Carbon fraction-specific microbial–mineral regulation outweighs direct calcium control in carbonate karst soils

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Table S1. Site characteristics of the study sites in Guizhou Province, southwest China.

Treatment	Lithology	Slope position	Replicates (n)	Slope length (m)	Slope width (m)	Land use	MAT (°C)	MAP (mm)	Elevation (m a.s.l.)
PD	Dolomite	Upper	3	352	30	Shrubland	16.35	1156.87	1180
PD	Dolomite	Middle	3	352	30	Shrubland	16.35	1156.87	1172
PD	Dolomite	Lower	3	352	30	Cropland	16.35	1156.87	1153
PL	Limestone	Upper	3	268	30	Orchard	15.74	1161.24	1245
PL	Limestone	Middle	3	268	30	Orchard	15.74	1161.24	1241
PL	Limestone	Lower	3	268	30	Orchard	15.74	1161.24	1170
ZD	Dolomite	Upper	3	198	30	Orchard	16	1089.87	900
ZD	Dolomite	Middle	3	198	30	Orchard	16	1089.87	877
ZD	Dolomite	Lower	3	198	30	Orchard	16	1089.87	836
ZL	Limestone	Upper	3	135	30	Shrubland	16.05	1090.87	981
ZL	Limestone	Middle	3	135	30	Shrubland	16.05	1090.87	947
ZL	Limestone	Lower	3	135	30	Cropland	16.05	1090.87	910

Note: PD, PL, ZD, and ZL denote Puding Dolomite, Puding Limestone, Zunyi Dolomite, and Zunyi Limestone treatments, respectively

Table S2. Three-way ANOVA of the effects of site, parent rock type, slope position, and their interactions on soil carbon fractions, mineral and calcium properties and microbial variables.

Variable	Site	Rock type	Slope	Site×Rock	Site×Slope	Rock×Slope	Site×Rock×Slope
TN	40.19***	24.93***	5.22*	11.34**	0.34ns	1.48ns	1.44ns
TP	20.37***	51.53***	6.78**	5.70*	1.58ns	0.89ns	1.70ns
pH	30.68***	0.50ns	17.59***	0.07ns	1.44ns	1.10ns	2.16ns
AN	46.59***	17.51***	5.84**	10.44**	2.78ns	2.61ns	2.61ns
$CaCO_3$	0.07ns	8.53**	6.36**	5.89*	0.89ns	2.80ns	2.5ns
Ca_s	1.28ns	1.80ns	0.04ns	0.80ns	2.22ns	0.87ns	0.52ns
E-Ca^{2+}	44.65***	64.13***	81.09***	0.28ns	1.84ns	0.90ns	1.5ns
Moisture	176.33***	3.86ns	2.56ns	11.59**	1.43ns	2.75ns	2.20ns
BD	21.08***	5.02*	2.03ns	19.03***	1.71ns	0.58ns	0.04ns
Clay	23.55***	65.39***	6.87**	15.12***	0.26ns	1.27ns	2.99ns
Silt	2.13ns	0.13ns	2.14ns	0.70ns	3.72ns	0.57ns	0.63ns
Sand	7.99**	44.11***	4.53*	6.23*	1.00ns	0.33ns	1.87ns
SOC	182.99***	135.52***	32.91***	125.52***	0.69ns	2.49ns	1.53ns
POC	44.53***	69.08***	32.52***	129.42***	1.71ns	0.06ns	2.13ns
MAOC	182.88***	88.12***	17.86***	58.02***	0.83ns	0.33ns	0.55ns
CEC	33.45***	22.54***	6.99**	0.28ns	0.43ns	1.37ns	0.37ns
GP	8.39**	29.04***	15.87***	12.70**	0.05ns	1.47ns	1.86ns
GN	5.27*	13.60**	8.70**	4.66*	0.38ns	0.05ns	3.28ns
Actinomycetes	19.34***	28.44***	16.32***	19.13***	0.28ns	0.76ns	2.46ns
FunPLFA	0.00ns	7.11*	12.66***	15.65***	2.68ns	1.24ns	0.43ns
BacPLFA	9.26**	22.82***	13.05***	10.52**	0.01ns	0.50ns	0.19ns
TotalPLFA	6.64*	21.03***	14.15***	12.57**	0.10ns	0.56ns	3.61ns
F:B	11.82**	0.00ns	2.38ns	10.23**	0.93ns	1.08ns	2.48ns
MBC	111.92***	138.52***	122.50***	57.33***	1.98ns	2.56ns	2.98ns
0.5Feo+Alo	83.59***	0.39ns	0.68ns	0.11ns	0.31ns	0.69ns	3.06ns
0.5Fep+Alp	1.26ns	0.67ns	1.37ns	0.01ns	3.12ns	0.52ns	0.91ns
0.5Fed+Ald	143.50***	0.00ns	28.03***	1.09ns	0.81ns	0.89ns	0.08ns
GP:GN	1.12ns	1.75ns	5.27*	1.96ns	3.13ns	0.25ns	1.31ns

Note: Values are (*F*)-statistics from factorial ANOVA with Site, Rock type, and Slope position as fixed factors. TN, total nitrogen; AN, available nitrogen; $CaCO_3$, calcium carbonate; Ca_s, sulfate-extractable Ca; E-Ca^{2+}, exchangeable Ca^{2+}; BD, bulk density; SOC, soil organic carbon; POC, particulate organic carbon; MAOC, mineral-associated organic carbon; CEC, cation exchange capacity; GP, Gram-positive bacteria; GN, Gram-negative bacteria; Actinomycetes; FunPLFA, fungal phospholipid fatty acid; BacPLFA, bacterial phospholipid fatty acid; TotalPLFA, total phospholipid fatty acid; F:B, fungal-to-bacterial ratio; MBC, microbial biomass carbon; (0.5Feo+Alo), (0.5Fep+Alp), and (0.5Fed+Ald) denote oxalate-, pyrophosphate-, and dithionite-extractable Fe–Al indices, respectively; GP:GN, Gram-positive to Gram-negative ratio. * ($p<0.05$); ** ($p<0.01$); *** ($p<0.001$); ns, ($p \geq 0.05$.)

Table S3. Table S3. Variance inflation factors (VIF) of indicators retained in the PLS-SEM.

Construct	Variable	VIF
Microbial	BacPLFA	6.275
	MBC	4.416
	FunPLFA	3.033
Mineral	0.5Feo+Alo	2.09
	0.5Fed+Ald	1.753
	CEC	1.386
Calcium	$CaCO_3$	1.06
	E-Ca^{2+}	1.06

Note: Variance inflation factors (VIF) of indicators retained in the partial least-squares structural equation models (PLS-SEM). Variables are grouped according to the Microbial, Mineral, and Calcium constructs used in the PLS-PM. VIF values ≤5 indicate low collinearity; values >5 but <10 indicate moderate collinearity (Hair et al., 2011). All retained indicators had VIF values below 10, indicating acceptable multicollinearity. CEC, cation exchange capacity; E-Ca^{2+}, exchangeable Ca^{2+}; MBC, microbial biomass carbon; BacPLFA, bacterial phospholipid fatty acid; FunPLFA, fungal phospholipid fatty acid; (0.5Feo+Alo), oxalate-extractable Fe–Al; (0.5Fed+Ald), dithionite-extractable Fe–Al.