Ecosphere

MACROSYSTEMS ECOLOGY

Spatial turnover of multiple ecosystem functions is more associated with plant than soil microbial β-diversity

Xin Jing, Case, M. Prager, Elizabeth T. Borer, Nicholas J. Gotelli, Daniel S. Gruner, Jin-Sheng He, Kevin Kirkman, Andrew S. MacDougall, Rebecca L. McCulley, Suzanne M. Prober, Eric W. Seabloom, Carly J. Stevens, Aimée T. Classen, Nathan J. Sanders

Appendix S1

Supporting information

Fig. S1 Nutrient Network sites sampled for this study. A total of 18 sites were used in this study. Points represent the sampling sites. Details of the study locations and site code are given in Table S1.

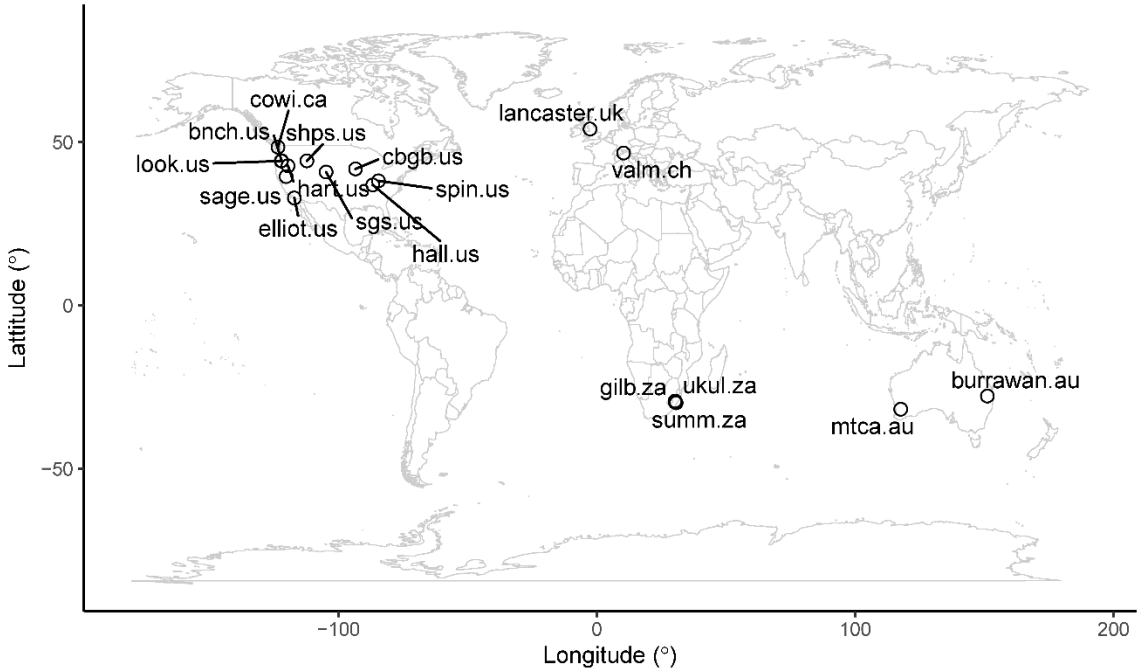

Fig. S2 Sensitivity analysis for the number of functions. All combinations of the six single ecosystem functions are considered that are indicated by the points. Mantel coefficient (r) denotes the Spearman's correlation coefficient (rho). Bivariate associations between plant β-diversity and spatial turnover in multiple ecosystem functions are given.

