

Front. Agr. Sci. Eng.

<https://doi.org/10.15302/J-FASE-2025604>

Verso: Front. Agr. Sci. Eng.

Recto: Yixuan CHEN et al. Faba bean-based rotation enhances soil and microbial communities

**RESEARCH ARTICLE**

# Faba bean enhances soil multifunctionality through shaping rhizosphere microbial communities in legume-cereal crop rotations

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Received June 21, 2024;

Accepted December 26, 2024.

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**Table S1** Soil physicochemical properties under different rotation systems

Treatment	SWC (%)	pH	EC ( $\mu\text{S}\cdot\text{cm}^{-1}$ )	BD ( $\text{g}\cdot\text{cm}^{-3}$ )	Multi1	Multi2	TC ( $\text{g}\cdot\text{kg}^{-1}$ )	SOC ( $\text{g}\cdot\text{kg}^{-1}$ )	DOC ( $\text{mg}\cdot\text{kg}^{-1}$ )	MBC ( $\text{mg}\cdot\text{kg}^{-1}$ )	XYL ( $\text{nmol}\cdot\text{g}^{-1}\cdot\text{h}^{-1}$ )	TN ( $\text{g}\cdot\text{kg}^{-1}$ )	TP ( $\text{g}\cdot\text{kg}^{-1}$ )	NH <sub>4</sub> -N ( $\text{mg}\cdot\text{kg}^{-1}$ )	NO <sub>3</sub> -N ( $\text{mg}\cdot\text{kg}^{-1}$ )	OlsenP ( $\text{mg}\cdot\text{kg}^{-1}$ )
Cowpea	0.15 ± 0.02ab	6.71 ± 0.53b	80.94 ± 14.71b	1.26 ± 0.04abc	-0.17 ± 0.11cd	-0.30 ± 0.20b	13.63 ± 1.42b	10.22 ± 1.93b	29.28 ± 17.88	106.44 ± 29.16	7.81 ± 1.51b	1.06 ± 0.20b	0.63 ± 0.06abc	2.66 ± 1.32ab	9.99 ±2.06a	44.85 ± 15.62ab
Faba bean	0.16 ± 0.00a	7.31 ± 0.12ab	261.58 ± 34.63a	1.20 ± 0.02bc	0.18 ± 0.04a	0.49 ± 0.11a	22.28 ± 1.25a	16.99 ± 1.04a	33.09 ± 26.69	329.57 ± 261.11	22.22 ± 1.88b	1.74 ± 0.10a	0.81 ± 0.03ab	2.14 ± 0.44ab	25.04 ± 2.92a	35.24 ± 3.35ab
Kidney bean	0.13 ± 0.02abc	7.68 ± 0.21a	125 ± 14.56ab	1.17 ± 0.05c	0.00 ± 0.15abc	0.11 ±0.34ab	20.69 ± 3.98ab	13.24 ± 2.68ab	29.86 ± 16.97	469.18 ± 757.63	51.76 ± 16.31b	1.45 ± 0.35ab	0.74 ± 0.09abc	0.64 ± 0.10b	15.59 ± 3.98a	56.58 ± 12.13a
Mung bean	0.10 ± 0.00abc	7.73 ± 0.14a	128.40 ± 7.35ab	1.31 ± 0.02a	-0.22 ± 0.03d	-0.45 ± 0.06b	15.13 ± 1.12ab	8.64 ± 0.56b	30.36 ± 26.87	126.81 ± 88.52	19.88 ± 5.17b	0.90 ± 0.05b	0.59 ± 0.04bc	2.92 ± 0.61ab	20.05 ± 6.50a	24.89 ± 3.93b
Pea	0.13 ± 0.01c	7.38 ± 0.21ab	151.66 ± 14.50ab	1.23 ± 0.03abc	0.03 ± 0.06abc	-0.08 ± 0.11ab	15.72 ± 1.42ab	11.12 ± 1.00b	30.34 ± 24.04	137.29 ± 60.50	49.65 ± 22.56b	1.33 ± 0.11ab	0.82 ± 0.08a	5.80 ± 3.37a	24.48 ± 6.15a	46.39 ± 9.86ab
Azuki bean	0.11 ± 0.01bc	7.98 ± 0.16a	118.21 ± 10.17ab	1.29 ± 0.02ab	-0.12 ± 0.08bcd	-0.36 ± 0.15b	16.20 ± 1.45ab	10.34 ± 1.37b	21.32 ± 11.71	204.22 ± 123.16	139.36 ± 45.15a	1.05 ± 0.12b	0.55 ± 0.04c	1.83 ± 0.64ab	11.90 ± 2.10a	26.28 ± 5.49b
Soybean	0.15 ± 0.01ab	7.39 ± 0.28ab	152.71 ± 30.26ab	1.23 ± 0.02abc	0.01 ± 0.11abc	-0.25 ± 0.11b	13.68 ± 1.23b	9.66 ± 1.67b	27.94 ± 18.67	167.65 ± 87.64	26.55 ± 7.47b	1.07 ± 0.16b	0.69 ± 0.08abc	2.52 ± 1.58ab	20.59 ± 8.46a	34.64 ± 8.00ab
Other beans	0.16 ± 0.08a	7.35 ± 1.14ab	240.05 ± 66.49ab	1.23 ± 0.09abc	0.07 ± 0.07ab	-0.07 ± 0.18ab	15.62 ± 2.56ab	10.37 ± 0.90b	33.50 ± 40.32	159.82 ± 280.30	32.20 ± 18.72b	1.28 ± 0.22ab	0.82 ± 0.06a	2.69 ± 0.74ab	31.04 ± 6.98a	75.39 ± 15.36a
Legumes	***	***	**	-	*	*	-	-	-	-	***	-	*	-	*	-
Region	-	-	-	-	-	-	-	*	*	**	-	*	-	-	*	-
Climate	-	-	-	-	-	-	*	-	-	-	-	-	-	-	-	-
Total effect	***	***	***	***	*	*	**	*	***	***	***	***	***	***	***	***

