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Scale-dependent changes in ecosystem temporal stability over six decades of succession

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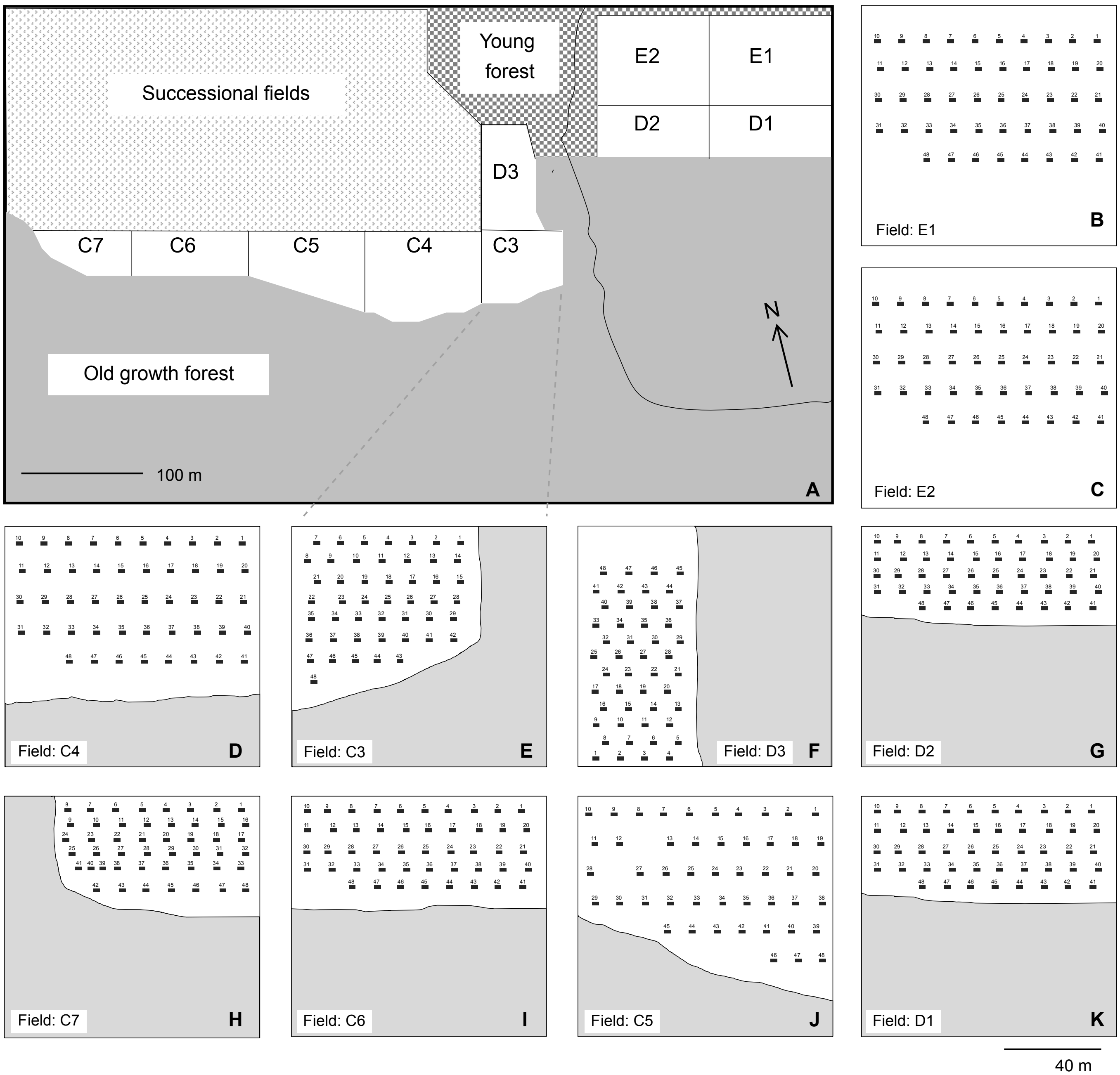

Fig. S1. Locations of the 480 plots nested within the ten fields of the Buell-Small Succession Study within the Hutcheson Memorial Forest.

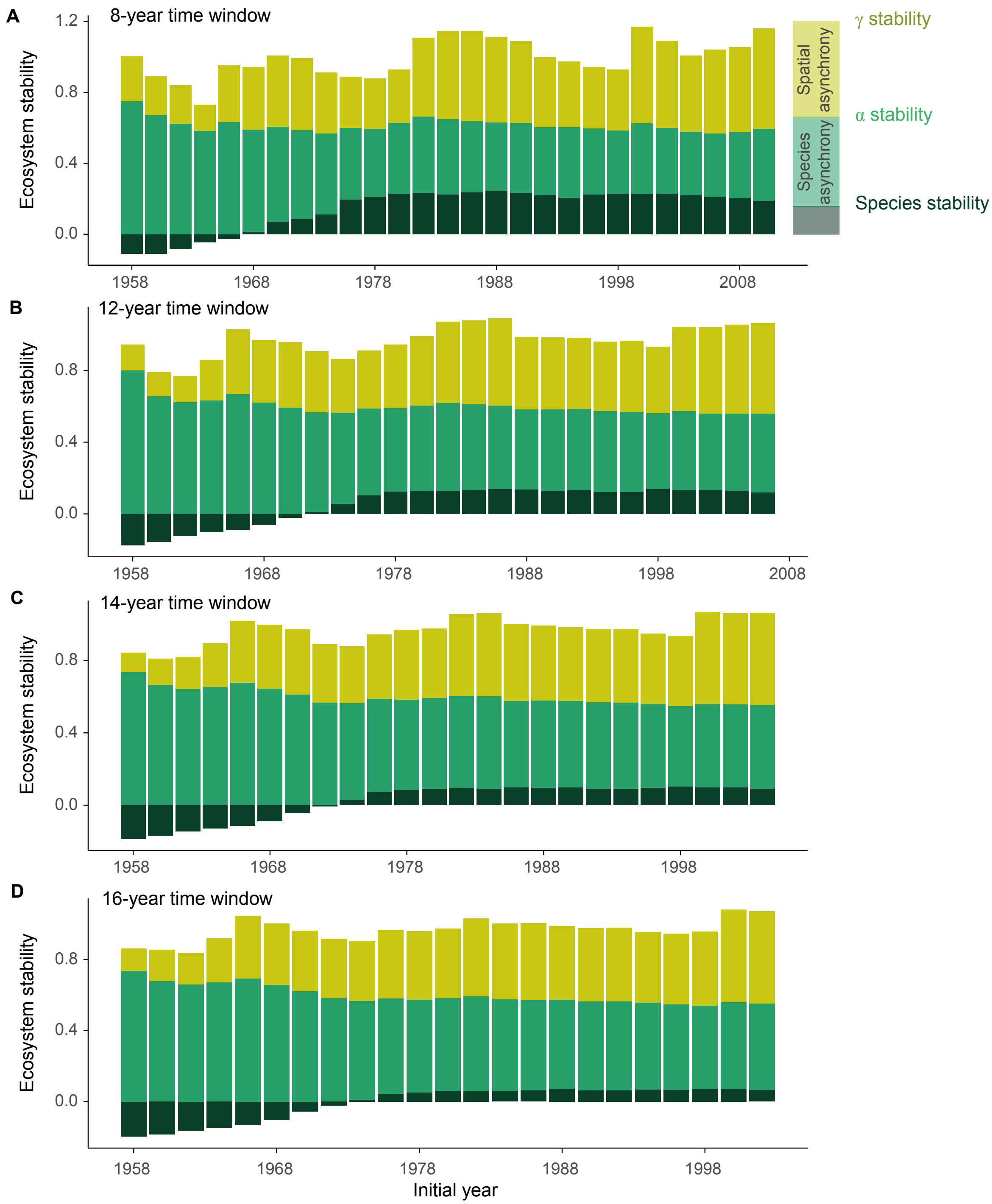

Fig. S2. Temporal trends in stability and asynchrony using different lengths of moving-window time intervals. The x-axis represents the initial year in each time window. The widths of the shades represent the logarithm-transformed mean values of species stability (dark green), species asynchrony (bright green), and spatial asynchrony (dark yellow) within each 10-year time interval. Mathematically, at the logarithm-transformed scale, the α stability can be viewed as the sum of species stability and species synchrony, and the γ stability can be viewed as the sum of α stability and spatial synchrony.

