应用与环境生物学报
CHIN J APPL ENVIRON BIOL
CSTR: 32241.14.CJAEBiology.2024.08010
DOI: 10.19675/j.cnki.1006-687x.2024.08010
http://www.cibj.com/

于婧, 肖娟, 罗尚华, 刘东辉, 周宇. 川西亚高山云杉人工林根际和非根际土壤有机碳含量与稳定性差异[J]. 应用与环境生物学报, 2025, **31** (3): 394-403
Yu J, Xiao J, Luo SH, Liu DH, Zhou Y. Differences in organic carbon content and stability between the rhizosphere and bulk soils of subalpine spruce plantations in western Sichuan, China [J]. *Chin J Appl Environ Biol*, 2025, **31** (3): 394-403

川西亚高山云杉人工林根际和非根际土壤有机碳含量与稳定性差异

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摘要 根际作为典型的土壤微生物热点区，是深入理解土壤碳循环过程与高效发挥土壤固碳功能的关键环节. 尽管以往的研究初步揭示了川西亚高山森林根际与非根际土壤碳储量的差异，但对二者间土壤有机碳（SOC）稳定的差异仍缺乏应有的认识，一定程度上限制了对川西亚高山森林土壤碳汇潜力的预测和评估. 对典型川西亚高山森林云杉人工林多点系统采样，测定根际和非根际SOC的含量，并同步分析SOC的稳定性指标：颗粒态有机碳（POC）、矿物结合态有机碳（MAOC）、官能团特征和土壤金属有机复合体中结合态铁、铝离子含量. 结果表明：4个采样点中，根际SOC含量均显著高于非根际土壤，平均比非根际土壤高37.3%. 根际土壤中MAOC的比例均显著高于非根际土壤，POC的占比呈现相反趋势，根际土壤中惰性碳官能团组分（alkyl-C和aromatic C=C）和稳定性指数（脂肪族性、芳香性和组合指数）以及金属有机复合体中结合态铁、铝离子含量均显著高于非根际土壤，并与根际土壤SOC含量具有显著的正相关关系. 这些结果表明川西亚高山云杉人工林根际SOC含量的大小与SOC的物理和化学保护能力密切关联. 本研究揭示了亚高山森林根系活动在调控SOC积累和稳定中的关键作用，为评估川西亚高山森林土壤固碳效应提供了科学根据.（图5 表3 参61）

关键词 土壤有机碳；土壤碳稳定性；根际土壤；非根际土壤；云杉人工林

Differences in organic carbon content and stability between the rhizosphere and bulk soils of subalpine spruce plantations in western Sichuan, China

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Abstract We aim to study the differences in the stability of soil organic carbon (SOC) between rhizosphere and bulk soils in high-altitude mountain forests in western Sichuan, which will help improve the prediction and assessment of soil carbon sink potential in these forests. We conducted a multiple-site sampling campaign in a typical high-altitude mountain forest in western Sichuan, including four spruce plantations, to measure the contents of rhizosphere and bulk soil organic carbon (SOC) and simultaneously analyze the stability indicators of SOC including particulate organic carbon (POC), mineral-associated organic carbon (MAOC), functional group characteristics, and the concentrations of bound Fe and Al ions in soil metal-organic complexes. At the four sampling sites, the SOC content in the rhizosphere was significantly higher than that in the bulk soil, with an average increase of 37.3%. The proportion of MAOC in the rhizosphere was significantly higher than that in bulk soil, while the proportion of POC showed the opposite trend. The composition of inert carbon functional groups (alkyl-C and aromatic C=C) and stability indices (aliphatic, aromaticity, and combined index) in the rhizosphere soil, as well as the concentrations of bound Fe and Al ions in metal-organic complexes, were significantly higher than those in bulk soil and had a significant positive correlation with SOC content in rhizosphere soil. These results indicate that the magnitude of the rhizosphere SOC content in subalpine spruce plantations in western Sichuan is closely related to the physical and chemical protection mechanisms of SOC. This study revealed the key role of root activity in regulating SOC accumulation and stability in subalpine forests, providing a scientific basis for evaluating soil carbon sequestration potential in high-altitude forests in western Sichuan.

