occurrence frequencies across plots during the study period (2001–2020). The x axis indicates the number of occurrences per plot, and the y axis indicates the number of plots.



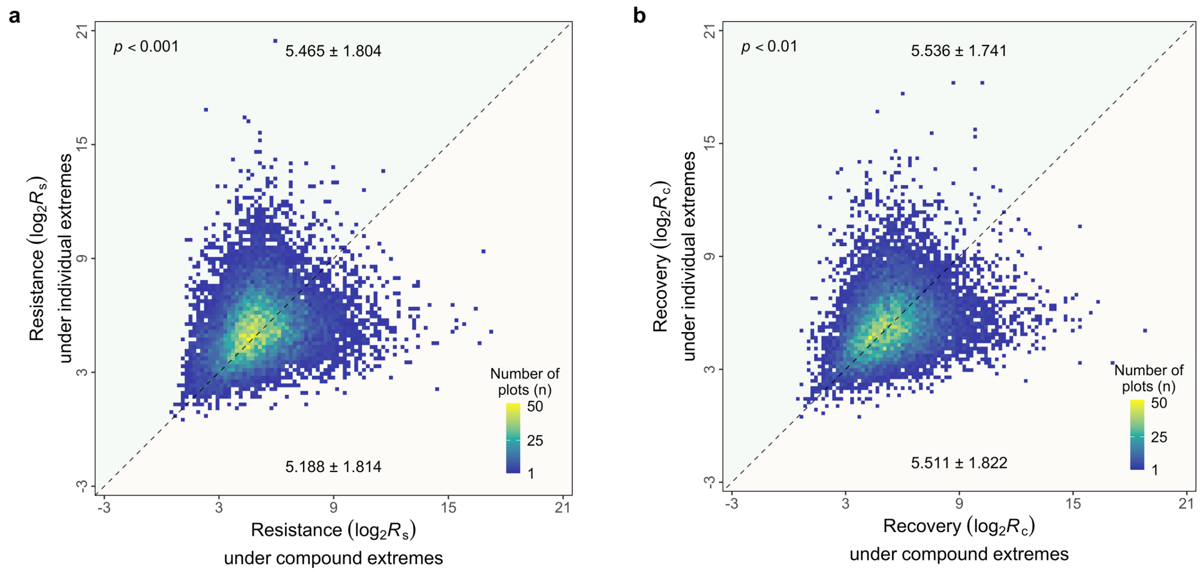
Supplementary Figure 6. Effects of compound and individual climate extremes on forest ecosystem stability during disturbance and post-disturbance phases. Violin plots showing the distributions of (a) resistance and (b) recovery under compound and individual climate extremes. Violin width indicates the kernel density of the data. Orange circles indicate mean values for compound extremes, and green triangles indicate mean values for individual extremes; vertical bars denote ±1 SD. Numbers in parentheses indicate n = number of climate-extreme observations included in each group (compound extremes, n = 34,539; individual extremes, n = 180,546). Different letters indicate significant differences between compound and individual extremes within each panel, based on two-sided t-tests ($p < 0.05$).


a
Compound heat and moisture excess
Heat alone
Moisture excess alone
Resistance ($\log_2 R_s$)
0 2 4 6 8 10 12
211 212 222 223 251 331
Ecological regions
331 251 212 222 223 211
b
Compound heat and drought
Heat alone
Drought alone
Resistance ($\log_2 R_s$)
0 2 4 6 8 10 12
223 231 251 255 261 313 315 322 331 332 333 334 341 342
Ecological regions
333 334 342 331 332 251 261 341 313 223 322 231 255 315
c
Compound heat and moisture excess
Heat alone
Moisture excess alone
Recovery ($\log_2 R_c$)
0 2 4 6 8 10 12
211 212 222 223 251 331
Ecological regions
331 251 212 222 223 211
d
Compound heat and drought
Heat alone
Drought alone
Recovery ($\log_2 R_c$)
0 2 4 6 8 10 12
223 231 251 255 261 313 315 322 331 332 333 334 341 342
Ecological regions
333 334 342 331 332 251 261 341 313 223 322 231 255 315