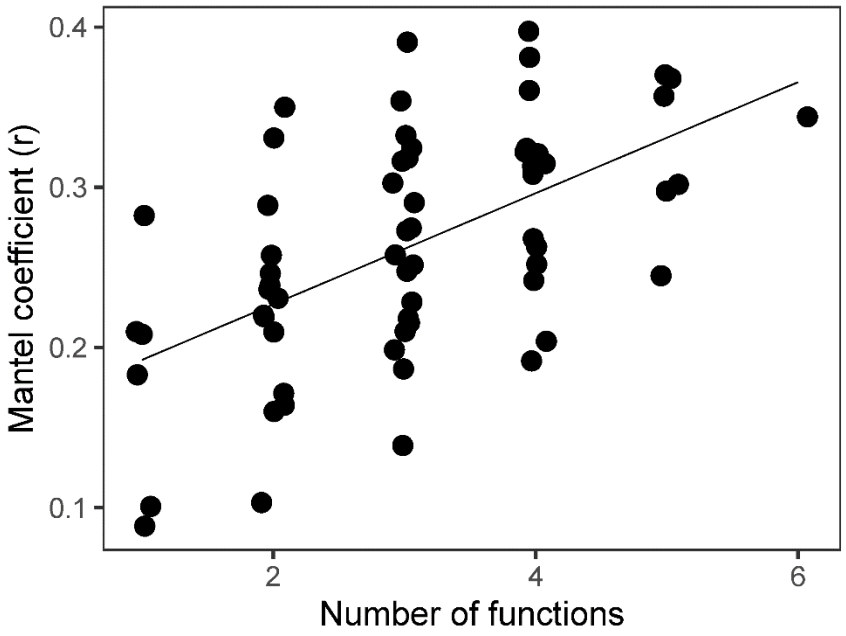

Fig. S3 Conceptual structural equation model representing the effects of geographic distance, environmental distance and above- and belowground β-diversity on spatial turnover in multiple ecosystem functions. Double-headed arrows represent residual correlations. Note that soil pH distance was initially included in the conceptual model but was removed in the final model. See details in the methods section.

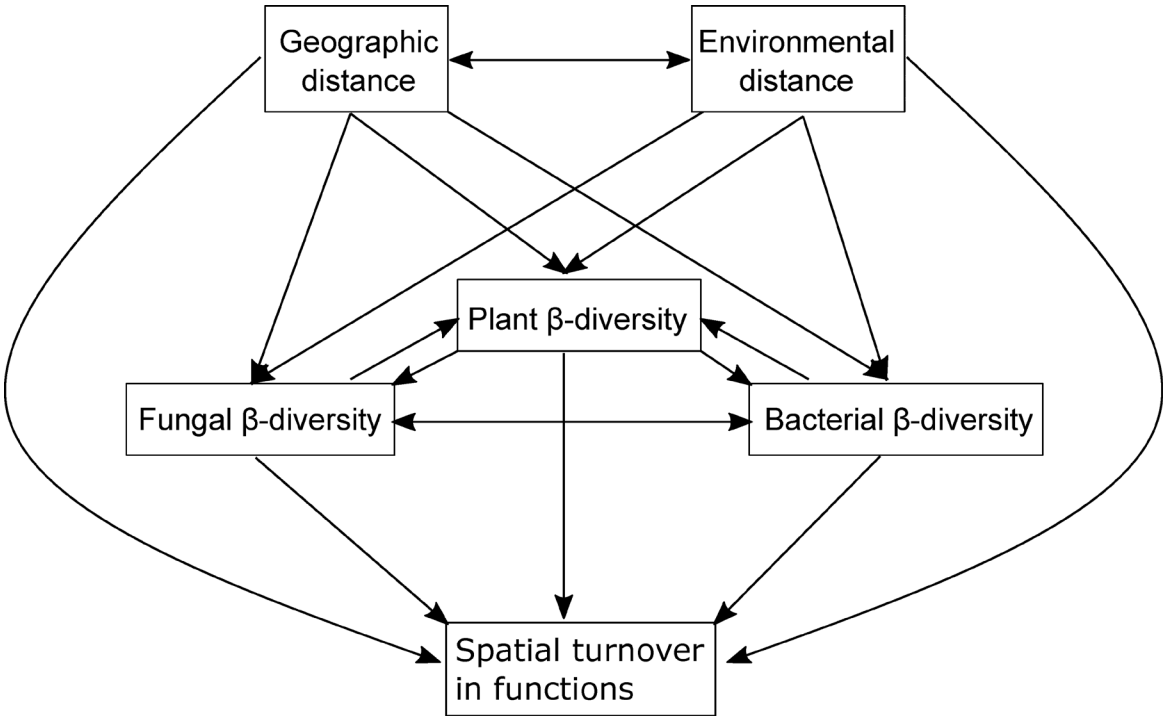

Table S1 Geographic locations of the 18 grassland sites.