Keywords soil organic carbon; soil carbon stability; rhizosphere soil; bulk soil; spruce plantation

收稿日期 Received: 2024-08-09　接受日期 Accepted: 2024-10-21
国家自然科学基金项目（31700387）、四川省科技厅科技计划项目（2021YJ0283）和西华师范大学校级创新团队项目（KCXTD2024-3）资助　Supported by the National Natural Science Foundation of China (31700387), Science and Technology Program of Sichuan Province (2021YJ0283), and Innovation Team Fund of China West Normal University (KCXTD2024-3)
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土壤作为陆地生态系统最大的碳（C）库[1]，其收支平衡的微小变化都可能对区域乃至全球的气候及碳循环产生重大影响. 相应地，深入理解土壤有机碳（SOC）固持及其稳定性机制，高效发挥土壤碳汇功能已经成为缓解全球气候变化压力、实现“碳中和”目标的重要途径之一[2]. 森林是陆地生态系统重要的组成部分，森林的覆盖面积约为全球总陆地面积的1/3 [3]， 是陆地生态系统最重要的碳汇[4]. 其中，森林土壤碳库是陆地生态系统中最大的碳库，约占全球陆地总土壤碳储量的25%-50% [5]，它在调控陆地生态系统碳排放与固存、实现碳中和愿景中发挥着不可替代的重要作用. 因此，深入认识并理解SOC形成、稳定和固持等关键过程的变化特征已经成为当前碳中和背景下高效发挥森林碳汇功能的优先主题. SOC的积累受控于碳收支的平衡，碳输出通量主要由陆地土壤中易分解的具有高生物活性的活性组分控制，而碳的长期储存则主要由难分解的顽抗组分和稳定性所决定[6]. 稳定性高的碳组分能够促进土壤碳的长期固存[7-8]. 将SOC按照密度粒度分级可分为颗粒态有机碳（POC）和矿物结合态有机碳（MAOC）[9]. POC由不受矿物保护的动植物残体分解副产物构成，更容易被微生物利用分解. MAOC为黏粒、粉砂等土壤颗粒与矿物伴生的SOC组分，相对稳定并且通常难以降解，SOC随MAOC的增加可能产生持久性的积累[1, 10]. 因此，从多角度去探究土壤碳库的组成和稳定，可以为研究土壤碳固存对环境变化的差异化响应提供新的切入点，并提升全球变化下对土壤碳—气候反馈效应的认识.

根系是植物—土壤的重要桥梁与核心纽带，它不仅是吸收养分和水分的通道，还可以通过分泌、周转与菌根共生等一系列生命活动在根际界面形成独特的微生物热点，从而深刻调控着土壤碳动态[11]. 据估算，全球范围内根际过程释放的二氧化碳可能比人类活动燃烧化石燃料释放的二氧化碳多3-10倍[12]，约占全球陆地总初级生产力的30%-60%，独特地调控了生物地球化学循环诸多关键过程[13-14]. 根源活性碳的持续大量输入不仅可以通过刺激微生物活性而增强激发效应导致SOC损失[15]，而且还可以通过诱导土壤物理化学过程（团聚体包裹和矿物表面吸附等）提高SOC稳定性而导致SOC积累，从而在土壤碳固持和稳定中发挥“双刃剑”作用[14]. 此外，根系还可以通过释放分泌物和菌根共生产生外延菌丝来促进土壤团聚体的形成，从而对SOC构成物理保护而避免了被微生物和酶直接接触[16-17]，某些根系分泌物成分（如碳水化合物）能够通过促进金属有机络合物（MOC）的形成来增加SOC的稳定性和积累[18-19]. 外生菌根真菌（ECM）通过释放矿物表面结合的反应性代谢物来促进矿物稳定的土壤有机质（SOM，如MOC）的形成[20-21]. 正是由于根际存在的这些复杂的根系—土壤—微生物互作过程，导致我们目前对根际土壤碳固存潜力和稳定性的评估仍然存在许多不确定性，特别是在不同环境条件下或不同生态系统中根际土壤碳源/汇功能的反转[22-23]. 总之，根际比非根际驱动了更高的有机碳积累能力，一方面根际促进了团聚体的形成从而减缓了SOC的分解，另一方面根际中的铁（Fe）、铝（Al）氧化物与矿物结合进一步增强了碳的稳定性[24-26]. 此外，由于受野外研究方法和技术手段等诸多因素的限制，以往关于森林SOC储量和稳定性的研究更多将林下土壤视为一个整体考虑，而很少聚焦于“根际”这一独特的微生物热点区. 因此，亟须开展森林根际土壤碳储量与稳定性机制的普适性研究，以提升森林土壤碳汇能力的系统性评估.