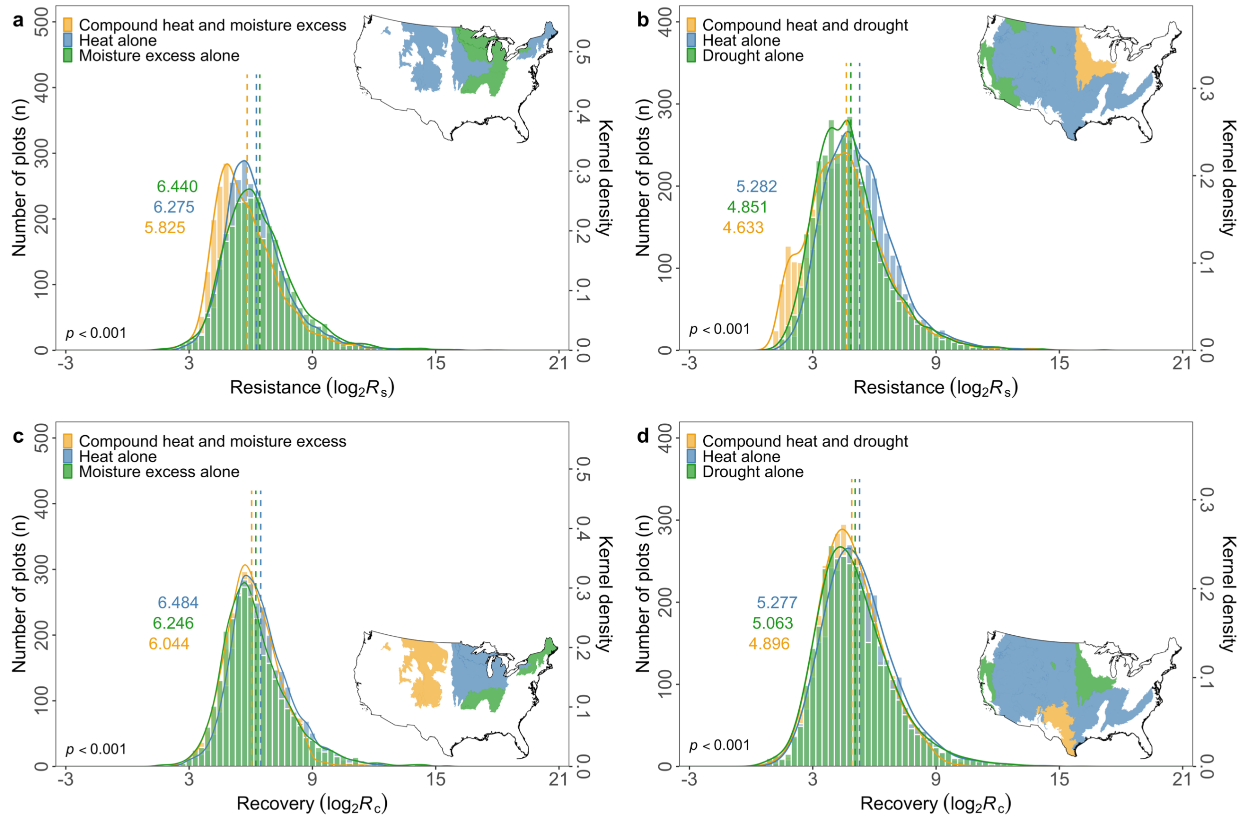
Supplementary Figure 7. Differences in forest ecosystem stability under compound extremes versus individual extremes across ecoregions. Bar plots (left) show mean resistance or recovery values across ecoregions, and maps (right) indicate the corresponding ecoregions. Panels (a) and (c) compare compound heat and moisture excess extremes with their individual components (heat alone and moisture excess alone), whereas panels (b) and (d) compare compound heat and drought extremes with their individual components (heat alone and drought alone). The maps on the right indicate, for each ecoregion that contains forest plots meeting the selection criteria, which extreme type is associated with the highest mean resistance (a, b) or recovery (c, d) in forested landscapes. Bars indicate mean values, and error bars denote ± SD. Ecoregion codes follow the U.S. ecoregion classification (Supplementary Fig. 1). Colours identify the extreme type associated with the highest mean value in each ecoregion, as indicated in the panel-specific keys. Base map from United States Forest Service Ecological Subregions of the U.S.A, USDA - Forest Service ECOMAP Team. ref. 1 published under CC BY 3.0: https://creativecommons.org/licenses/by/3.0/.