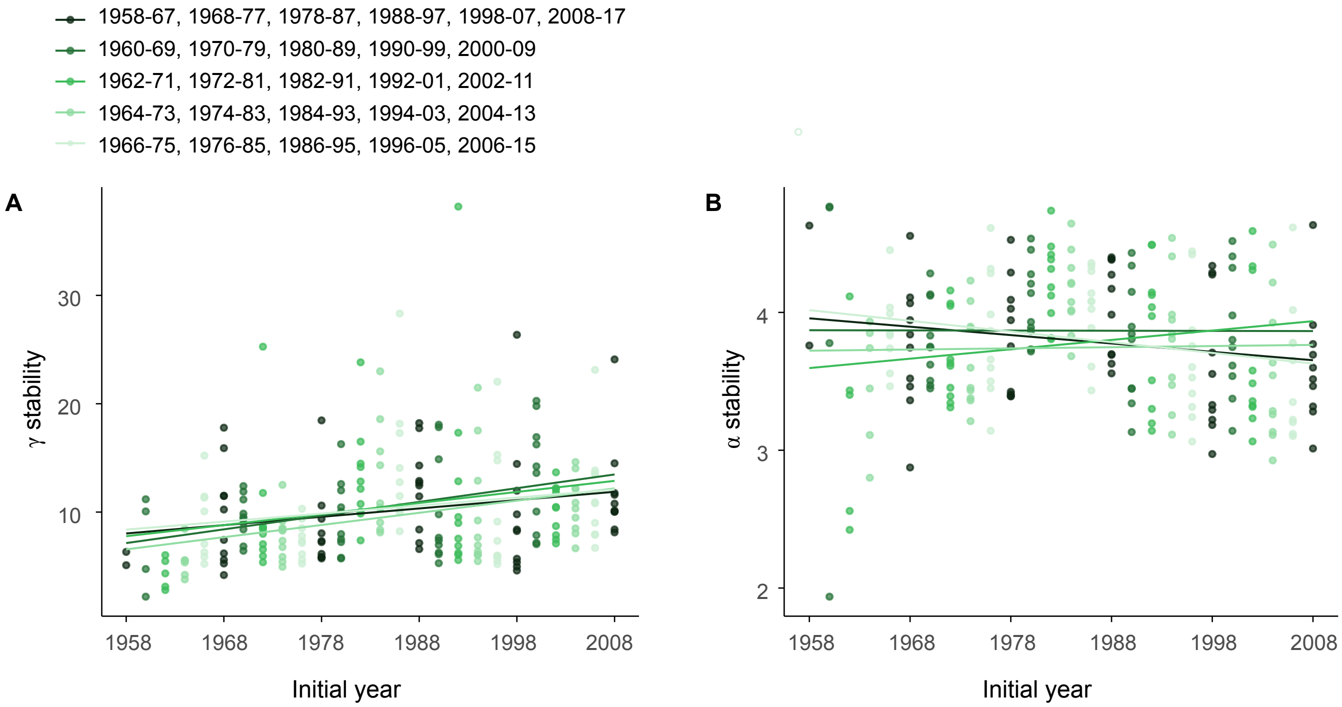

Fig. S3. Temporal trends in γ and α stability using non-overlapping time intervals. The x-axis represents the initial year of each time interval.

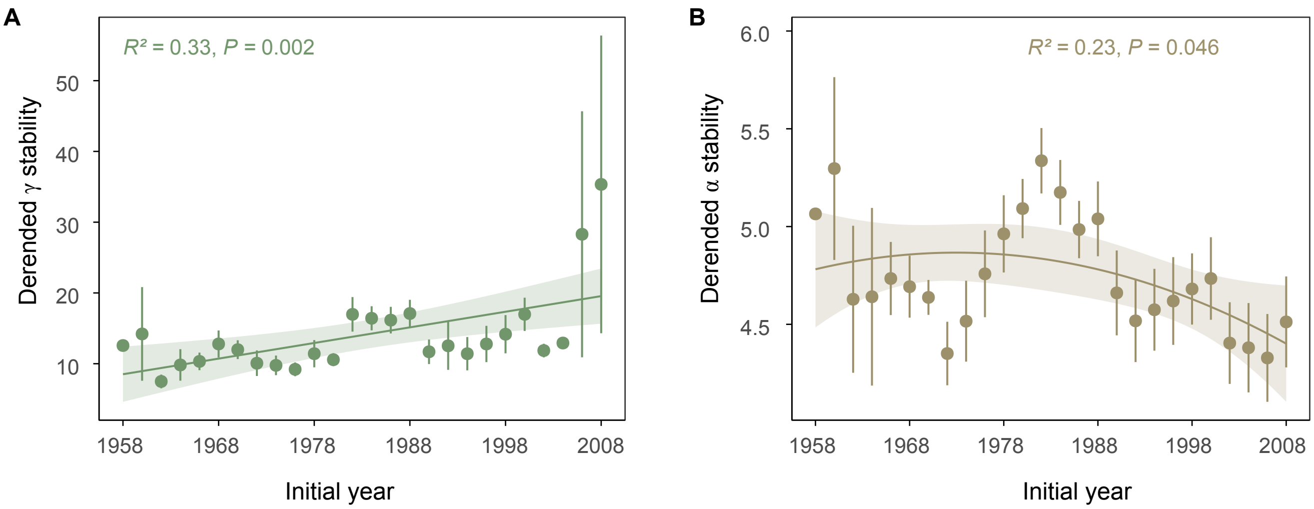

Fig. S4. Temporal trends in detrended γ and α stability. Temporal trend lines were fitted using simply linear (A) and quadratic regression (B), respectively.