Note: Abbreviations: BD, bulk density; DOC, dissolved organic carbon; EC, electrical conductivity; MBC, soil microbial biomass carbon; Multi1, soil multifunctionality index by standardized scores; Multi2, soil multifunctionality index by factor analysis; NH<sub>4</sub>-N, soil ammonia nitrogen content; NO<sub>3</sub>-N, soil nitrate nitrogen content; Phos, phosphatase; SOC, soil organic carbon; SWC, soil water content; TC, soil total carbon content; TN, soil total nitrogen content; TP, soil total phosphorus content; and XYL,  $\beta$ -1,4-xylosidase. Different lowercase letters indicate significant differences between rotation systems. Mixed effect model was performed among groups. \*, \*\*, and \*\*\* indicate  $P < 0.05$ ,  $P < 0.01$ , and  $P < 0.001$ , respectively.

**Table S2** Data Description of one-way analysis of variance (ANOVA) and effect sizes

Index	<i>F</i>	<i>P</i>	$\eta^2$
RichnessB	6.638	0.000	0.155
ShannonB	4.399	0.000	0.109
SimpsonB	2.297	0.028	0.060
PielouB	1.459	0.182	0.039
RichnessF	3.479	0.001	0.088
ShannonF	1.913	0.068	0.050
SimpsonF	1.054	0.394	0.028
PielouF	1.772	0.093	0.047
Multi1	6.904	0.000	0.160
Multi2	6.790	0.000	0.158
SWC	6.070	0.000	0.144
EC	2.877	0.007	0.074
pH	2.297	0.028	0.060
BD	4.277	0.000	0.106
SRR	5.701	0.000	0.136
TC	3.341	0.002	0.085
SOC	7.587	0.000	0.173
DOC	0.544	0.801	0.015
DON	3.935	0.000	0.098
MBC	5.693	0.000	0.136
MBN	3.428	0.002	0.125
BG	0.913	0.497	0.025
CBH	2.592	0.013	0.067
NAG	0.993	0.437	0.027
XYL	6.110	0.000	0.145
Phos	2.356	0.024	0.061
NH <sub>4</sub> -N	1.437	0.191	0.038
NO <sub>3</sub> -N	0.975	0.450	0.026
OlsenP	4.782	0.000	0.117
AK	2.950	0.005	0.075
TN	5.219	0.000	0.127
TP	4.408	0.000	0.109