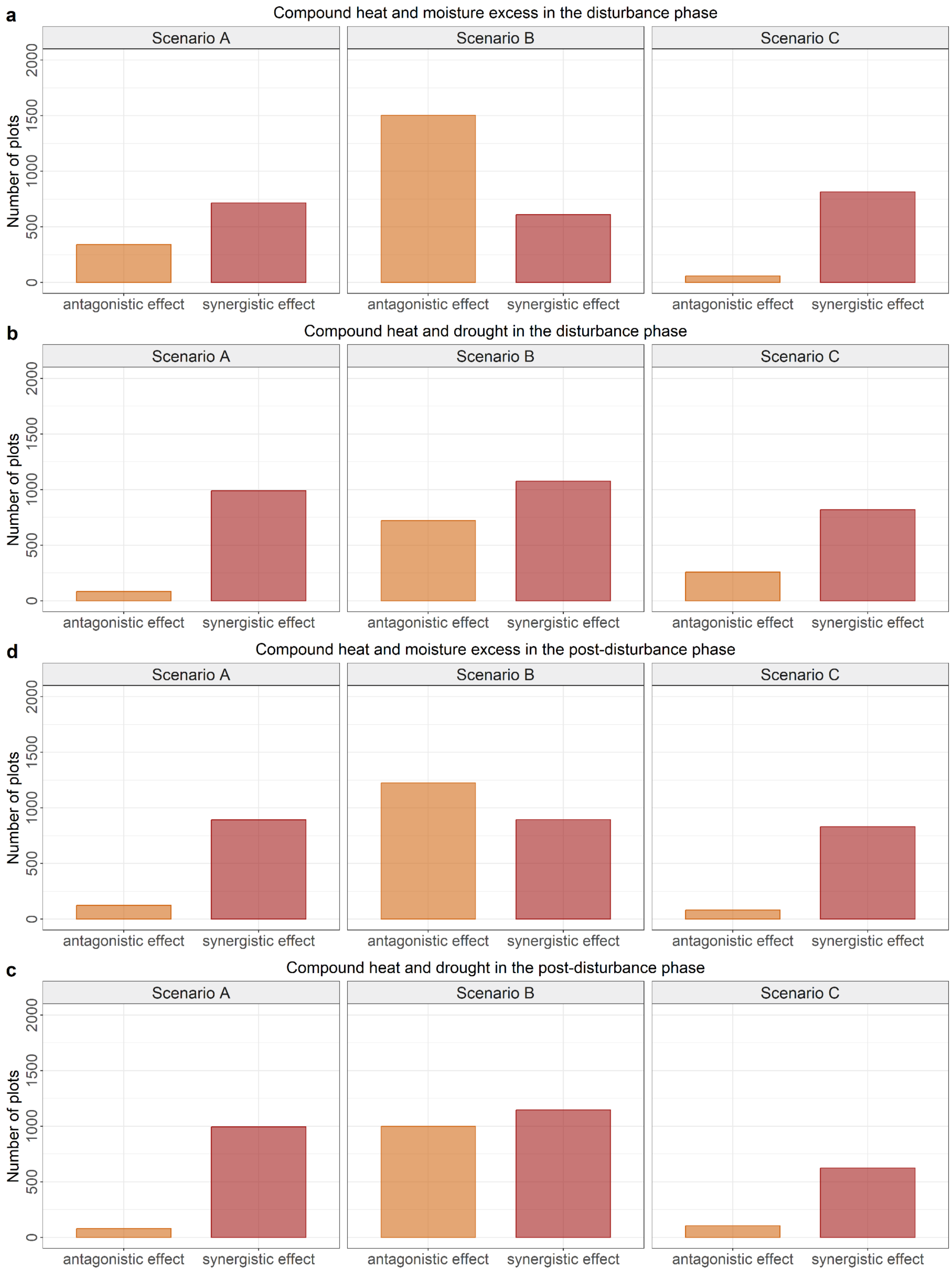
Supplementary Figure 8. Effects of compound versus individual extremes on forest recovery estimated using the predictive method within the same plots. Recovery was calculated using the predictive method (see Methods: Defining resistance and recovery measures) for the same forest plots under compound and individual extremes. (a) Paired comparison of plot-level recovery under compound extremes (x-axis) versus individual extremes (y-axis). Colors indicate the number of plots in each binned cell, and the dashed line denotes the 1:1 relationship. Text annotations report mean ± SD of recovery under compound (x-axis) and individual (y-axis) extremes. (b) Distributions of recovery under compound heat and moisture excess and the corresponding individual extremes (heat alone and moisture excess alone). (c) Distributions of recovery under compound heat and drought and the corresponding individual extremes (heat alone and drought alone). For panels (b) and (c), analyses were restricted to plots that experienced at least one compound extreme and at least one occurrence of each corresponding individual extreme (panel b: ≥1 heat alone and ≥1 moisture excess alone; panel c: ≥1 heat alone and ≥1 drought alone). For each plot, recovery under compound extremes was paired with recovery under the corresponding individual extremes. Histograms show the number of plots (left axis), and the overlaid curves show kernel density estimates (right axis). Vertical dashed lines indicate the mean of each distribution, with mean values labeled. Differences were evaluated using two-sided paired Wilcoxon signed-rank tests, and p values are shown in each panel. Inset maps indicate, for each ecoregion, which extreme type is associated with the highest mean recovery in forested landscapes. In panels (b) and (c), colours correspond to the extreme types indicated in the panel-specific keys; in panel (a), the colour sc ale denotes the number of plots per hexagonal bin. Base map from United States Forest Service Ecological Subregions of the U.S.A, USDA - Forest Service ECOMAP Team. ref. 1 published u nder CC BY 3.0: https://creativecommons.org/licenses/by/3.0/.