Site name	Site code	Continent	Country	Ecosystem	# plots	Latitude	Longitude
Bunchgrass	bnch.us	North America	USA	Montane grassland	3	44.3	-122.0
Burrawan	burrawan.au	Australasia	Australia	Semiarid grassland	2	-27.7	151.1
Chichaqua Bottoms	cbgb.us	North America	USA	Tallgrass prairie	3	41.8	-93.4
Cowichan	cowi.ca	North America	Canada	Old field	1	48.5	-123.4
Elliott Chaparral	elliot.us	North America	USA	Annual grassland	3	32.9	-117.1
Mt. Gilboa	gilb.za	Africa	South Africa	Montane grassland	3	-29.3	30.3
Hall's Prairie	hall.us	North America	USA	Tallgrass prairie	3	36.9	-86.7
Hart Mountain	hart.us	North America	USA	Shrub steppe	3	42.7	-119.5
Lancaster	lancaster.uk	Europe	UK	Mesic grassland	3	54.0	-2.6
Lookout	look.us	North America	USA	Montane grassland	2	44.2	-122.1
Mt. Caroline	mtca.au	Australasia	Australia	Savanna	3	-31.8	117.6
Sagehen Creek	sage.us	North America	USA	Montane grassland	2	39.4	-120.2
Shortgrass Steppe	sgs.us	North America	USA	Shortgrass prairie	3	40.8	-104.8
Sheep Experimental Station	shps.us	North America	USA	Shrub steppe	3	44.2	-112.2
Spindletop	spin.us	North America	USA	Pasture	1	38.1	-84.5
Summerveld	summ.za	Africa	South Africa	Mesic grassland	3	-29.8	30.7
Ukulinga	ukul.za	Africa	South Africa	Mesic grassland	5	-29.7	30.4
Val Mustair	valm.ch	Europe	Switzerland	Alpine grassland	1	46.6	10.4

Table S2 Sensitivity analysis for β-diversity indices. Five β-diversity indices are compared including Sorensen index, the replacement and richness difference of Sorensen index, Horn index and Morisita-Horn index. Mantel r, Spearman correlation coefficient; pval1, one-tailed P value (null hypothesis, H0: r <= 0); pval2, one-tailed P value (H0: r >= 0); pval3, two-tailed P value (H0: r = 0); llim, lower confidence interval; ulim, upper confidence interval. Note the sensitivity analysis indicates that there are no significant differences among the Spearman correlation coefficients of Sorensen index, Horn index and Morisita-Horn index. This result suggests that the relationships between β-diversity and spatial turnover in multiple ecosystem functions are not sensitive to changes in the relative weights on rare vs. common species (see Methods section for the rationale of the different β-diversity indices).

Organism	Index	Mantel r	pval1	pval2	pval3	llim	ulim
Plant	Sorensen	0.34	0.000	1.000	0.000	0.29	0.41
	Replacement	0.12	0.064	0.936	0.142	0.06	0.18
	Richness difference	0.11	0.074	0.926	0.126	0.05	0.17
	Horn	0.35	0.000	1.000	0.000	0.29	0.42
	Morisita-Horn	0.34	0.000	1.000	0.000	0.28	0.40
Bacteria	Sorensen	0.22	0.004	0.996	0.004	0.17	0.29
	Replacement	0.17	0.001	0.999	0.001	0.12	0.22
	Richness difference	0.04	0.214	0.786	0.453	-0.01	0.09
	Horn	0.21	0.002	0.998	0.002	0.16	0.26
	Morisita-Horn	0.19	0.005	0.995	0.006	0.13	0.25
Fungi	Sorensen	0.24	0.003	0.997	0.003	0.18	0.31