Note: Abbreviations, AK, available potassium; BK, bulk density; BG,  $\beta$ -glucosidase; CBH, cellobiohydrolase; DOC, dissolved organic carbon; DON, dissolved organic nitrogen; MBC, soil microbial biomass carbon; MBN, soil microbial biomass nitrogen; Multi1, soil multifunctionality index by standardized scores; Multi2, soil multifunctionality index by factor analysis; NAG, N-acetyl- $\beta$ -glucosaminidase; NH<sub>4</sub>-N, soil ammonia nitrogen content; NO<sub>3</sub>-N, soil nitrate nitrogen content; Phos, phosphatase, SOC, soil organic carbon; SRR, soil respiration rate; SWC, soil water content; TC, soil TC content; TN, soil total nitrogen content; TP, soil total phosphorus content; and XYL,  $\beta$ -1,4-xylosidase.

**Table S3** Attributes of the co-occurrence network

	No.-edges	No.-nodes	Average degree	Clustering coefficient	Modularity	No.-community
a	286	70	8.171	0.548	0.485	8
b	47	23	4.087	0.615	0.312	4
c	75	41	3.659	0.391	0.499	7
d	72	33	4.364	0.414	0.413	5
e	151	72	4.194	0.307	0.612	8
f	151	56	5.393	0.379	0.464	6
g	588	84	14	0.579	0.334	6
h	48	24	4	0.488	0.49	4

**Table S4** Keystone and bridge species according to the co-occurrence network

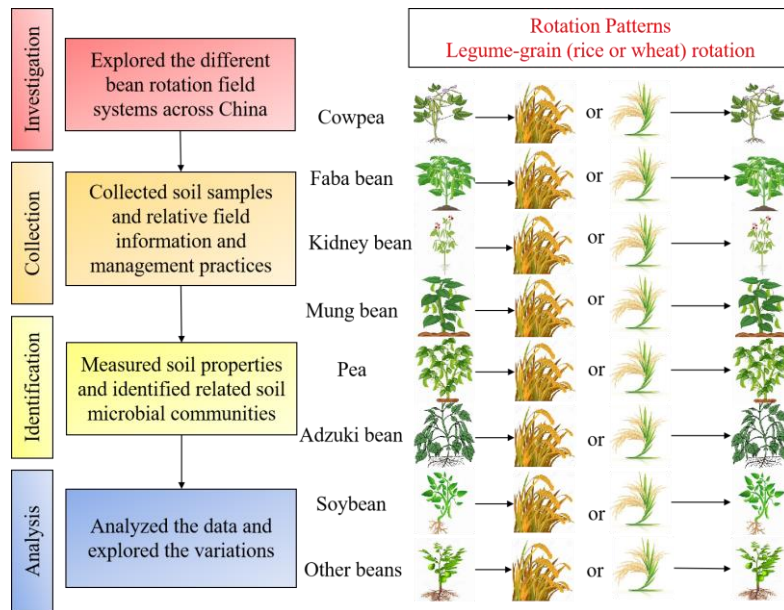
Group	Phylum	Degree	Eigenvector centrality	Closeness centrality	Betweenness centrality
Cowpea	Gemmatimonadota	7	1.000	0.554	4.667
Faba bean	Desulfobacterota	10	1.000	0.571	27.217
	Latescibacterota	10	0.982	0.645	51.793
Kidney bean	Proteobacteria	5	1.000	0.444	12.000
	Methylomirabilota	4	0.425	0.500	39.000
Mung bean	Desulfobacterota	5	0.971	0.400	33.833
	Planctomycetota	5	0.768	0.381	55.333
Pea	NB1,j	9	1.000	0.491	129.883
Azuki bean	Armatimonadota	6	1.000	0.268	15.000
	Planctomycetota	5	0.826	0.322	79.000
Soybean	Proteobacteria	20	1.000	0.660	66.362
Other beans	Desulfobacterota	15	0.987	0.576	63.381
	Hydrogenedentes	14	0.922	0.576	67.908