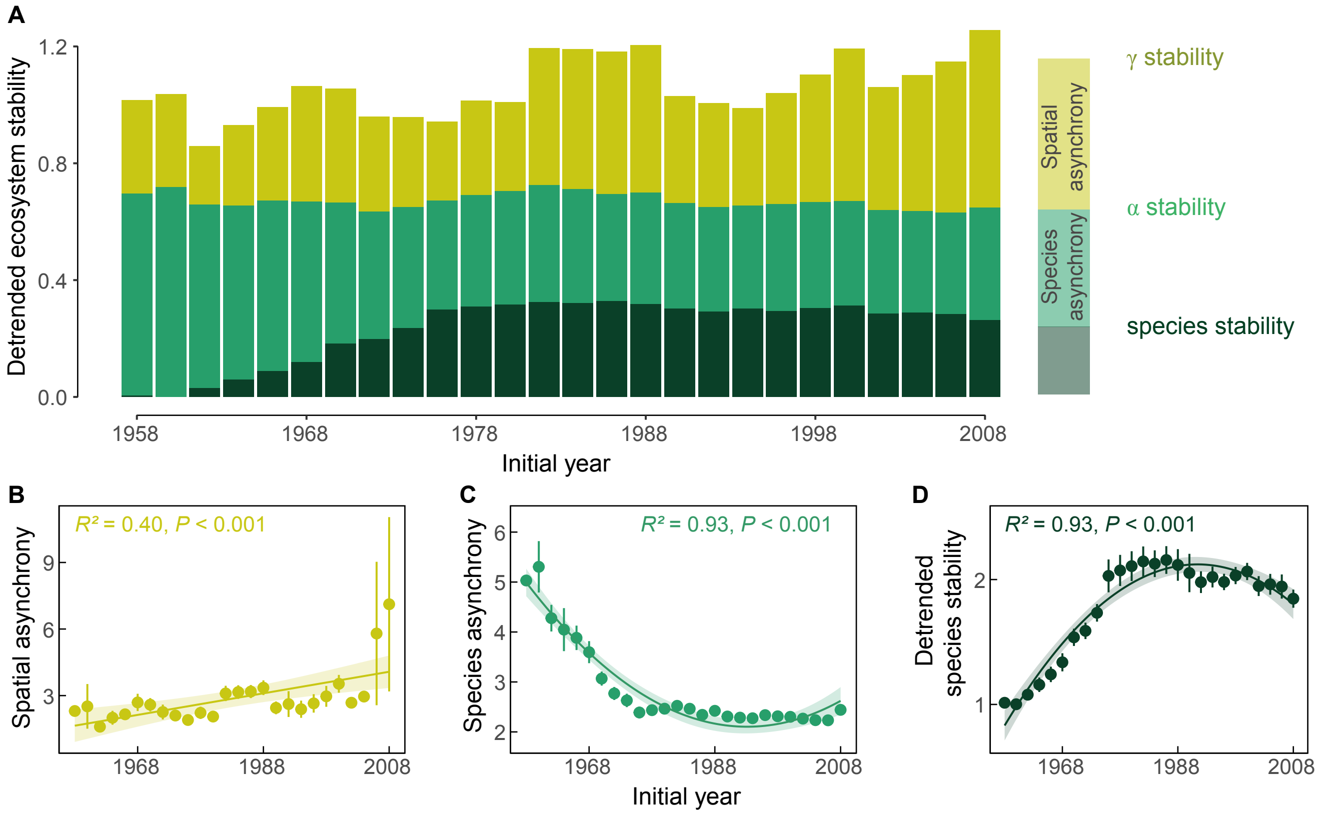

Fig. S5. Visualized temporal trends of detrended species stability, species asynchrony and spatial asynchrony over succession. Note the y-axis is log-transformed in (A). Temporal trend lines were fitted using simply linear (B) and quadratic regression (C, D), respectively.

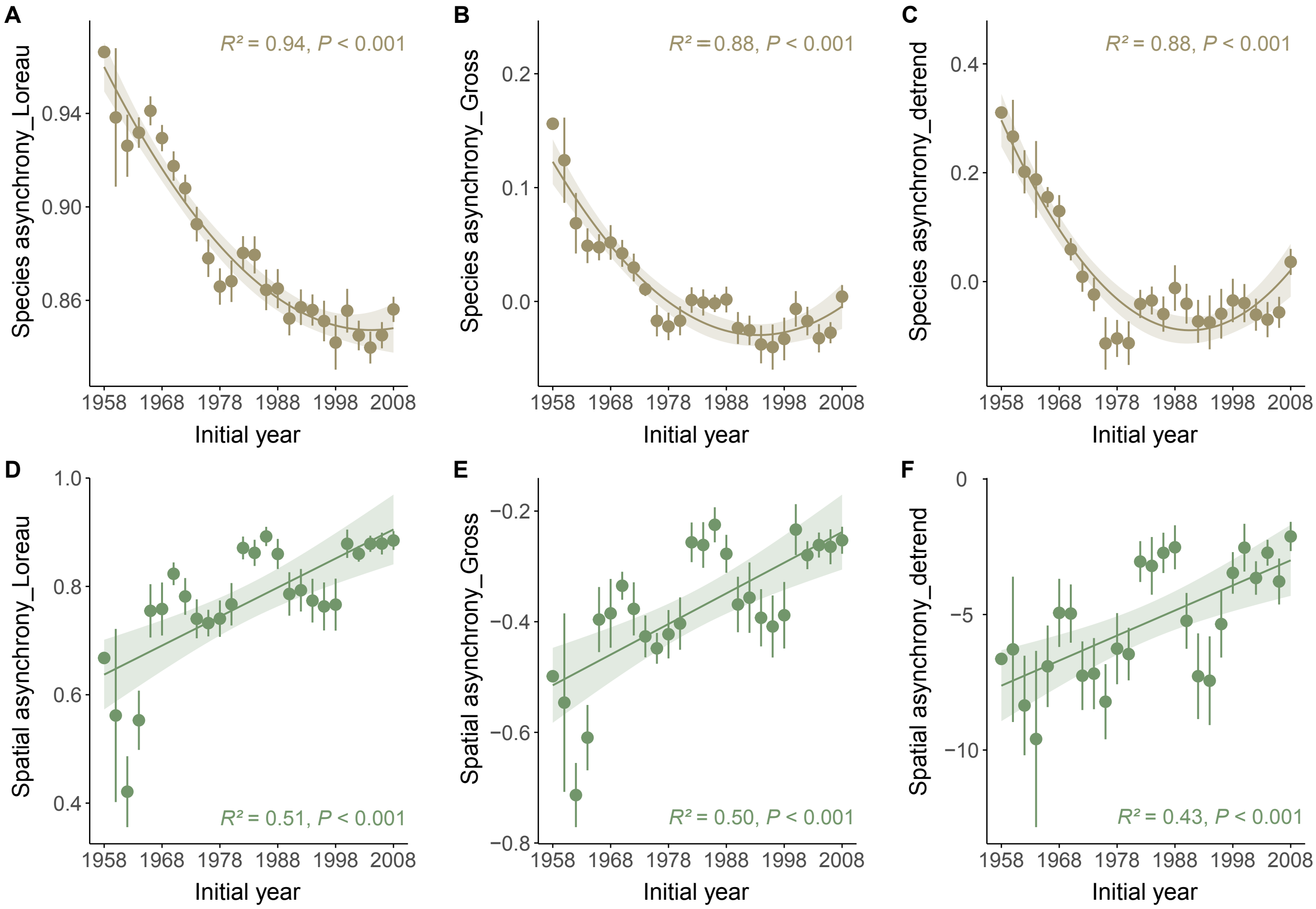

Fig. S6. Temporal trends in species and spatial asynchrony based on different asynchrony indices. Species asynchrony within plots (A-C) and spatial asynchrony among plots (D-F) are calculated by original data according to Loreau & de Mazancourt (*60*) and Gross *et al.* (*61*) and by detrend data following Lepš *et al.* (*62*), respectively. Species asynchrony within plots consistently increased, and spatial asynchrony among plots consistently decreased over succession. Points show 10-year spatial asynchrony averaged across all observed fields or species asynchrony averaged across all 48 plots among 10 fields of the same period. Error bars represent standard errors. Temporal trend lines were fitted using simply linear (D-F) and quadratic regression (A-C), respectively.