	Replacement	0.07	0.149	0.852	0.296	0.02	0.13
	Richness difference	0.06	0.212	0.788	0.433	-0.00	0.12
	Horn	0.15	0.029	0.972	0.042	0.11	0.20
	Morisita-Horn	0.06	0.223	0.777	0.449	0.02	0.10

Table S3 Simple and partial Mantel tests for the bivariate associations between spatial turnover in multiple ecosystem functions and above- and belowground β-diversity. Xs are one of groups of β-diversity (*i.e.*, plant, bacterial and fungi). Geo, geographic distance; Clim, climatic distance; pH, pH distance. Mantel r, Spearman correlation coefficient; pval1, one-tailed P value (null hypothesis, H0: r <= 0); pval2, one-tailed P value (H0: r >= 0); pval3, two-tailed P value (H0: r = 0); llim, lower confidence interval; ulim, upper confidence interval.

Function	Organism	Variable	Mantel r	pval1	pval2	pval3	llim	ulim
Aboveground plant biomass	Plant	X	0.21	0.003	0.997	0.003	0.15	0.27
		X|Geo	0.15	0.034	0.966	0.047	0.08	0.21
		X|Clim	0.20	0.006	0.994	0.006	0.14	0.26
		X|pH	0.22	0.002	0.998	0.002	0.15	0.28
		X|Geo+Clim	0.15	0.034	0.966	0.047	0.09	0.21
		X|Geo+pH	0.15	0.031	0.969	0.044	0.09	0.20
		X|Clim+pH	0.21	0.006	0.994	0.006	0.15	0.27
		X|Geo+Clim+pH	0.15	0.031	0.970	0.042	0.09	0.22
	Bacteria	X	0.12	0.055	0.945	0.087	0.06	0.18
		X|Geo	0.00	0.467	0.533	0.974	-0.04	0.05
		X|Clim	0.11	0.088	0.912	0.173	0.05	0.17
		X|pH	0.16	0.026	0.974	0.030	0.10	0.24
		X|Geo+Clim	0.01	0.434	0.566	0.896	-0.04	0.06
		X|Geo+pH	0.05	0.226	0.775	0.464	-0.01	0.11
		X|Clim+pH	0.14	0.051	0.949	0.081	0.09	0.20
		X|Geo+Clim+pH	0.05	0.242	0.758	0.505	-0.01	0.10
	Fungi	X	0.17	0.021	0.979	0.024	0.09	0.24
		X|Geo	0.06	0.199	0.801	0.400	0.00	0.12
		X|Clim	0.16	0.036	0.964	0.055	0.09	0.22
		X|pH	0.18	0.015	0.986	0.016	0.10	0.27
		X|Geo+Clim	0.07	0.193	0.807	0.386	0.00	0.13
		X|Geo+pH	0.08	0.152	0.848	0.300	0.01	0.15
		X|Clim+pH	0.17	0.034	0.966	0.048	0.09	0.24
		X|Geo+Clim+pH	0.08	0.168	0.833	0.328	0.00	0.13
Plant nitrogen	Plant	X	0.10	0.053	0.948	0.071	0.05	0.16
		X|Geo	0.04	0.239	0.761	0.492	-0.02	0.10
		X|Clim	0.06	0.173	0.827	0.361	0.01	0.11
		X|pH	0.10	0.064	0.937	0.099	0.05	0.15
		X|Geo+Clim	0.04	0.255	0.745	0.539	-0.04	0.09