**Table S5** The mixed effect model of legume, region and climate on observed indices

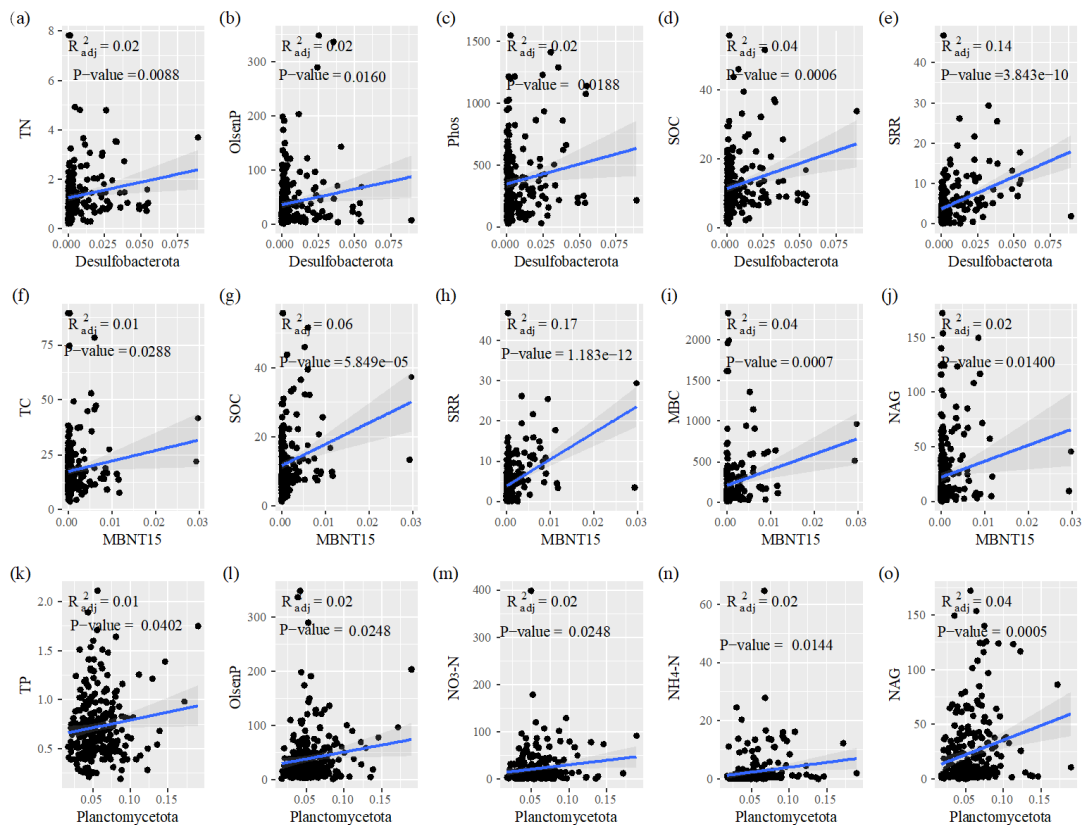
Index	<i>F</i> -statistic	<i>P</i> -value	<i>F</i> -statistic	<i>P</i> -value	<i>F</i> -statistic	<i>P</i> -value	<i>F</i> -statistic	<i>P</i> -value
	Total effect	Total effect	Legume	Legume	Region	Region	Climate	Climate
RichnessB	1.677	0.099	1.973	0.177	1.004	0.33	0.157	0.693
ShannonB	1.319	0.252	2.744	0.115	0.554	0.466	0.522	0.471
SimpsonB	0.613	0.946	0.486	0.495	0.106	0.748	1.025	0.312
PielouB	1.512	0.153	4.662	0.045	0.055	0.818	0.78	0.378
RichnessF	2.706	0.008	1.427	0.248	2.153	0.16	0.042	0.837
ShannonF	2.243	0.024	0.842	0.371	0.044	0.836	2.815	0.095
SimpsonF	2.399	0.016	0.038	0.848	0.03	0.865	1.699	0.194
PielouF	1.756	0.081	0.267	0.611	1.466	0.242	3.354	0.068
SWC	5.643	0	11.25	0.004	1.406	0.251	2.002	0.158
EC	11.397	0	0.033	0.859	0.1	0.756	0.255	0.614
pH	10.455	0	12.334	0.002	0.162	0.692	0.811	0.369
BD	4.637	0	7.35	0.014	0	1	1.497	0.222