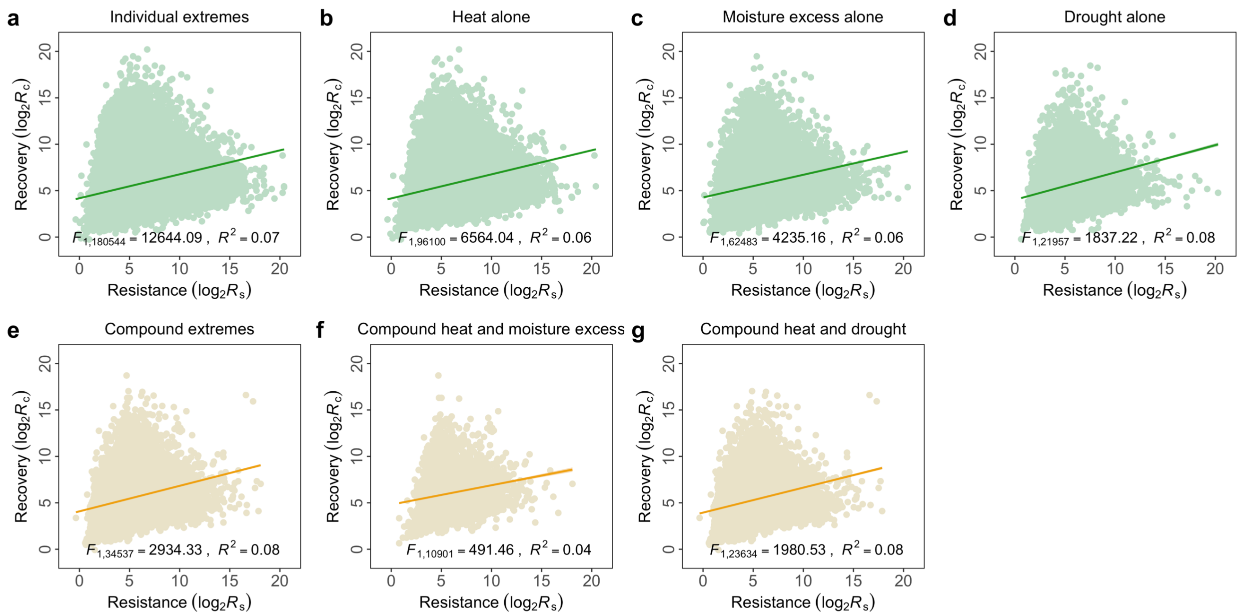
Supplementary Figure 9. Paired comparisons of forest stability under compound versus individual climate extremes after trimming extreme values. Forest plots with values below the 5th percentile or above the 95th percentile of the corresponding metric were excluded. (a) Paired comparison of resistance under compound extremes (x-axis) versus individual extremes (y-axis) within the same plots. (b) Paired comparison of recovery under compound extremes (x-axis) versus individual extremes (y-axis) within the same plots. In both panels, the colour scale denotes the number of plots per hexagonal bin, and the dashed line indicates the 1:1 relationship. Text annotations report the mean ± SD for compound extremes **(**bottom; x axis**)** and individual extremes **(**top; y axis**).** Differences were evaluated using two-sided paired Wilcoxon signed-rank tests, and p values are shown in the upper left of each panel.