		X|Geo+pH	0.04	0.254	0.746	0.523	-0.01	0.10
		X|Clim+pH	0.06	0.183	0.817	0.375	0.00	0.11
		X|Geo+Clim+pH	0.04	0.250	0.751	0.533	-0.02	0.09
	Bacteria	X	0.01	0.430	0.570	0.916	-0.03	0.06
		X|Geo	-0.11	0.985	0.015	0.048	-0.15	-0.07
		X|Clim	-0.14	0.985	0.015	0.042	-0.20	-0.08
		X|pH	-0.03	0.633	0.367	0.684	-0.07	0.03
		X|Geo+Clim	-0.20	1.000	0.000	0.002	-0.24	-0.16
		X|Geo+pH	-0.15	0.998	0.002	0.010	-0.19	-0.11
		X|Clim+pH	-0.13	0.985	0.015	0.050	-0.20	-0.06
		X|Geo+Clim+pH	-0.20	1.000	0.000	0.002	-0.24	-0.15
	Fungi	X	0.06	0.175	0.825	0.363	0.01	0.12
		X|Geo	-0.05	0.776	0.224	0.427	-0.09	-0.01
		X|Clim	-0.05	0.755	0.245	0.477	-0.11	0.02
		X|pH	0.04	0.233	0.767	0.504	0.00	0.10
		X|Geo+Clim	-0.10	0.947	0.053	0.132	-0.15	-0.05
		X|Geo+pH	-0.06	0.835	0.165	0.342	-0.11	-0.02
		X|Clim+pH	-0.05	0.748	0.253	0.484	-0.11	0.01
		X|Geo+Clim+pH	-0.10	0.944	0.056	0.134	-0.15	-0.06
Plant phosphorus	Plant	X	0.28	0.000	1.000	0.000	0.23	0.34
		X|Geo	0.24	0.001	0.999	0.001	0.18	0.29
		X|Clim	0.27	0.000	1.000	0.000	0.22	0.33
		X|pH	0.28	0.000	1.000	0.000	0.23	0.33
		X|Geo+Clim	0.24	0.001	0.999	0.001	0.19	0.30
		X|Geo+pH	0.24	0.001	0.999	0.001	0.18	0.29
		X|Clim+pH	0.27	0.000	1.000	0.000	0.22	0.33
		X|Geo+Clim+pH	0.24	0.000	1.000	0.000	0.18	0.29
	Bacteria	X	0.03	0.302	0.698	0.644	-0.01	0.07
		X|Geo	-0.10	0.968	0.032	0.080	-0.12	-0.07
		X|Clim	-0.01	0.521	0.479	0.924	-0.05	0.04
		X|pH	0.01	0.413	0.587	0.880	-0.03	0.06
		X|Geo+Clim	-0.11	0.964	0.036	0.079	-0.14	-0.07
		X|Geo+pH	-0.12	0.986	0.014	0.040	-0.16	-0.09
		X|Clim+pH	-0.01	0.549	0.451	0.860	-0.05	0.03
		X|Geo+Clim+pH	-0.12	0.985	0.015	0.044	-0.16	-0.09
	Fungi	X	0.08	0.119	0.881	0.220	0.03	0.14
		X|Geo	-0.04	0.726	0.274	0.533	-0.08	0.01
		X|Clim	0.05	0.220	0.780	0.459	0.00	0.10
		X|pH	0.07	0.141	0.859	0.288	0.02	0.12
		X|Geo+Clim	-0.04	0.741	0.259	0.509	-0.10	0.00
		X|Geo+pH	-0.04	0.747	0.253	0.485	-0.08	0.01
		X|Clim+pH	0.05	0.233	0.767	0.475	0.01	0.11
		X|Geo+Clim+pH	-0.05	0.748	0.252	0.477	-0.09	0.00