SRR	2.838	0.006	0.007	0.936	0.16	0.694	0.102	0.75
TC	2.351	0.018	0.807	0.381	0.151	0.703	4.896	0.028
SOC	2.265	0.023	1.896	0.185	0.048	0.829	0.321	0.571
DOC	6.42	0	6.302	0.022	0.018	0.895	0.01	0.919
DON	3.092	0.004	0.182	0.674	0.003	0.959	0.173	0.678
MBC	13.532	0	3.623	0.073	0.078	0.783	8.902	0.003
MBN	0.154	1	10.777	0.004	0.012	0.913	6.343	0.012
BG	0.669	0.908	8.011	0.011	0.019	0.891	4.77	0.03
CBH	0.867	0.698	13.592	0.002	0.008	0.93	11.03	0.001
NAG	1.309	0.259	3.981	0.061	0.007	0.935	0.27	0.604
XYL	29.623	0	8.935	0.008	0.024	0.878	0.74	0.39
Phos	1.629	0.113	3.443	0.08	0.181	0.676	0.064	0.8
NH <sub>4</sub> -N	3.949	0.001	0.001	0.973	0.029	0.867	0.605	0.437
NO <sub>3</sub> -N	4.432	0	1.92	0.183	0.013	0.91	0.33	0.566
OlsenP	3.343	0.002	0.417	0.526	0.018	0.896	1.659	0.199
AK	0.834	0.737	0.311	0.584	0.004	0.952	1.242	0.266
TN	3.095	0.004	1.158	0.296	0.036	0.851	3.502	0.062
TP	3.454	0.002	6.148	0.023	0.357	0.557	9.099	0.003
Multi1	2.326	0.023	4.975	0.02	4.38	0.052	4.648	0.121
Multi2	1.196	0.035	2.344	0.013	2.182	0.158	5.173	0.247