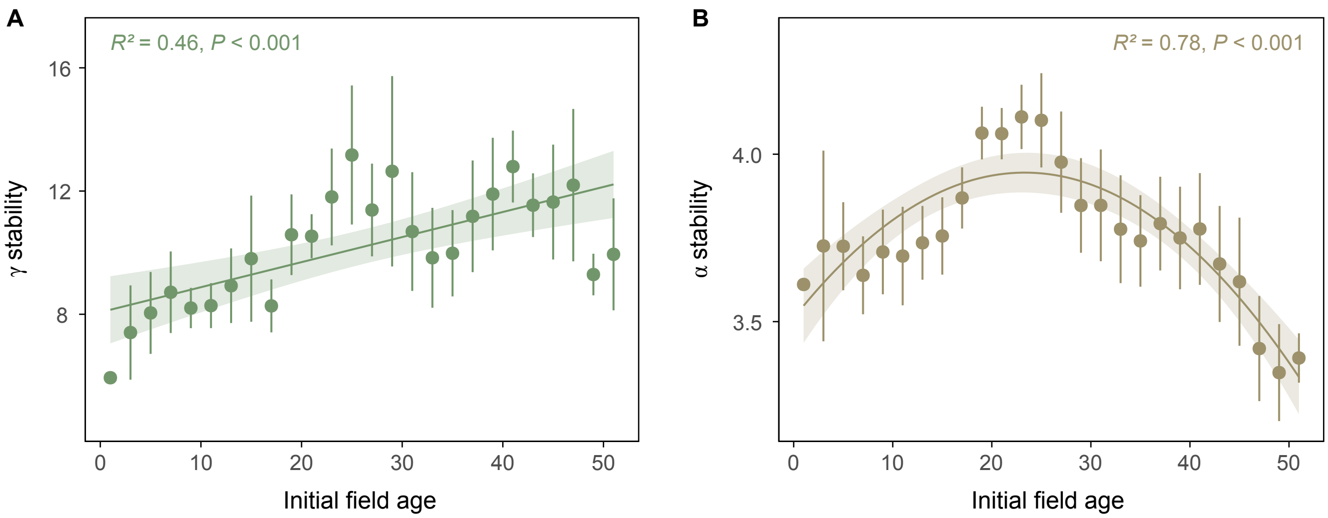

Fig. S7. Temporal trends in γ and α stability based on field ages instead of calendar years. Similar to the analysis based on calendar years, γ stability (A) significantly increased with age. While α stability (B) initially increased but subsequently decreased with increasing field age. The x-axis represents the initial field age in each 10-year rolling window, ranging from 1–10 to 51–60. Temporal trend lines were fitted using simply linear (A) and quadratic regression (B), respectively.

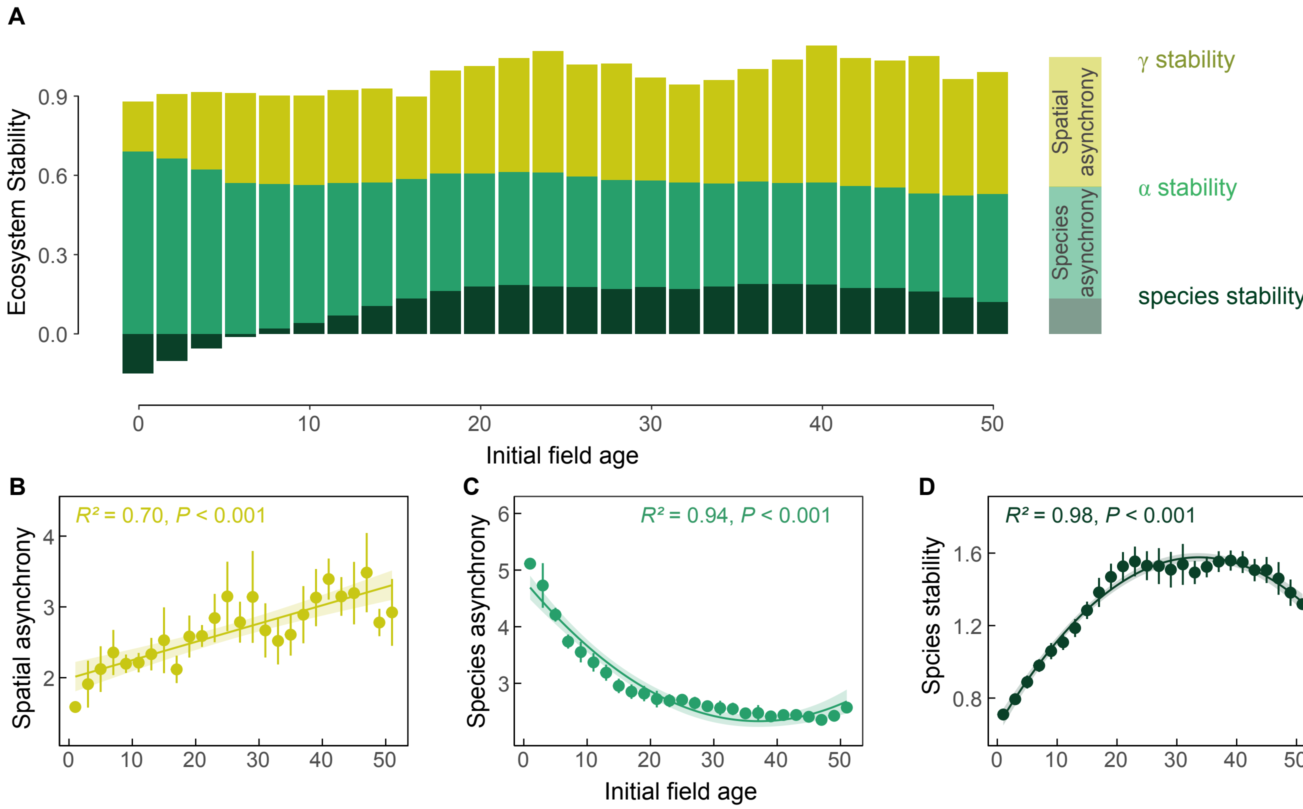

Fig. S8. Visualized temporal trends of species stability, species asynchrony and spatial asynchrony over succession based on field ages instead of calendar years. The x-axis represents the initial field age in each 10-year rolling window, ranging from 1–10 to 51–60. Note y-axis is log-transformed in (A). Temporal trend lines were fitted using simply linear (B) and quadratic regression (C, D), respectively.