Root biomass	Plant	X	0.09	0.119	0.881	0.224	0.04	0.15
		X|Geo	0.04	0.286	0.715	0.599	-0.01	0.10
		X|Clim	0.08	0.148	0.852	0.294	0.03	0.15
		X|pH	0.09	0.109	0.891	0.207	0.04	0.15
		X|Geo+Clim	0.04	0.287	0.713	0.611	-0.01	0.10
		X|Geo+pH	0.04	0.283	0.717	0.590	-0.01	0.10
		X|Clim+pH	0.08	0.149	0.851	0.291	0.03	0.14
		X|Geo+Clim+pH	0.04	0.285	0.715	0.599	-0.01	0.10
	Bacteria	X	0.17	0.020	0.980	0.025	0.09	0.24
		X|Geo	0.12	0.060	0.940	0.104	0.06	0.17
		X|Clim	0.16	0.042	0.958	0.072	0.07	0.24
		X|pH	0.19	0.018	0.982	0.019	0.12	0.27
		X|Geo+Clim	0.12	0.071	0.929	0.127	0.05	0.18
		X|Geo+pH	0.15	0.029	0.972	0.047	0.09	0.21
		X|Clim+pH	0.18	0.031	0.969	0.045	0.08	0.26
		X|Geo+Clim+pH	0.14	0.042	0.958	0.067	0.07	0.22
	Fungi	X	0.11	0.095	0.905	0.169	0.05	0.17
		X|Geo	0.04	0.281	0.719	0.598	0.00	0.10
		X|Clim	0.10	0.143	0.857	0.282	0.02	0.18
		X|pH	0.12	0.089	0.911	0.161	0.05	0.18
		X|Geo+Clim	0.04	0.303	0.697	0.626	-0.01	0.09
		X|Geo+pH	0.05	0.267	0.733	0.555	0.00	0.10
		X|Clim+pH	0.10	0.134	0.866	0.276	0.02	0.16
		X|Geo+Clim+pH	0.05	0.276	0.724	0.595	-0.01	0.10
Soil total nitrogen	Plant	X	0.18	0.008	0.992	0.008	0.13	0.24
		X|Geo	0.15	0.029	0.971	0.037	0.09	0.20
		X|Clim	0.15	0.024	0.976	0.026	0.11	0.22
		X|pH	0.17	0.012	0.988	0.012	0.12	0.23
		X|Geo+Clim	0.15	0.032	0.968	0.044	0.08	0.21
		X|Geo+pH	0.14	0.031	0.969	0.041	0.09	0.21
		X|Clim+pH	0.15	0.023	0.977	0.027	0.10	0.22
		X|Geo+Clim+pH	0.14	0.030	0.970	0.041	0.10	0.20
	Bacteria	X	0.18	0.009	0.991	0.010	0.12	0.23
		X|Geo	0.13	0.028	0.972	0.039	0.08	0.18
		X|Clim	0.10	0.104	0.896	0.201	0.01	0.17
		X|pH	0.13	0.052	0.948	0.072	0.07	0.19
		X|Geo+Clim	0.09	0.115	0.885	0.218	0.03	0.14
		X|Geo+pH	0.08	0.112	0.888	0.219	0.02	0.14
		X|Clim+pH	0.08	0.156	0.844	0.317	0.01	0.17
		X|Geo+Clim+pH	0.06	0.185	0.815	0.377	-0.01	0.13
	Fungi	X	0.13	0.045	0.955	0.064	0.08	0.18
		X|Geo	0.07	0.158	0.843	0.324	0.01	0.12
		X|Clim	0.06	0.230	0.770	0.455	0.00	0.14

		X|pH	0.11	0.085	0.915	0.145	0.06	0.15
		X|Geo+Clim	0.04	0.284	0.716	0.589	-0.02	0.10
		X|Geo+pH	0.05	0.228	0.772	0.473	-0.01	0.11
		X|Clim+pH	0.06	0.224	0.776	0.469	-0.01	0.13
		X|Geo+Clim+pH	0.04	0.301	0.699	0.629	-0.04	0.10
Extractable soil phosphorus	Plant	X	0.21	0.001	0.999	0.001	0.13	0.25
		X|Geo	0.19	0.006	0.994	0.006	0.11	0.23
		X|Clim	0.18	0.005	0.995	0.005	0.11	0.23
		X|pH	0.20	0.002	0.998	0.002	0.13	0.25
		X|Geo+Clim	0.19	0.006	0.994	0.006	0.11	0.23
		X|Geo+pH	0.18	0.006	0.994	0.007	0.10	0.24
		X|Clim+pH	0.19	0.005	0.996	0.005	0.11	0.23
		X|Geo+Clim+pH	0.18	0.005	0.995	0.006	0.08	0.23
	Bacteria	X	0.02	0.339	0.661	0.718	-0.03	0.07
		X|Geo	-0.05	0.810	0.190	0.384	-0.09	-0.01
		X|Clim	-0.07	0.825	0.175	0.344	-0.10	-0.03
		X|pH	-0.09	0.925	0.075	0.178	-0.12	-0.04
		X|Geo+Clim	-0.10	0.957	0.043	0.104	-0.14	-0.06
		X|Geo+pH	-0.17	0.999	0.001	0.004	-0.20	-0.14
		X|Clim+pH	-0.12	0.971	0.029	0.076	-0.15	-0.09
		X|Geo+Clim+pH	-0.19	1.000	0.000	0.002	-0.22	-0.15
	Fungi	X	0.05	0.201	0.799	0.406	0.01	0.11
		X|Geo	-0.01	0.554	0.446	0.838	-0.06	0.04
		X|Clim	-0.01	0.561	0.439	0.846	-0.06	0.03
		X|pH	0.01	0.405	0.595	0.873	-0.03	0.06
		X|Geo+Clim	-0.04	0.721	0.279	0.522	-0.09	0.01
		X|Geo+pH	-0.05	0.770	0.231	0.452	-0.09	0.00
		X|Clim+pH	-0.02	0.585	0.415	0.790	-0.06	0.03
		X|Geo+Clim+pH	-0.06	0.817	0.184	0.363	-0.11	-0.02