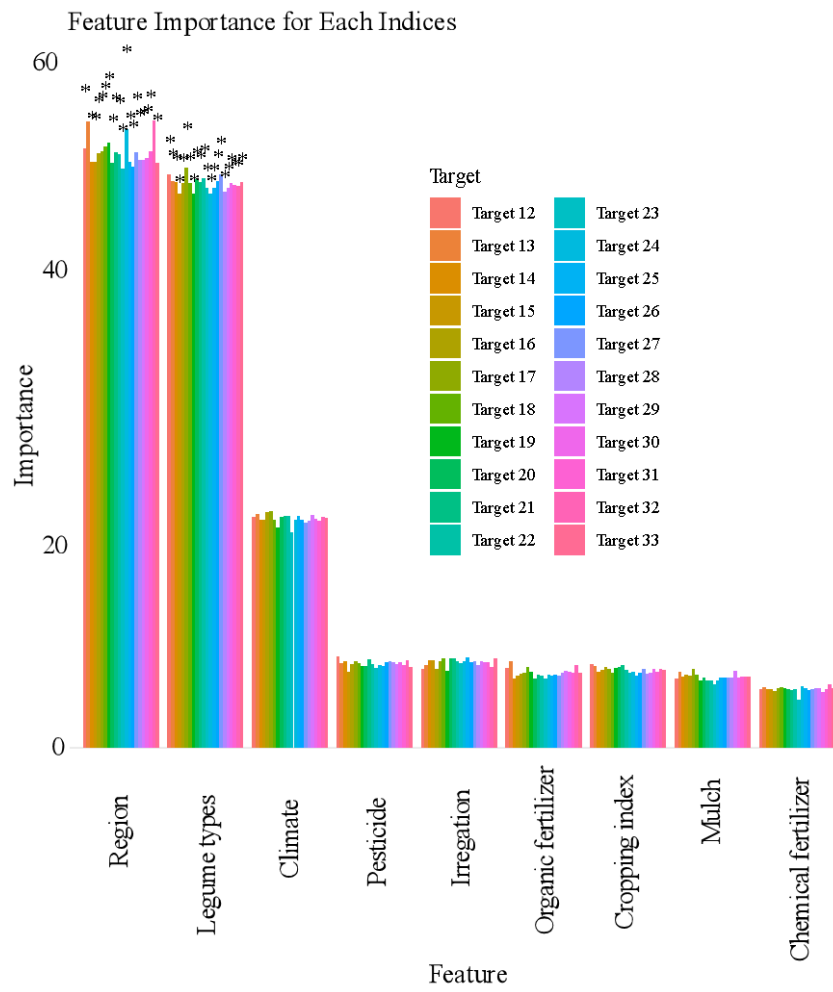
Note: AK, available potassium; BD, bulk density; BG,  $\beta$ -glucosidase; CBH, cellobiohydrolase; DOC, dissolved organic carbon; DON, dissolved organic nitrogen; MBC, soil microbial biomass carbon; MBN, soil microbial biomass nitrogen; Multi1, soil multifunctionality index by standardized scores; Multi2, soil multifunctionality index by factor analysis; NAG, N-acetyl- $\beta$ -glucosaminidase; NH<sub>4</sub>-N, soil ammonia nitrogen content; NO<sub>3</sub>-N, soil nitrate nitrogen content; Phos, phosphatase, SOC, soil organic carbon; SRR, soil respiration rate; SWC, soil water content; TC, soil TC content; TN, soil total nitrogen content; TP, soil total phosphorus content; and XYL,  $\beta$ -1,4-xylosidase.



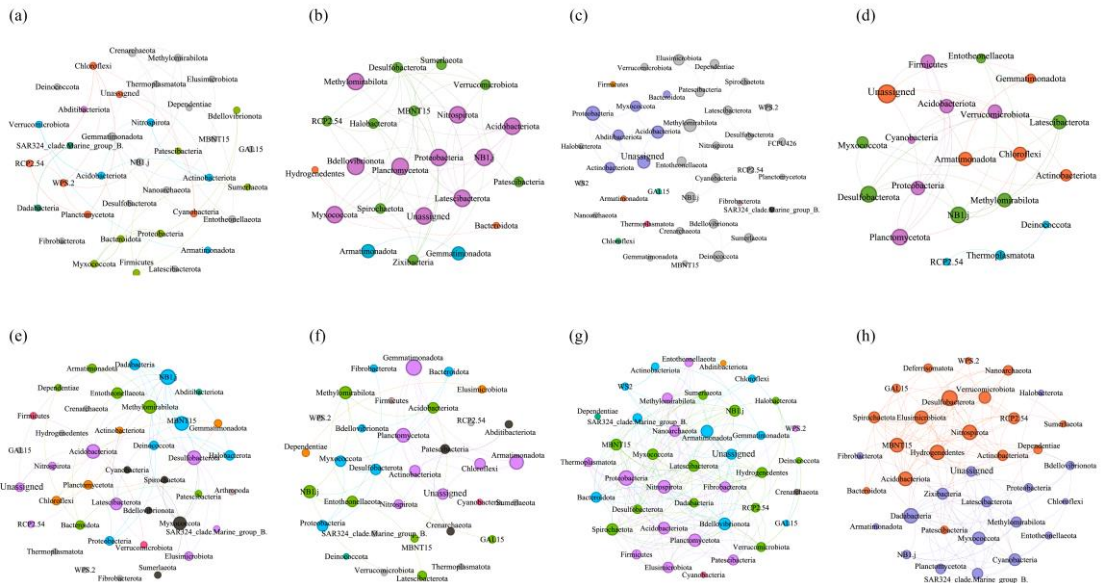
**Fig. S1** Flow chart and rotation patterns of this analysis.



