Supplementary Materials S1. Calculation of plant community indices

Vegetation coverage was calculated as the proportion of ground area covered by live plant canopy:

$$C = \frac{\sum_{i=1}^{n} A_i}{A} \times 100\%$$

Where A_i is the canopy-covered area of species *i*, *A* is the total area of the quadrat.

Mean plant height was calculated as the arithmetic mean of individual plant heights measured within each quadrat:

$$\bar{H} = \frac{1}{n}\sum_{i=1}^{n} h_i$$

Where h_j is the height of the *j*-th plant, m is the total number of measured individuals.

Species richness was defined as the total number of plant species recorded within each quadrat:

$$S = n$$

Where n is the number of plant species observed in the quadrat.

The Shannon–Wiener diversity index was calculated as:

$$H = -\sum_{i=1}^{S} p_i \ln\ p_i$$

Where p_i is the proportion of species *i* based on coverage or abundance.

Simpson dominance index was calculated as:

$$D = \sum_{i=1}^{S} p_i^2$$

Where p_i is the relative coverage of species *i*.

Pielou evenness index was calculated as:

$$J_{sw} = \frac{H}{\ln S}$$

Where H is the Shannon–Wiener diversity index, S is species richness.

Whittaker β-diversity index was used to describe species turnover among quadrats within the same restoration stage:

$$B = \frac{S_T}{\bar{S}} - 1$$

Where S_T is the total number of species recorded across all quadrats within a restoration stage, $\bar{S}$ is the mean species richness per quadrat.

Supplementary Materials S2. Calculation of soil aggregate stability indices

Aggregate size fractions used in the calculations were > 2 mm, 2–0.25 mm, 0.25–0.053 mm, and < 0.053 mm. For the < 0.053 mm fraction, the representative diameter was set to 0.0265 mm. All calculations were based on oven-dried aggregate mass.

The mean weight diameter (MWD) was calculated to characterize the overall stability of water-stable soil aggregates as:

$$\mathrm{MWD} = \sum_{i=1}^{n} x_i \ w_i$$

where x_i(mm) is the mean diameter of the *i*th aggregate size fraction, calculated as the arithmetic mean of the upper and lower sieve sizes, and $w_i$is the mass proportion of aggregates in the *i*th size fraction relative to the total sample mass. A higher MWD indicates greater soil aggregate stability.

The geometric mean diameter (GMD) was calculated to describe the central tendency of aggregate size distribution:

$$\mathrm{GMD} = \exp\left(\sum_{i=1}^{n} w_i \ln x_i\right)$$

where $x_i$and $w_i$are defined as above. GMD is less influenced by extreme aggregate sizes than MWD and provides a complementary measure of soil structural stability.

The fractal dimension (D) of soil aggregates was calculated based on the mass–size distribution of water-stable aggregates according to the fractal theory:

$$\frac{M(r < R_i)}{M_T} = \left(\frac{R_i}{R_{\max}}\right)^{3-D}$$

where $M(r < R_i)$is the cumulative mass of aggregates with particle size smaller than R_i, $M_T$is the total mass of all aggregates, $R_i$is the mean diameter of the *i*th aggregate size fraction, and $R_{\max}$is the maximum aggregate diameter. The fractal dimension (D) was obtained from the slope of the linear regression between $\log[M(r < R_i)/M_T]$and $\log(R_i/R_{\max})$. Higher D values indicate a more fragmented and unstable aggregate structure.

The aggregate destruction rate (R) was calculated to quantify the susceptibility of soil

aggregates to water-induced breakdown:

$$R = \left(\frac{M_{dry} - M_{wet}}{M_{dry}} \right) \times 100\%$$

where $M_{dry}$is the proportion of macroaggregates (> 0.25 mm) obtained by dry sieving, and $M_{wet}$is the proportion of macroaggregates (> 0.25 mm) obtained by wet sieving. A higher R value indicates greater aggregate destruction and lower soil structural stability.

Table S1 Geographic features of the sampling sites.

Restoration period	Northern latitude	East longitude	Elevation （m）	Exposure	Slope(°)
R1	30°54′48.1″-30°54′49.9″	117°48′56.6″-117°48′57.9″	139.25	Southwestern	24.4
R10	30°26′47.4″-30°54′26.8″	117°16′12.2″-117°48′48.1″	74	Northwestern	24
R30	30°54′56.3″-30°54′56.8″	117°48′44.2″-117°48′50.5″	140.4	Southwestern	20.2
R45	30°54′25.1″-30°54′33.3″	117°48′48.1″-117°48′48.2″	137.75	Northwest	35.25

Table S2 Soil property variations across distinct successional stages.

