Supplementary Material

Supplementary Table S1 Initial soil conditions in the study area

Soil physicochemical properties	Soil sample area		
	PT	PE	MP
pH	8.42	8.37	8.47
Bulk density ($g \cdot cm^{-3}$)	1.51	1.49	1.53
Organic matter ($g \cdot kg^{-1}$)	0.33	0.34	0.31
Total N ($g \cdot kg^{-1}$)	0.22	0.22	0.21
Olsen P ($mg \cdot kg^{-1}$)	0.77	0.73	0.74
Sand fraction (%)	14.24	13.75	13.92
Pb ($mg \cdot kg^{-1}$)	17.63	18.27	17.91
Cr ($mg \cdot kg^{-1}$)	42.32	43.18	41.86
As ($mg \cdot kg^{-1}$)	5.76	5.83	5.62
Cd ($mg \cdot kg^{-1}$)	0.82	0.77	0.76
Hg ($mg \cdot kg^{-1}$)	0.02	0.02	0.02
Cu ($mg \cdot kg^{-1}$)	0.03	0.03	0.03

Supplementary Table S2 The values and variable composition of composite indicators in structural equation models

Sample	Soil Enzymes	Soil	Plant	Fungi	Bacteria
Component variable	ALP, URE	SOM, TN, AP	Coverage, Number of species	Shannon, Abundance	Shannon, Abundance
Proportion of Variance	0.7372	0.6324	0.9828	0.507	0.5046
PT1	-1.0622542	-0.764399	-1.5457302	-0.46632	-1.77383163
PT2	-0.5536781	-0.4187709	-1.5457302	0.554702	0.50317633
PT3	-1.0728145	-0.524898	-1.5457302	-2.29672	-2.05299645
PT4	-0.9105191	-0.3325244	-1.5457302	-0.53155	-1.0036402
PT5	-1.8602127	-1.0174871	-1.5457302	0.386097	0.81534434
PT6	-0.825537	-0.5110361	-1.5457302	0.49941	0.73773282
PT7	-0.9747671	-0.5750926	-1.5457302	0.55675	0.47979423
PT8	-1.0761779	-1.0157962	-1.5457302	0.720234	-0.94336152
PT9	-0.8697817	-0.6206457	-1.5457302	0.243877	-2.37527504
PT10	-0.7216052	-0.9085701	-1.5457302	0.667175	-0.23592027
PE1	-1.0611567	-0.6810541	-0.2557803	0.872505	-0.59900984
PE2	1.4135409	-0.5209737	-0.2557803	0.424383	-0.32029677
PE3	0.5621387	-0.1139432	-0.2557803	0.87234	0.50891921
PE4	2.4229371	0.471443	-0.2557803	1.029718	0.43192308
PE5	-0.8083037	-0.6321893	-0.2557803	-1.04102	0.53120307
PE6	-0.5510765	-0.5029373	-0.2557803	-2.80881	-0.36904091
PE7	0.1735269	-0.2214357	-0.2557803	0.558756	1.41040281
PE8	0.7133893	-0.4637172	-0.2557803	0.897091	-0.30969118
PE9	-1.1850799	-0.5524263	-0.2557803	0.534911	-1.50959475
PE10	-0.3923194	-0.5796243	-0.2557803	1.358102	0.58733033

MP1	2.6406608	6.3109388	1.8015105	1.148199	1.11705435
MP2	0.1967972	0.4513045	1.8015105	0.739324	1.01662457
MP3	1.5626421	2.3253341	1.8015105	-1.23669	0.72175389
MP4	2.6348095	0.5734173	1.8015105	-0.66738	0.77937118
MP5	0.5559363	0.3043187	1.8015105	-2.5506	0.56760131
MP6	0.2394238	0.9231766	1.8015105	-1.02104	-0.09755343
MP7	0.1382172	-0.2029917	1.8015105	-0.56184	-0.62034318
MP8	1.241235	0.6048891	1.8015105	-0.43733	1.31460273
MP9	0.4106077	-0.2675937	1.8015105	0.457674	0.84154205
MP10	-0.9805788	-0.513777146	1.8015105	1.098051	-0.15382111

More information could be found in tables in Supplementary Material.