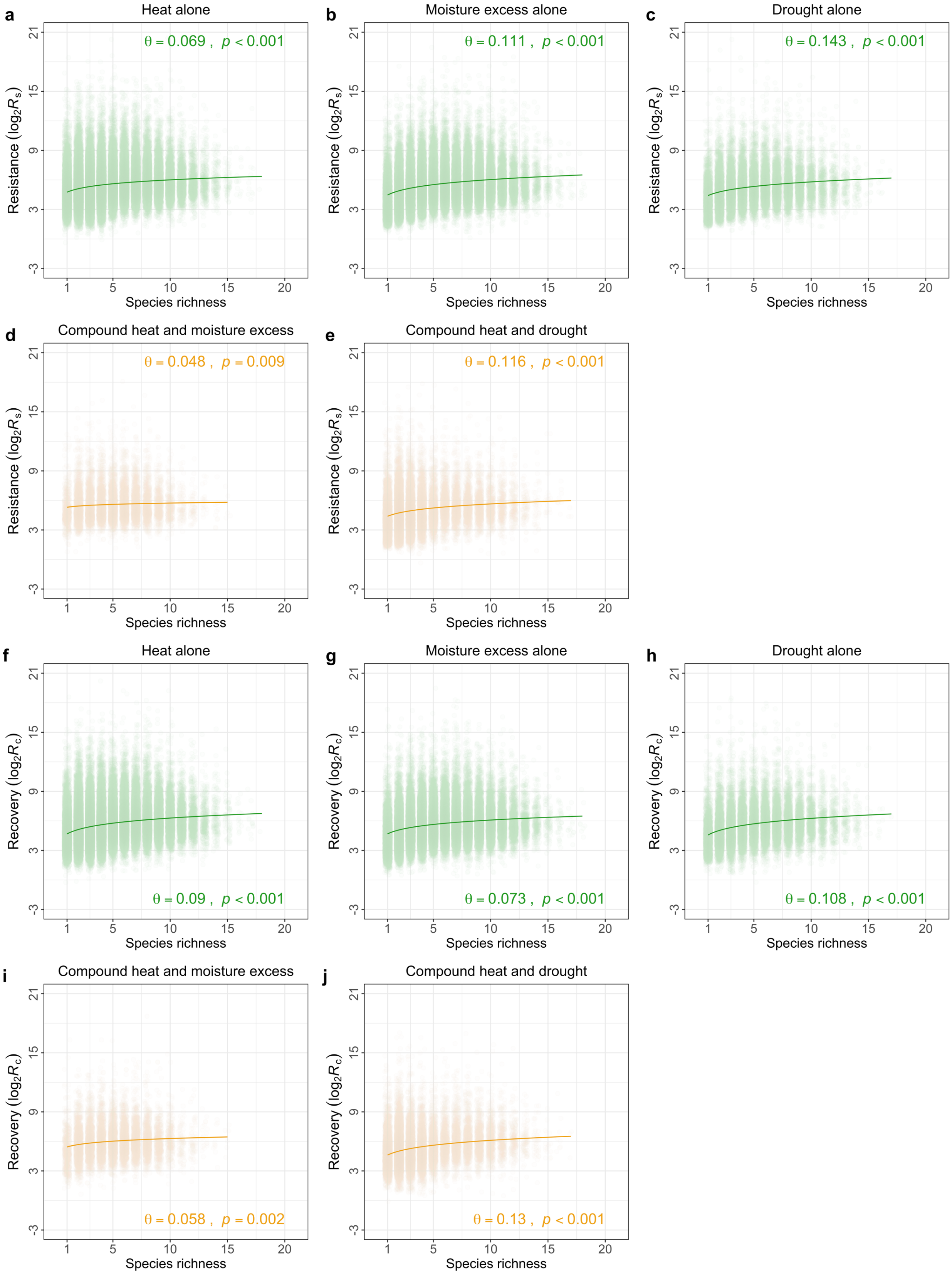
Supplementary Figure 10. Distributions of forest resistance and recovery under compound and individual extremes within the same plots after trimming extreme values. Distributions of resistance (a, b) and recovery (c, d) are shown for the same forest plots after excluding values below the 5th percentile and above the 95th percentile of the corresponding metric. Panels (a) an d (c) compare compound heat and moisture excess extremes with the corresponding individual e xtremes (heat alone and moisture excess alone), whereas panels (b) and (d) compare compound h eat and drought extremes with the corresponding individual extremes (heat alone and drought alo ne). Histograms show the number of plots (left axis), and the overlaid curves show kernel density estimates (right axis). Vertical dashed lines denote the mean of each distribution, with mean val ues labeled. Differences were evaluated using two-sided paired Wilcoxon signed-rank tests, and *p* values are shown in each panel. Inset maps indicate, for each ecoregion, which extreme type is associated with the highest mean resistance (a, b) or recovery (c, d) in forested landscapes. In all panels, colours correspond to the extreme types indicated in the panel-specific keys. Base map fr om United States Forest Service Ecological Subregions of the U.S.A, USDA - Forest Service EC OMAP Team. ref. 1 published under CC BY 3.0: https://creativecommons.org/licenses/by/3.0/.