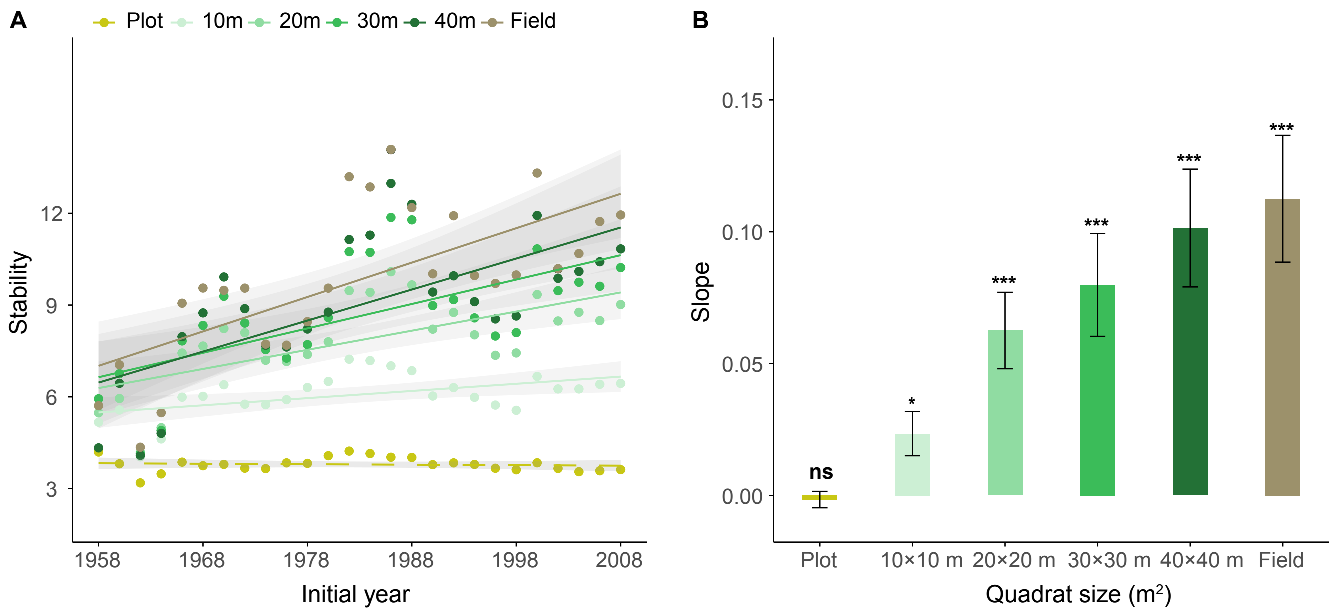

Fig. S9. Changes in temporal stability over succession using multiple quadrat size (A). Temporal trend lines are coded solid if significant ($P < 0.05$) and dashed if not significant. The slopes of all temporal trend lines at different quadrat scales are shown in panel B (ns, no significant; *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$).

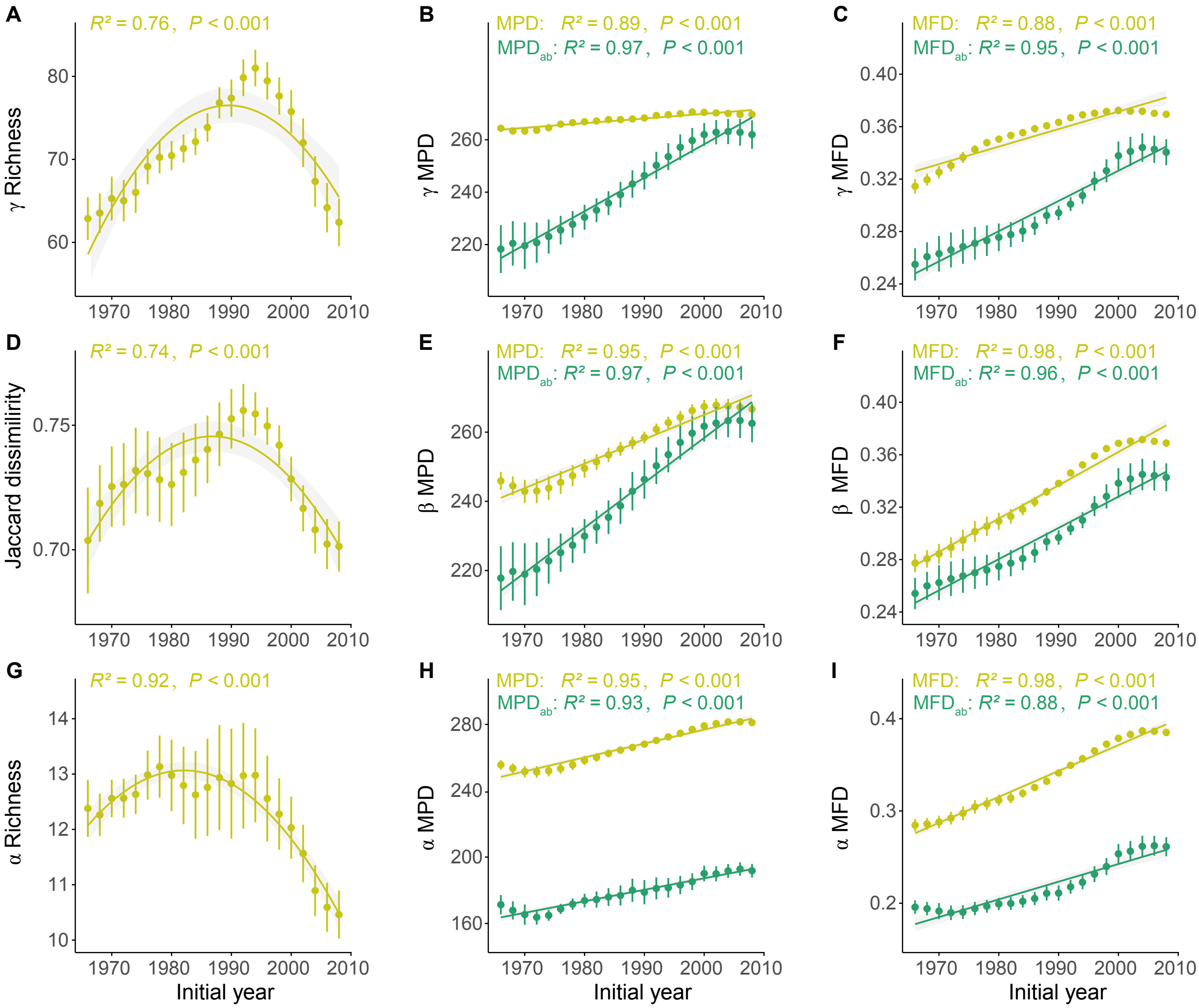

Fig. S10. Temporal trends in γ, β and α diversity based on taxonomic (species richness, A, D and G), phylogenetic (MPD & MPD_{ab}, B, E and H), and functional (MFD & MFD_{ab}, C, F and I) diversity measures. Points show γ and β diversity averaged across 10 years and all observed fields (A-C, G-I), or α diversity averaged across all 48 plots among 10 fields of the same period (D-F). Error bars represent standard errors. The x-axis represents the initial year in each 10-year time window. Temporal trend lines are solid if significant ($P < 0.05$) and dashed if not significant. Temporal trend lines were fitted using simply linear (B, C, E, F, H and I) and quadratic regression (A, D and G), respectively.