Supplementary Table S3 The values and variable composition of composite indicators in structural equation models

Specificmodel								
Path			Estimate	S.E.	C.R.	P	Label	Weights
SOM	<---	PPO	0	0	-3.417	***	par_1	-0.352
SOM	<---	CAT	-0.021	0.007	-3.185	0.001	par_10	-0.31
SOM	<---	URE	0.069	0.017	4.096	***	par_11	0.53
NN	<---	ALP	0.043	0.012	3.576	***	par_12	0.385
NN	<---	URE	18.826	5.354	3.516	***	par_13	0.486
AN	<---	URE	-34.01	10.645	-3.195	0.001	par_14	-0.49
AN	<---	FDA	0.586	0.238	2.46	0.014	par_15	0.364
AP	<---	BG	0.031	0.008	4.025	***	par_16	0.52
Coverage	<---	SOM	458.869	222.436	2.063	0.039	par_2	0.238
Species	<---	SOM	84.519	40.692	2.077	0.038	par_3	0.234
Coverage	<---	AN	-1.36	0.401	-3.391	***	par_4	-0.375
Coverage	<---	NN	3.316	0.782	4.243	***	par_5	0.509
Species	<---	AP	-0.408	0.111	-3.682	***	par_6	-0.389
Coverage	<---	AP	-1.77	0.608	-2.91	0.004	par_7	-0.316
Species	<---	AN	-0.219	0.073	-2.987	0.003	par_27	-0.322
Species	<---	NN	0.646	0.141	4.594	***	par_28	0.531
Fungi	<---	Coverage	0.014	0.012	1.156	0.248	par_8	0.212
Bac_shannon	<---	Species	0.016	0.007	2.235	0.025	par_9	0.471
Framework model								
Fungi	<---	Plant	-0.141	0.154	-0.915	0.36	par_1	-0.177
Soil Enzymes	<---	Fungi	-0.01	0.192	-0.055	0.956	par_2	-0.01
Soil	<---	Soil Enzymes	0.724	0.158	4.577	***	par_3	0.639
Soil Enzymes	<---	Bacteria	0.473	0.214	2.203	0.028	par_4	0.391
Bacteria	<---	Plant	0.261	0.126	2.064	0.039	par_5	0.364
Plant	<---	Soil	0.48	0.167	2.868	0.004	par_7	0.472

More information could be found in tables in Supplementary Material.

Supplementary Table S4 Vegetation characteristics aroundeach sample point

Samples	Coverage	Arbor	DHB	Species

PT1	31.16	16.82	7.57	5
PT2	34.62	13.82	7.55	4
PT3	34.43	16.45	6.96	4
PT4	37.65	16.49	7.37	5
PT5	39.26	12.28	7.59	5
PT6	38.72	17.39	7.24	5
PT7	33.79	16.16	7.48	5
PT8	30.82	12.10	6.99	5
PT9	37.17	12.12	7.58	5
PT10	30.33	13.25	6.91	4
PE1	61.13	27.01	9.56	7
PE2	66.33	21.02	8.97	9
PE3	63.28	26.03	9.13	9
PE4	61.42	27.11	9.22	9
PE5	64.49	20.61	8.93	8
PE6	67.59	25.93	9.16	7
PE7	64.61	20.32	9.32	9
PE8	68.32	24.20	8.96	9
PE9	60.07	23.34	8.83	9
PE10	69.67	24.62	9.05	9
MP1	96.49	39.10	11.38	16
MP2	91.75	37.34	10.95	15
MP3	92.18	39.28	11.49	16
MP4	97.64	32.75	10.99	16
MP5	99.08	32.23	11.27	14
MP6	93.38	33.53	10.89	13
MP7	98.01	33.24	11.44	16
MP8	97.02	38.69	11.45	16
MP9	93.86	32.72	11.21	15
MP10	95.94	33.12	11.56	16

Note: Coverage represents the average vegetation coverage. DBH (diameter at breast height) represents the diameter at the breast height (1.3 m) of the trees. Arbor represents the number of trees in the survey square, including *Pinus tabulaeformis*, *Ulmus pumila*, *Robinia pseudoacacia*, and *Salix cheilophila*. Species represents the number of plant species in all survey plots in the area.