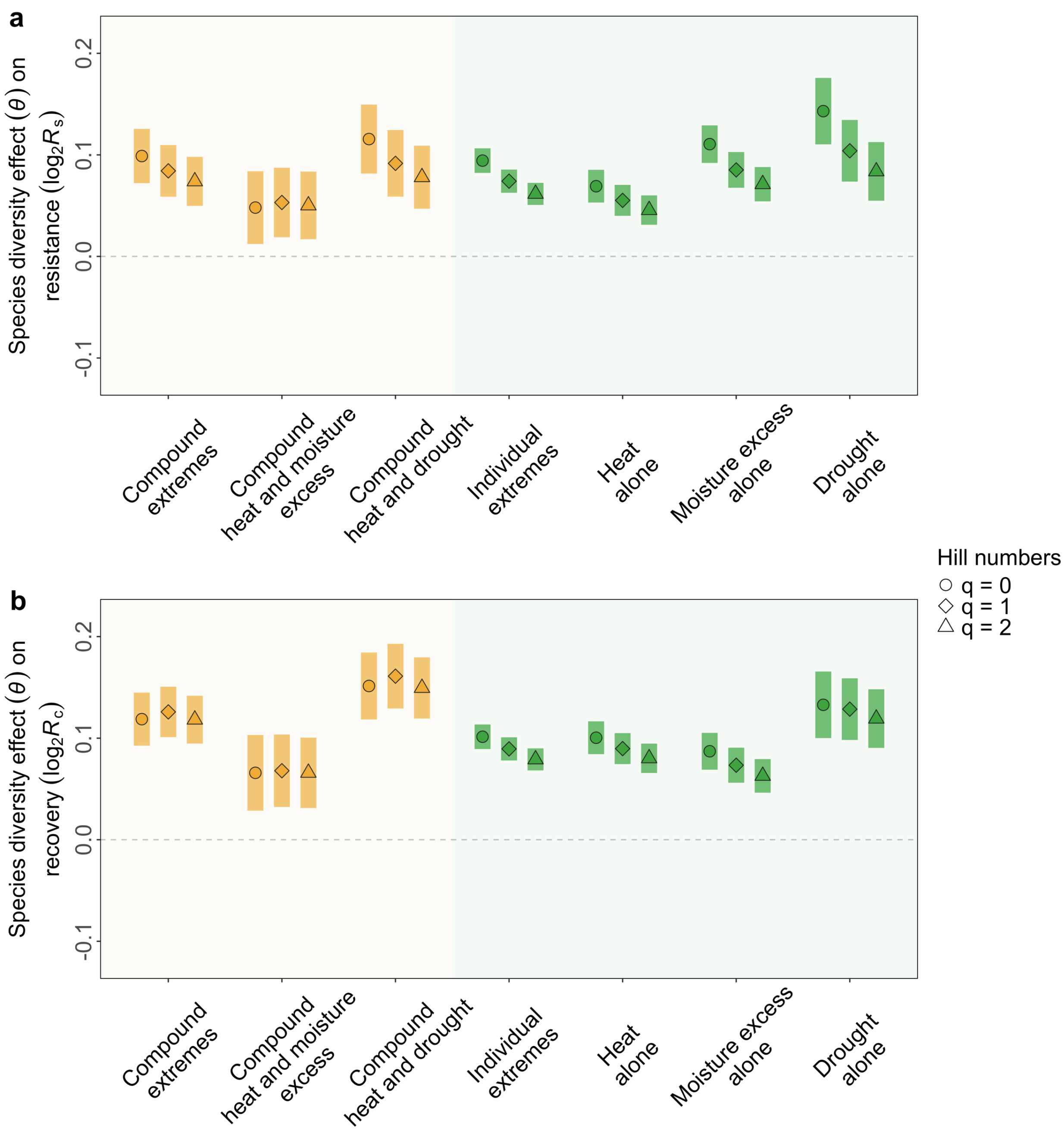
Supplementary Figure 11. Counts of forest plots exhibiting antagonistic or synergistic effects under different scenarios during disturbance and post-disturbance phases. Bar plots show the number of forest plots classified as exhibiting antagonistic or synergistic effects across three scenarios (Scenario A, Scenario B, and Scenario C; see Fig. 4 and Methods) during the disturbance (a, b) and post-disturbance phases (c, d). Panels (a) and (b) show results for the disturbance phase under compound heat and moisture excess and compound heat and drought, respectively. Panels (d) and (c) show results for the post-disturbance phase under compound heat and moisture excess and compound heat and drought, respectively. For each scenario, bars indicate the count of plots.