Type	R1	R10	R30	R45
SWC(%)	5.27±0.91a	11.12±0.74b	6.69±1.04a	16.96±2.08c
pH	6.57	6.09	6.47	5.65
TC (g/kg)	33.02±4.49b	16.60±0.40a	27.13±0.91b	18.44±0.51a
SOC (g/kg)	14.68±0.72d	4.85±0.15b	6.90±0.46c	3.09±0.12a
TN (g/kg)	4.19±0.46c	1.62±0.14a	3.33±0.39bc	2.94±0.12b
AN (mg/kg)	40.53±3.02b	22.92±1.21a	39.14±3.16b	26.66±1.10a
TP (g/kg)	8.47±0.46a	14.00±0.77a	30.35±4.15b	6.60±0.52a
AP (mg/kg)	2.88±0.12a	13.89±0.78b	13.92±0.49b	13.12±0.53b
MBC (mg/kg)	401.28±61.74a	157.21±13.12a	212.82±14.16b	649.91±61.73c
MBN (mg/kg)	8.01±0.28b	4.97±0.28a	8.68±0.28b	9.88±0.28c
MBP (mg/kg)	4.91±0.16a	6.26±0.37b	5.66±0.36ab	5.61±0.28ab
TCd (mg/kg)	6.68±0.67a	12.77±2.25a	54.57±14.14b	3.40±0.27a
TPb (mg/kg)	215.44±26.33a	458.29±84.19b	403.11±44.77ab	225.23±21.05a
TCu (mg/kg)	53031.82±3349.23b	16587.44±3586.30a	52341.53±6617.25b	23498.77±1817.12a
TZn (mg/kg)	2504.58±115.70ab	3052.38±570.73ab	3344.43±336.26b	1784.59±147.35a
TAs (mg/kg)	125.24±18.12a	941.35±191.93b	643.57±79.31b	139.05±21.25a
ACd (mg/kg)	0.007±0.001ab	0.005±0.001a	0.029±0.006c	0.017±0.001bc

ACu (mg/kg)	6.14±1.02b	1.07±0.44a	5.21±1.05b	11.03±1.41c
AZn (mg/kg)	0.43±0.08a	0.27±0.09a	0.56±0.12a	1.21±0.08b

Distinct lowercase letters signify significant differences among treatments ($P < 0.05$). SWC: soil water content, TC: total carbon, SOC: soil organic carbon, TN: total nitrogen, AN: alkali-hydrolyzale nitrogen, TP: total phosphorus, AP: available phosphorus, MBC: microbial biomass carbon, MBN: microbial biomass nitrogen, MBP: microbial phosphorus, TCd: soil total cadmium, TPb: soil total lead, TCu: soil total copper, TZn: soil total zinc, TAs: soil total arsenic, ACd: soil available cadmium, ACu: soil available copper, AZn: soil available zinc.

Table S3 Soil physicochemical properties at different successional stages.

Type	R1	R10	R30	R45
Plant community total coverage	62.60±2.40a	60.87±3.19a	59.47±1.43a	59.00±3.58a
Plant community plant height	51.94±1.45a	64.73±9.07a	40.41±2.30a	23.85±0.93b
Species richness index	7.00±0.17a	6.00±0.56a	7.00±0.53a	3.20±0.43b
Shannon–Wiener index	0.78±0.04bc	1.38±0.09a	1.11±0.10ab	0.33±0.08c
Simpson index	0.36±0.03b	0.68±0.02a	0.68±0.05a	0.18±0.04b
Pielou evenness index	0.51±0.03a	0.45±0.04ab	0.35±0.02bc	0.19±0.04c
Whittaker β index	0.30±0.03b	1.81±0.24a	1.00±0.27a	1.68±0.48a
Aboveground biomass	129.23±14.16a	141.87±19.59a	129.91±10.50a	47.60±7.55b
Underground biomass	0.07±0.02ab	0.08±0.01a	0.12±0.04ab	0.03±0.01b

Table S4 The critical explanatory rate of the effect of major environmental factors on multiple soil functions in the Redundancy analysis（RDA).