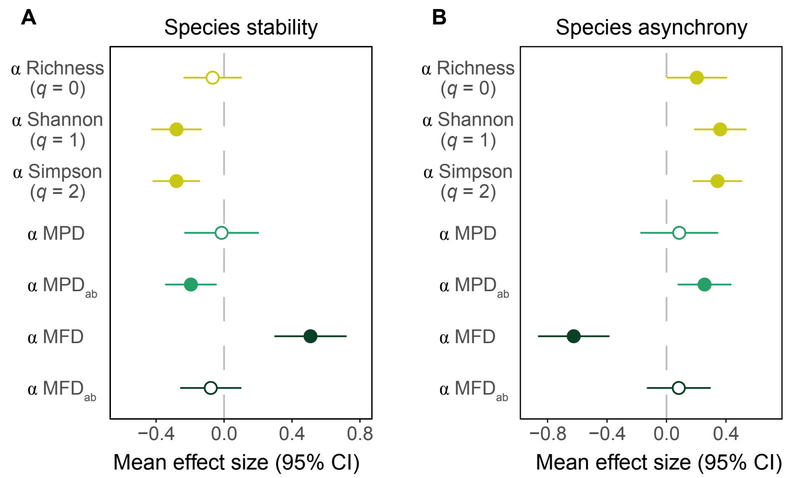

Fig. S11. Effect size of taxonomic, phylogenetic and functional α diversity on species stability (A) and species asynchrony (B) at the plot scale. Effect sizes are standardized coefficients from linear mixed-effects models that account for temporal autocorrelation, estimated separately for each predictor variable. Solid circles indicate significant effects ($P < 0.05$) and open circles indicate non-significant effects.

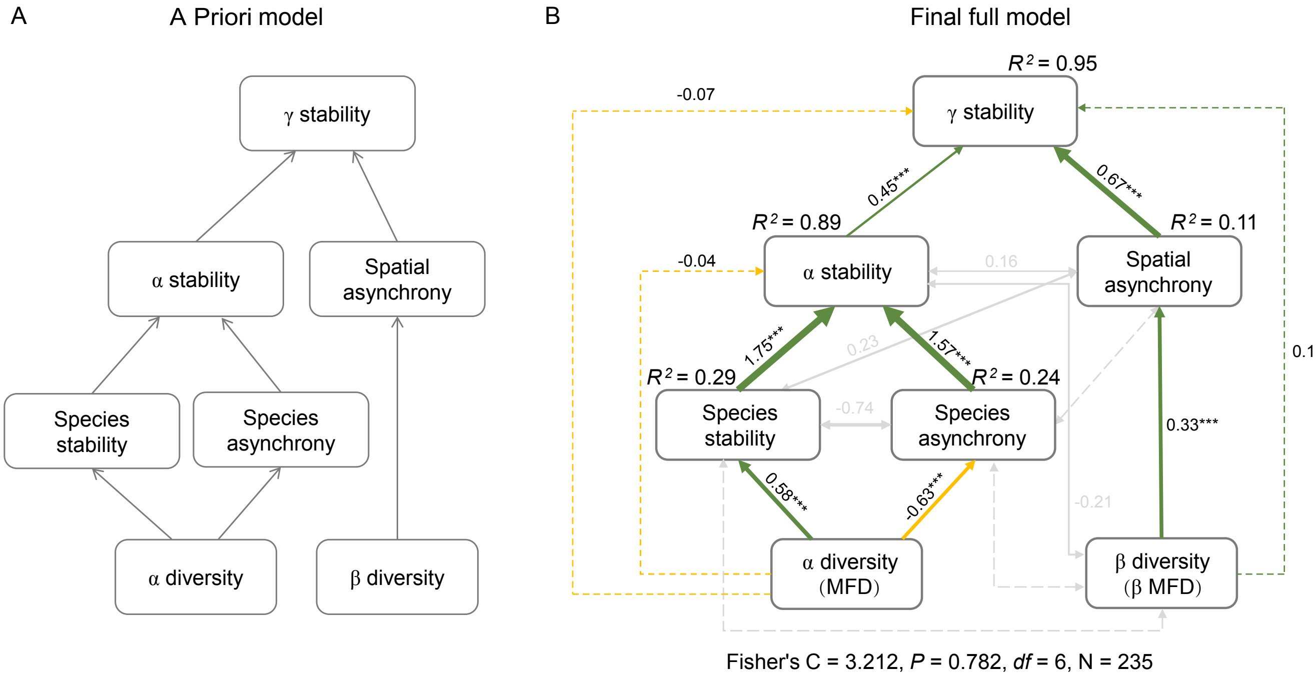

Fig. S12. The structural equation model (SEM) depicting the direct and indirect effects of functional diversity on ecosystem stability over succession across scales. (A) A priori SEM for assessing effect of diversity on promoting stability at multiple spatial scales. (B) A final SEM includes both causal paths and correlated paths. Boxes represent measured variables and arrows represent relationships among variables. Green and yellow solid arrows denote positive and negative associations, respectively, and dashed arrows represent nonsignificant relationships. Standardized path coefficients are given next to each path, and asterisks alongside indicate a significant path (*, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$); Grey arrows and numbers show correlated errors. The widths of significant paths are scaled by standardized path coefficients. Conditional R^2 are reported in the corresponding box. γ stability, α stability, species stability, MFD and βMFD were $\log_{10}$-transformed to improve normality and homogeneity of variance.