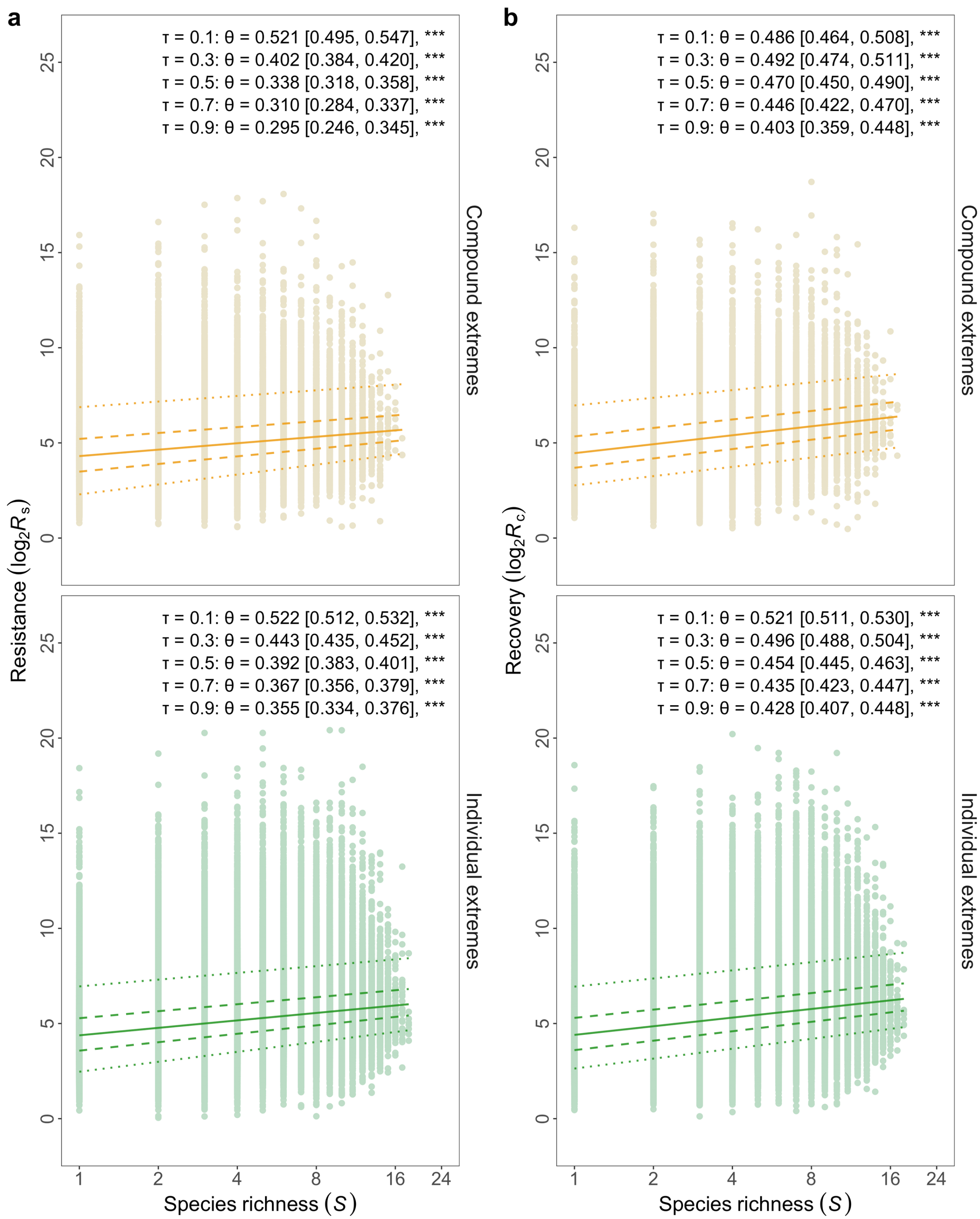
Supplementary Figure 12. Relationships between resistance and recovery across individual and compound climate extremes. Scatterplots show plot-level resistance versus recovery under (a) all individual extremes, (b) heat alone, (c) moisture excess alone, (d) drought alone, (e) all compound extremes, (f) compound heat and moisture excess, and (g) compound heat and drought. Each point represents one plot. Green points and fitted lines indicate individual extremes, and orange points and fitted lines indicate compound extremes. Solid lines show fitted linear regressions between resistance and recovery. The F statistic and coefficient of determination (R^2) are reported in each panel, and all regression slopes were significant (two-sided $p < 0.001$).


a
Heat alone
θ = 0.069 , p < 0.001
b
Moisture excess alone
θ = 0.111 , p < 0.001
c
Drought alone
θ = 0.143 , p < 0.001
d
Compound heat and moisture excess
θ = 0.048 , p = 0.009
e
Compound heat and drought
θ = 0.116 , p < 0.001
f
Heat alone
θ = 0.09 , p < 0.001
g
Moisture excess alone
θ = 0.073 , p < 0.001
h
Drought alone
θ = 0.108 , p < 0.001
i
Compound heat and moisture excess
θ = 0.058 , p = 0.002
j
Compound heat and drought
θ = 0.13 , p < 0.001
Resistance (log2Rs)
Recovery (log2Rc)
Species richness
-3
3
9
15
21
1
5
10
15
20