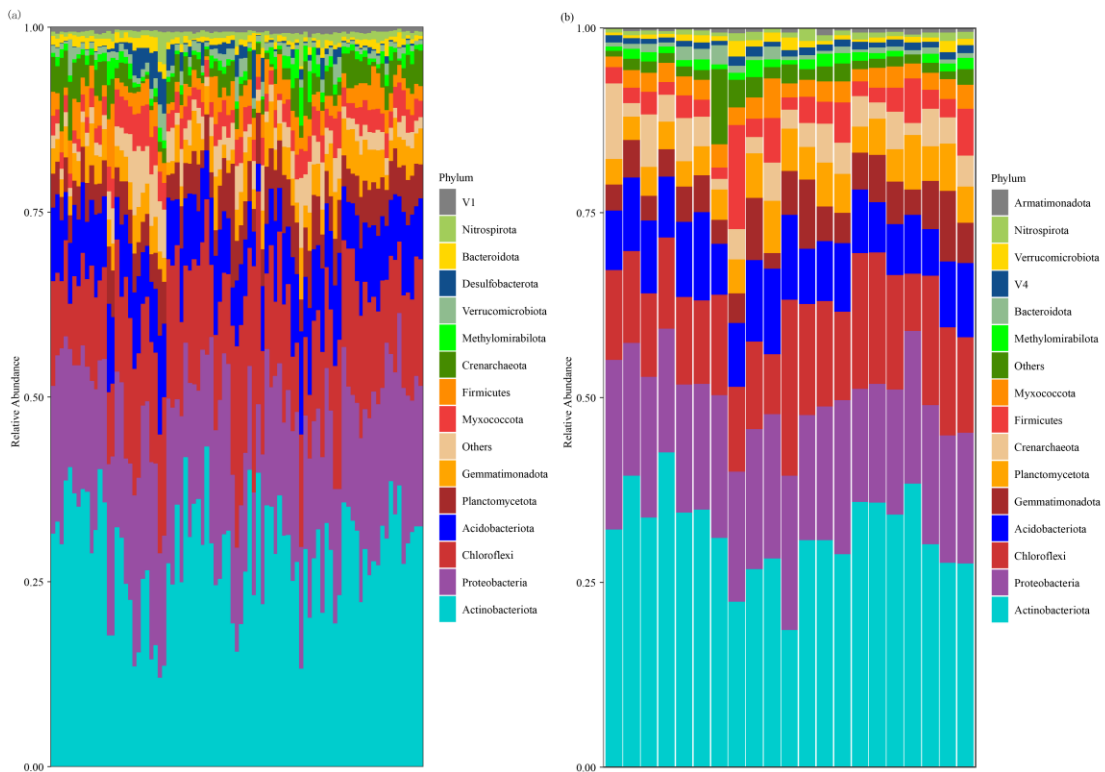
**Fig. S2** Linear correlation between selected phylum and environmental factors. MBC, soil microbial biomass carbon; NAG, N-acetyl- $\beta$ -glucosaminidase; NH<sub>4</sub>-N, soil ammonia nitrogen content; NO<sub>3</sub>-N, soil nitrate nitrogen content; Phos, phosphatase; SOC, soil organic carbon; SRR, soil respiration rate; TC, soil TC content; TN, soil total nitrogen content; and TP, soil total phosphorus content.



**Fig. S3** Random Forest mean predictor importance of different influence factors for soil properties.



**Fig. S4** Co-occurrence network of the soil microbial community under different rotation groups. Network of co-occurring 90% cutoff OTUs based on correlation analysis. A connection stands for a strong (Spearman's  $\rho > 0.6$ ) and significant ( $P < 0.01$ ) correlation. The size of each node is proportional to the number of connections (i.e., degree). (a) Cowpea; (b) faba bean; (c) kidney bean; (d) mung bean; (e) pea; (f) adzuki bean; (g) soybean; (h) other beans.



**Fig. S5** Top 16 phyla of faba bean group (a) and kidney bean group (b).