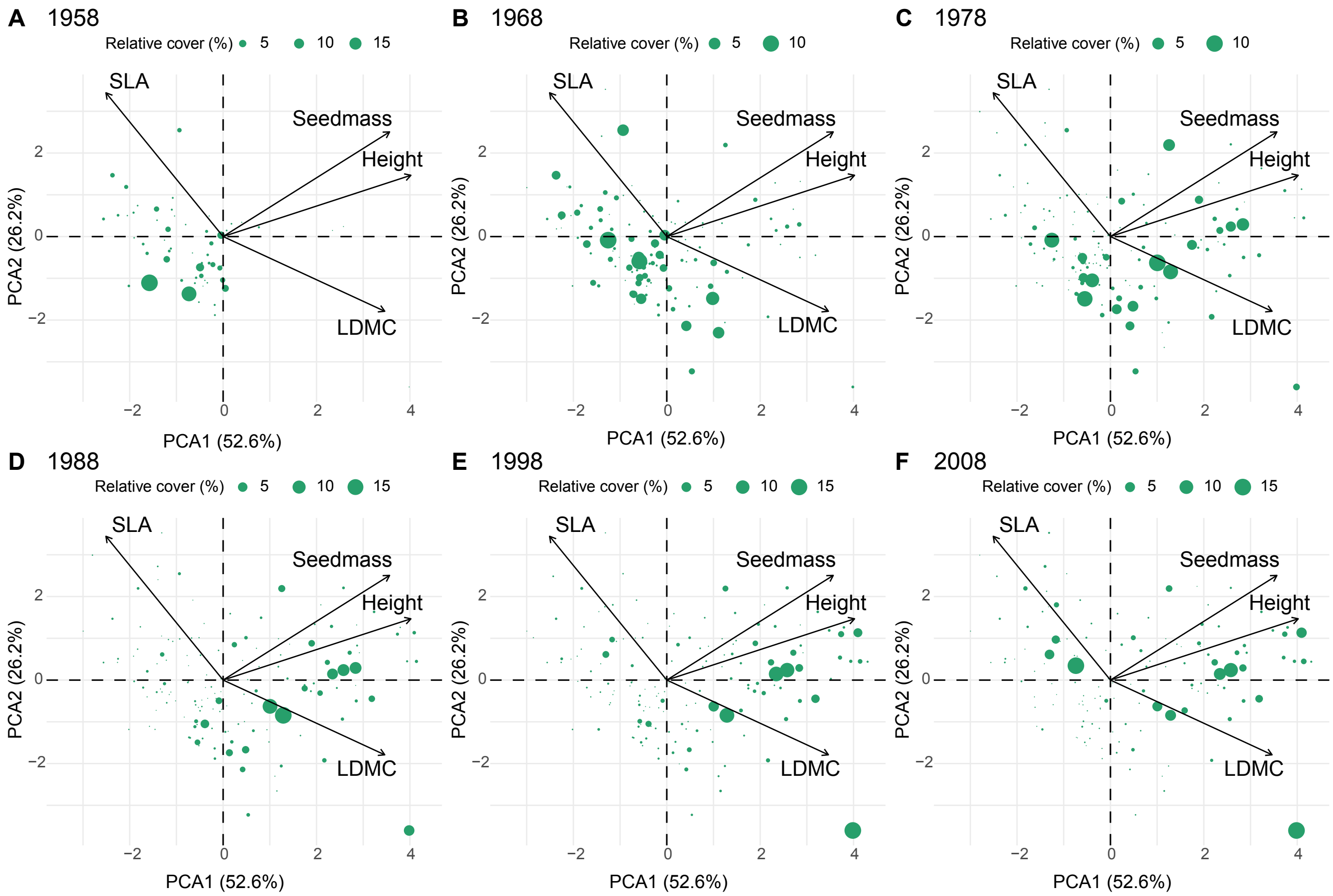

Fig. S13. Shifts in functional trait spaces over succession at the filed level. Principal component analysis (PCA) was conducted on four continuous functional traits, including specific leaf area (SLA), leaf dry matter content (LDMC), plant height and seed mass. Trait values were log transformed and scaled. The size of point represents the cover of each species in the respective successional year. PCA results are shown for the years 1958 (A), 1968 (B), 1978 (C), 1988 (D), 1998 (E), and 2008 (F) to illustrate the temporal trends. Similar temporal trends would be observed for other years.

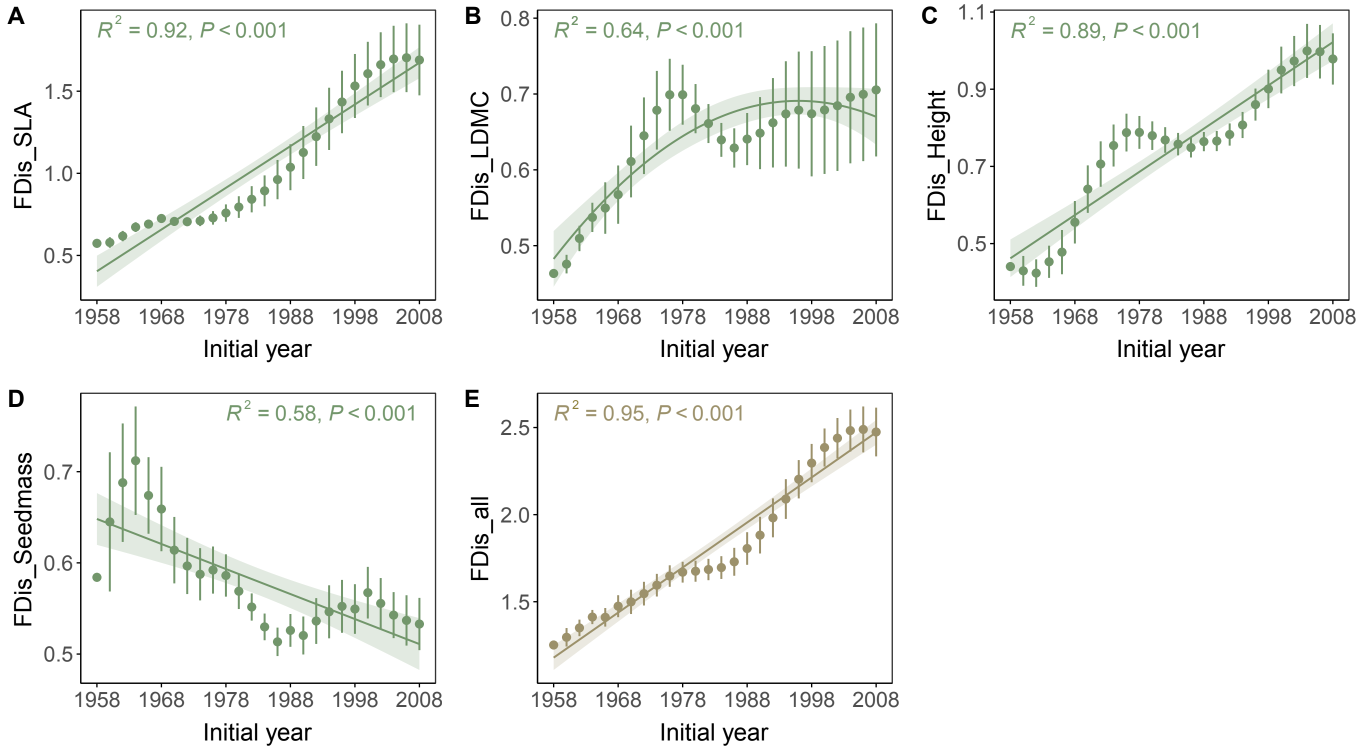

Fig. S14. Temporal trends of functional dispersion (FDis) at the field scale over succession. Functional dispersion of specific leaf area (SLA, A), leaf dry matter content (LDMC, B) and plant height (C) significantly increased, but seed mass (D) decreased over time. FDis calculated based on all four traits combined (E) also significantly increased over succession. Each point represents the average functional dispersion across all observed fields in each 10-year time window, with error bars indicating standard errors. Temporal trend lines are solid if significant (P < 0.05).