Supplementary Figure 13. Estimated effect size of species richness on resistance and recovery under individual and compound heat and moisture extremes. Relationships between species richness and resistance (a-e) and recovery (f-j) under different extreme types are shown, with θ indicating the estimated effect size of species richness (see Methods for model specification). Panels (a-c) show resistance under individual extremes (heat alone, moisture excess alone, and drought alone), and panels (d-e) show resistance under compound extremes (compound heat and moisture excess, and compound heat and drought). Panels (f-h) show recovery under individual extremes (heat alone, moisture excess alone, and drought alone), and panels (i-j) show recovery under compound extremes (compound heat and moisture excess, and compound heat and drought). Solid lines show the fitted relationships, and θ and two-sided p values are reported in each panel. p values ≥ 0.001 are reported as exact values, whereas p values < 0.001 are reported as $p < 0.001$.



Supplementary Figure 14. Effects of different Hill numbers on resistance and recovery under climate extremes. (a) and (b) Differences in the estimated effect size (θ) of diversity on resistance and recovery under compound extremes, compound heat and drought, compound heat and moisture excess, individual extremes, heat alone, drought alone and moisture excess alone, respectively. Species richness in the main analyses is expressed as the Hill number with q = 0. For comparison, q = 1 represents the exponential of Shannon entropy and measures the effective number of common species. The case of q = 2 represents the inverse Simpson index and measures the effective number of dominant species. Orange symbols and shaded intervals denote compound extreme categories, whereas green symbols and shaded intervals denote individual extreme categories. Circles, squares and triangles denote Hill numbers q = 0, q = 1 and q = 2, respectively. Points indicate estimated mean effect sizes, and shaded areas indicate 95% confidence intervals. Confidence intervals that do not overlap the dashed line ($\theta = 0$) indicate statistical significance ($p < 0.05$).



Supplementary Figure 15. Quantile regression reveals effects of tree species richness on resistance and recovery under compound and individual climate extremes. Panels a and b show resistance and recovery, respectively. Each point represents one plot-level observation. Orange points and fitted lines denote compound extremes, whereas green points and fitted lines denote individual extremes. Solid, dashed, and dotted lines are quantile regression fits for T = 0.5, T = 0.3 and 0.7, and T = 0.1 and 0.9, respectively. For each facet, the text reports the estimated effect size of species richness (θ, see Methods) with its 95% confidence interval, based on normal approximation standard errors. Statistical significance is indicated by asterisks, where *** denotes two-sided $p < 0.001$.

Supplementary Table 1. Model comparison for temporal autocorrelation in resistance and recovery analyses. Linear mixed-effects models with random intercepts for plots nested within ecoregions (ecoregion/plot) were fitted with and without a first-order autoregressive correlation structure, corAR1(form = ~ ECOT | ecoregion/plot), for resistance and recovery under compound and individual climate extremes. Model selection was based on Akaike's Information Criterion (AIC). For each response variable and extreme type, ΔAIC is reported relative to the lowest-AIC model (ΔAIC = AIC − min(AIC)); ΔAIC = 0 indicates the best-supported model. β denotes the standardized regression coefficient for $\log_2$-transformed species richness, and φ denotes the estimated autoregressive parameter of the AR(1) structure (φ values near 0 indicate negligible temporal autocorrelation). logLik is the model log-likelihood. Two-sided p values correspond to tests of β.

Response	Extreme type	Model	Temporal correlation	φ	ΔAIC	logLik	β	p value
Resistance	Compound	Base	None	NA	0	-67489.6	0.099	< 0.001
Resistance	Compound	AR1	AR1	0	2	-67489.6	0.099	< 0.001
Resistance	Individual	Base	None	NA	0	-351162.7	0.094	< 0.001
Resistance	Individual	AR1	AR1	0	2	-351162.7	0.094	< 0.001
Recovery	Compound	Base	None	NA	0	-66271.8	0.119	< 0.001
Recovery	Compound	AR1	AR1	0	2	-66271.8	0.119	< 0.001
Recovery	Individual	Base	None	NA	0	-349566.9	0.101	< 0.001
Recovery	Individual	AR1	AR1	0	2	-349566.9	0.101	< 0.001

References

1 Cleland, D. T. *et al.* Ecological Subregions: Sections and Subsections for the conterminous United States. (U.S. Department of Agriculture, Forest Service, 2007).