Table S4 Summary of the structural equation model that plant β-diversity affects soil microbial β-diversity.

Response	Predictor	Estimate	SE	Z	P
Turnover in function	Plant β-diversity	0.28	0.033	8.59	<0.001
Turnover in function	Fungal β-diversity	0.12	0.036	3.32	0.001
Plant β-diversity	Geographic distance	0.31	0.023	13.40	<0.001
Plant β-diversity	Climatic distance	0.29	0.038	7.57	<0.001
Bacterial β-diversity	Geographic distance	0.47	0.022	21.82	<0.001
Bacterial β-diversity	Climatic distance	0.24	0.022	10.93	<0.001
Bacterial β-diversity	Plant β-diversity	0.22	0.026	8.53	<0.001
Fungal β-diversity	Geographic distance	0.36	0.016	21.76	<0.001
Fungal β-diversity	Climatic distance	0.17	0.019	8.96	<0.001
Fungal β-diversity	Plant β-diversity	0.47	0.044	10.59	<0.001

Table S5 Summary of the structural equation model that soil microbial β-diversity affects plant β-diversity.

Response	Predictor	Estimate	SE	Z	P
Turnover in function	Plant β-diversity	0.29	0.033	8.62	<0.001
Turnover in function	Fungal β-diversity	0.12	0.037	3.25	0.001
Plant β-diversity	Climatic distance	0.10	0.029	3.47	0.001
Plant β-diversity	Fungal β-diversity	0.63	0.042	14.82	<0.001
Bacterial β-diversity	Geographic distance	0.54	0.021	26.46	<0.001
Bacterial β-diversity	Climatic distance	0.31	0.023	13.13	<0.001
Fungal β-diversity	Geographic distance	0.50	0.020	25.42	<0.001
Fungal β-diversity	Climatic distance	0.31	0.029	10.36	<0.001

Table S6 Authorship contribution table.

Name	Site(s) coordinated	Developed and framed research question(s)	Analyzed data	Contributed to data analyses	Wrote the paper	Contributed to paper writing	Site coordinator	Nutrient Network coordinator
Xin Jing		X	X	X	X	X		
Case Prager		X		X		X		
Elizabeth Borer	bnch.us, look.us	X				X	X	X
Nicholas Gotelli		X		X		X		
Jin-Sheng He		X				X		
Daniel Gruner	sage.us					X	X	
Kevin Kirkman	ukul.za					X	X	
Andrew MacDougall	cowi.ca					X	X	
Rebecca McCulley	hall.us, spin.us					X	X	
Suzanne M Prober[#]	mtca.au					X	X	
Eric W Seabloom	bnch.us, look.us					X	X	X
Carly Stevens	lancaster.uk					X	X	
Aimee Classen		X				X		
Nathan Sanders		X		X		X		

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