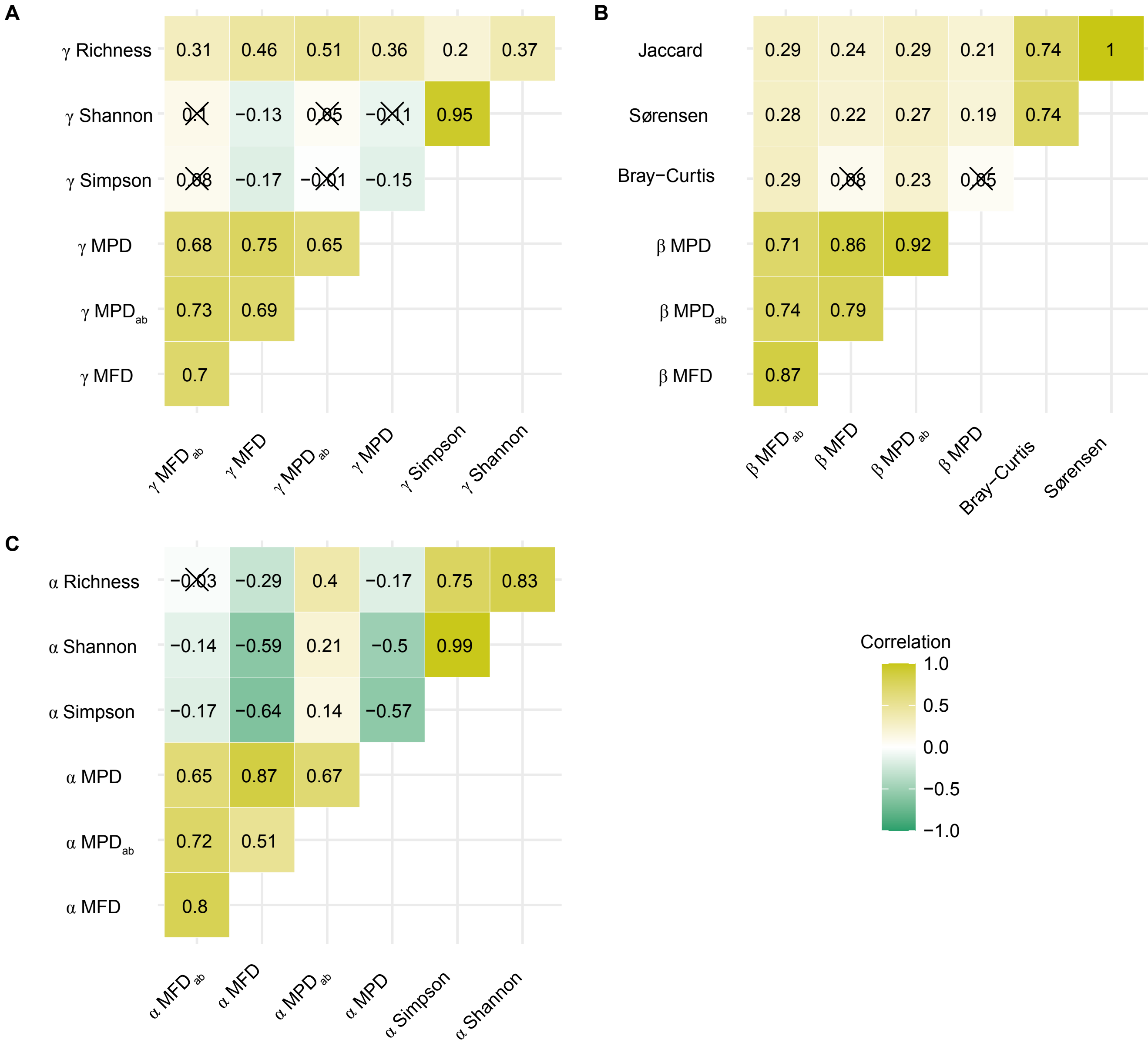

Fig. S15. Pearson's correlation analysis among taxonomic, phylogenetic and functional diversity indices at α (A), β (B), and γ (C) levels, respectively. Values represent Pearson correlation coefficients, and boxes without crosses indicate statistical significance ($P < 0.05$).

Table S1. Univariate linear mixed-effects models predicting the five temporal stability components across spatial scales. Each taxonomic, phylogenetic and functional diversity measure was evaluated separately as fixed effect, with the *field* included as random effect and temporal autocorrelation structure (AR1) was incorporated. γ stability, spatial asynchrony, and species asynchrony were log_{10}-transformed in all models. Marginal (R^2_m) and conditional (R^2_c) r-squared values, as well as Akaike information criterion (AIC) scores, were reported. The best univariate models with the lowest AIC are highlighted in bold.

Dependent variables	Independent variables	Estimate	Std. Error	*t-values*	*P-values*	R_m^2	R_c^2	*AIC*
γ stability	γ_Richness	0.004	0.002	1.57	0.118	0.03	0.03	-216.17
	γ_Shannon	-0.006	0.007	-0.92	0.358	0.01	0.01	-216.69
	γ_Simpson	-0.012	0.009	-1.34	0.182	0.02	0.02	-218.15
	γ_MPD	0.009	0.007	1.25	0.211	0.02	0.02	-217.32
	$γ\_MPD_{ab}$	0.001	0.001	1.01	0.315	0.02	0.02	-213.10
	γ_MFD	**3.301**	**0.911**	**3.62**	**0.000**	**0.14**	**0.14**	**-237.74**
	$γ\_MFD_{ab}$	1.276	0.528	2.41	0.017	0.07	0.07	-230.22
Spatial asynchrony	Jaccard	0.806	0.385	2.09	0.037	0.05	0.05	-306.74
	Sørensen	0.623	0.320	1.95	0.052	0.04	0.04	-305.81
	Bray-Curtis	0.336	0.274	1.23	0.221	0.02	0.02	-303.29
	βMPD	0.004	0.002	2.07	0.040	0.06	0.06	-295.75
	$βMPD_{ab}$	0.001	0.001	1.44	0.151	0.03	0.03	-292.25
	βMFD	**1.720**	**0.464**	**3.71**	**0.000**	**0.15**	**0.15**	**-315.00**
	$βMFD_{ab}$	1.200	0.414	2.90	0.004	0.10	0.10	-310.48
α stability	α_Richness	0.032	0.031	1.05	0.296	0.01	0.01	120.60
	α_Shannon	0.007	0.068	0.11	0.914	0.00	0.00	120.01
	α_Simpson	-0.009	0.096	-0.09	0.928	0.00	0.00	119.31
	α_MPD	0.002	0.005	0.30	0.761	0.00	0.00	124.97
	$α\_MPD_{ab}$	0.001	0.003	0.33	0.745	0.00	0.00	125.94
	α_MFD	0.112	1.760	0.06	0.949	0.00	0.00	113.52
	$α\_MFD_{ab}$	0.355	1.765	0.20	0.841	0.00	0.00	113.47
	α_Richness	0.010	0.005	-0.86	0.048	0.02	0.02	-758.44

Species asynchrony	α_Shannon	0.046	0.011	-0.86	0.000	0.09	0.09	-771.38
	α_Simpson	0.064	0.016	-0.86	0.000	0.08	0.08	-771.92
	α_MPD	0.001	0.001	-0.86	0.520	0.00	0.00	-751.73
	α_MPD_{ab}	0.002	0.001	-0.86	0.006	0.03	0.03	-757.51
	α_MFD	**-1.643**	**0.321**	**-0.86**	**0.000**	**0.30**	**0.30**	**-782.71**
	α_MFD_{ab}	0.245	0.324	-0.86	0.450	0.00	0.00	-763.30
Species stability	α_Richness	-0.011	0.014	-0.78	0.439	0.00	0.00	-316.68
	α_Shannon	-0.108	0.029	-3.72	0.000	0.07	0.07	-330.11
	α_Simpson	-0.161	0.041	-3.95	0.000	0.07	0.07	-332.14
	α_MPD	0.000	0.003	-0.13	0.897	0.00	0.00	-312.93
	α_MPD_{ab}	-0.004	0.001	-2.53	0.012	0.02	0.02	-317.81
	α_MFD	**4.097**	**0.867**	**4.72**	**0.000**	**0.25**	**0.25**	**-341.97**
	α_MFD_{ab}	-0.712	0.832	-0.86	0.393	0.00	0.00	-324.99

Table S2. The best multivariate linear mixed-effects models predict the five temporal stability components across spatial scales. The best models were selected using Akaike Information Criteria corrected for small sample size (*AIC_C*). Note *Null* means only intercepts were included in the best model.

Dependent variables	Independent variables	Estimate	Std. Error	*t-values*	*P-values*	R_m^2	R_c^2	*AICc*	*VIF*
γ stability	γ_MFD	3.301	0.911	3.63	0.000	0.14	0.14	-237.5	-
Spatial asynchrony	βMFD	3.961	1.068	3.71	0.000	0.15	0.15	71.5	-
α stability	*Null*	-	-	-	-	0	0	111.7	-
Species asynchrony	α_MPD_{ab}	0.006	0.001	4.62	0.000	0.37	0.37	-415.2	1.15
	α_MFD	-5.053	0.764	-6.61	0.000				1.15
Species stability	α_Richness	0.027	0.014	1.90	0.058	0.34	0.34	-361.9	1.33
	α_MPD_{ab}	-0.008	0.002	-4.77	0.000				1.49
	α_MFD	6.160	0.928	6.64	0.000				1.31