Variable	F value	P value	Adj. R^2 (%)	Arrow length
UGB	**7.70**	**0.002*** **	**25.20**	**0.81**
AGB	**7.64**	**0.001*** **	**17.09**	**0.81**
TCu	**7.19**	**0.001*** **	**18.41**	**0.86**
Fungi Shannon-Wiener index	0.66	0.58	11.90	0.64
Plant community total coverage	0.01	0.99	2.38	0.46
Plant community Shannon-Wiener index	0.64	0.56	0.17	0.48
Bacteria Shannon-Wiener index	0.14	0.93	-0.02	0.367
Plant community Whittaker β diversity index	0.63	0.59	-0.17	0.34

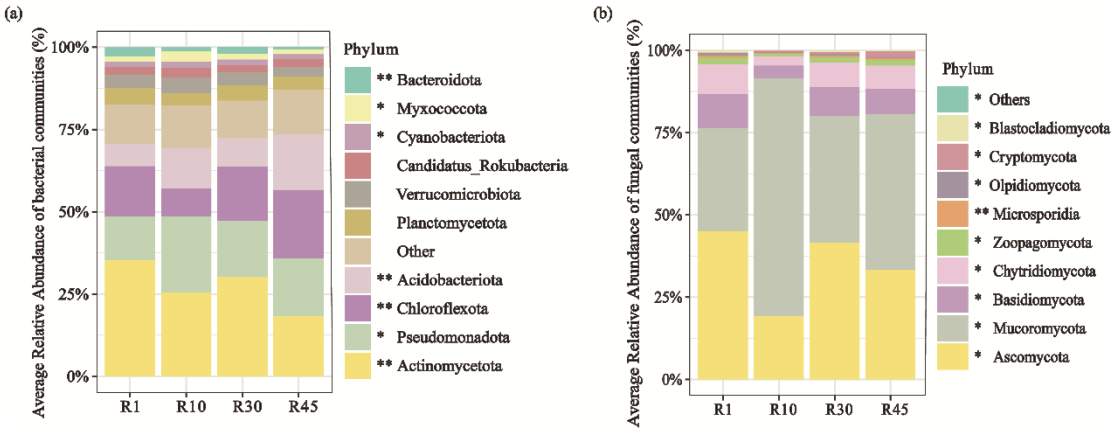


Figure S1. Differences in the top ten taxa at phylum level are also shown for soil fungi (a) and bacteria (b).

Note: The asterisk represents significant level of difference between groups. *, **, ***, and no asterisk indicate $P < 0.05$, $P < 0.01$, $P < 0.001$, and $P > 0.05$, respectively.

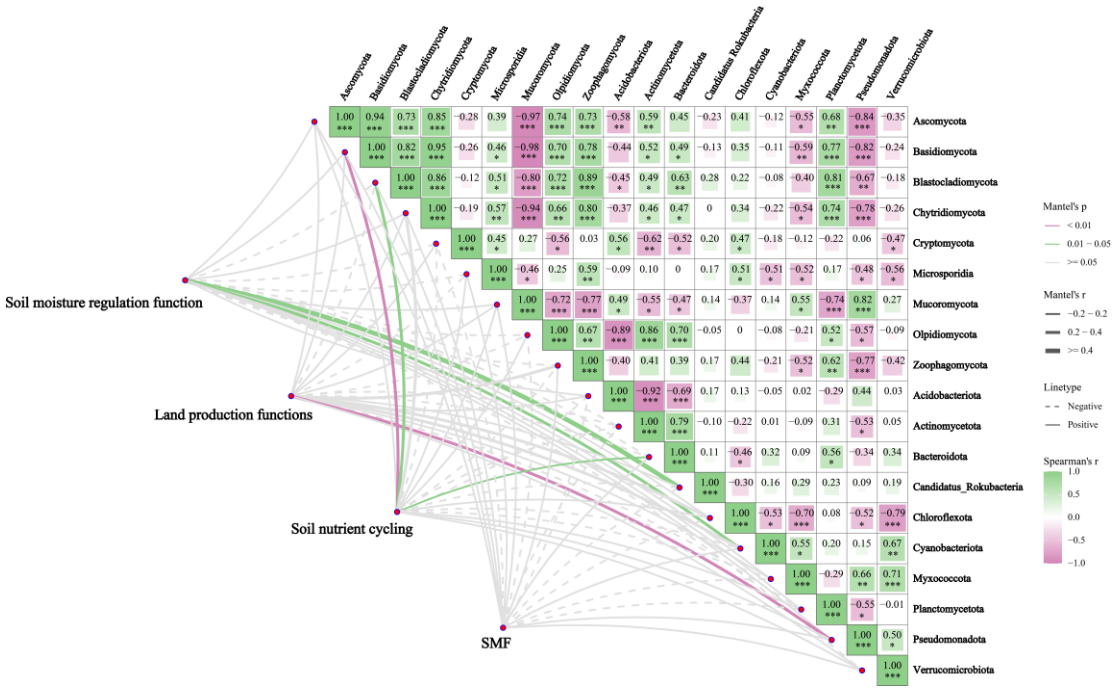


Figure S2. Relationships between soil multiple functions and soil microbial taxa.

Note: *, **, ***, and no asterisk indicate $P < 0.05$, $P < 0.01$, $P < 0.001$, and $P > 0.05$, respectively.