Supplementary Table S5 Soil physical and chemical properties and enzyme activities of three plantations with different types of secondary succession

Soil physicochemical properties	Soil sample position		
	PT	PE	MP
pH	8.12 ± 0.06a	8.06 ± 0.13a	8.04 ± 0.17a
EC ($ms \cdot cm^{-3}$)	179.1 ± 25.4a	208.0 ± 74.2a	188.5 ± 39.5a
ST (℃)	29.72 ± 2.02a	25.89 ± 0.89b	22.9 ± 1.31c
SWC (%)	8.69 ± 1.44a	9.84 ± 3.95b	11.53 ± 2.45c
AN ($mg \cdot kg^{-1}$)	15.71 ± 9.23a	7.98 ± 2.74b	7.19 ± 2.49b

NN ($mg \cdot kg^{-1}$)	2.81 ± 1.13a	6.17 ± 3.37b	8.47 ± 4.14c
AP ($mg \cdot kg^{-1}$)	8.57 ± 2.89a	12.49 ± 5.51b	7.3 ± 2.56a
TN ($g \cdot kg^{-1}$)	0.38 ± 0.11a	0.46 ± 0.25b	1.01 ± 0.78c
SOM ($g \cdot kg^{-1}$)	9.30 ± 3.00a	13.70 ± 4.90b	21.13 ± 1.30c
CAT ($mg\ (g\ min)^{-1}$)	0.70± 0.19a	0.79 ± 0.17a	0.66 ± 0.23a
DHA ($mg\ (g\ h)^{-1}$)	7.25 ± 5.54a	5.18 ± 4.69a	6.71 ± 6.00a
FDA ($ug\ (g \cdot min)^{-1}$)	10.91 ± 3.74a	8.86 ± 4.92b	8.24 ± 4.17b
ALP ($mg\ (g\ 24h)^{-1}$)	123.2 ± 69.1a	132.7 ± 88.5b	136.3 ± 79.1b
PPO ($ug\ (g \cdot 2h)^{-1}$)	267.8 ± 73.1a	279.8 ± 68.8a	137.8 ± 91.5b
URE ($mg\ (g \cdot 24h)^{-1}$)	0.085 ± 0.032a	0.197 ± 0.067b	0.230 ± 0.108c
BG ($ug\ (g \cdot h)^{-1}$)	75.47 ± 12.01a	90.61 ± 50.58b	115.94 ± 23.35c

Note: Data are presented as mean ± standard deviation. Values in the same row with the same letter(s) are not significantly different as per the Duncan analysis at $P < 0.05$ between different treatments. EC, electrical conductivity; ST, soil temperature; SWC, soil water content; AN, ammonium nitrogen; NN, nitrate nitrogen; AP, available phosphorus; TN, total nitrogen; SOM, soil organic matter; CAT, catalase; DHA, dehydrogenase; FDA, fluorescein diacetate; ALP, alkaline phosphatase ;PPO, polyphenol oxidase; URA, urease; BG, beta glucosidase.

Supplementary Table S6ASV data of soil bacteria from each sample

Supplementary Table S7 ASV data of soil fungi from each sample

Supplementary Table S8 Enzyme function gene data of soil microbes from each sample

Note: Thedata volumeof**Supplementary Table S6-S8**is too large, please check it in the attached xlsx filein**Supplementary Material.**