西南亚高山针叶林是我国的第二大林区，该区域的亚高山针叶林属于典型的山地寒温性针叶林带，具备有机质分解速率慢、土壤碳储量大等独特的生态学特征[27-28]. 然而，自20世纪50年代以来，该区森林资源遭受了长期的过度开发利用，天然林资源大幅锐减，取而代之的是在皆伐迹地营造了大面积的以云杉为主的人工针叶林. 据统计，仅川西高山峡谷区就有100万 hm^2以上的亚高山人工针叶林，占四川省人工林总面积的50%，占亚高山森林面积的40% [29-30]. 因此，本研究在川西亚高山林区选取多个典型的人工云杉林，系统分析云杉林根际和非根际SOC含量的差异，并通过分析土壤碳官能团特征和金属结合态铁铝离子含量比较根际和非根际间SOC的稳定性差异. 本研究旨在从根际视角进一步丰富对亚高山森林土壤碳汇效应理论的科学认识，并为全面认识亚高山森林土壤碳汇功能提供一定的理论依据.

1 材料与方法

1.1 研究区概况

本研究在青藏高原东部四川省理县米亚罗林区（31°35′N-31°49′N，102° 40′E-102°51′E，海拔2 800-3 400 m）内的4个云杉人工林样点进行，林龄介于30-75年之间. 该区域年平均气温8.9 ℃，7月最高平均气温12.6 ℃，1月最低气温-8 ℃，年降水量600-1 100 mm. 土壤类型为酸性棕壤（亚类）[31]. 林下有少量的林下植物，林下植被稀少，主要伴生有禾本科的羊茅（*Festuca ovina*）和野青茅（*Deyeuxia arundinacea*）、莎草科的丝叶苔草（*Carex capilliformis*）等少量草本植物. 4个样点的基本位置信息和土壤性质见表1.

1.2 土壤样品采集

本研究所有的根际土壤样品和非根际土壤样品均于2022年8月在矿物土壤的上部15 cm处对土壤进行采集. 为了确保采集到足够的根际土壤样品用于后续指标分析，我们在每个云杉人工林样地内建立了5

表1 4个样点的位置和土壤特性
Table 1 Location and soil characteristics at the four forest sites

参数 Parameter	土壤位置 Soil compartment	样点1 Site 1	样点2 Site 2	样点3 Site 3	样点4 Site 4
林龄 Age of plantations (*t*/a)		30	45	55	75
位置 Location		31°35′22″N, 102°50′37″E	31°47′48″N, 102°41′53″E	31°47′5″N, 102°42′14″E	31°37′18″N, 102°50′53″E
海拔 Elevation (*h*/m)		2947	3246	3190	3103
土壤容重 Bulk density (ρ/g cm^{-3})		0.88(0.01)^{bc}	0.90(0.01)^{b}	0.83(0.01)^{c}	1.03(0.02)^{a}
土壤含水量 Soil moisture content	RS BS	0.43(0.02)^{a} 0.39(0.01)^{a}	0.39(0.02)^{a} 0.35(0.03)^{a}	0.44(0.04)^{a} 0.34(0.01)^{ab}	0.34(0.02)^{a} 0.29(0.01)^{b}
土壤pH Soil pH	RS BS	5.37(0.03)^{c} 5.74(0.04)^{b}	4.82(0.04)^{d} 5.22(0.02)^{c}	5.51(0.02)^{b} 6.17(0.06)^{a}	5.82(0.05)^{a} 6.27(0.03)^{a}
总碳 Total C (*w*/g kg^{-1})	RS BS	78.50(3.23)^{a} 67.20(3.22)^{a}	78.18(6.34)^{a} 54.48(3.65)^{b}	83.43(0.94)^{a} 67.68(3.85)^{a}	71.68(1.30)^{a} 38.46(2.04)^{c}
总氮 Total N (*w*/g kg^{-1})	RS BS	6.90(0.27)^{ab} 5.66(0.22)^{a}	5.92(0.50)^{b} 3.72(0.23)^{b}	7.60(0.14)^{a} 5.62(0.33)^{a}	6.16(0.18)^{b} 2.58(0.20)^{c}
碳氮比 C:N ratio (*r*/%)	RS BS	11.37(0.11)^{b} 11.86(0.16)^{b}	13.23(0.17)^{a} 14.65(0.44)^{a}	11.00(0.26)^{b} 12.08(0.48)^{b}	11.67(0.39)^{b} 15.02(0.52)^{a}

RS：根际土壤；BS：非根际土壤. 表中数据表示平均值（标准误）. 同一行内不同小写字母表示不同林地之间指标差异显著（$P < 0.05$）.

RS: Rhizosphere soil; BS: Bulk soil. The data in the table represent average value (standard error). Different lowercase letters in the same row indicate significant differences among four forest sites ($P < 0.05$).

条30 m长的采样线，采样线间隔超过20 m，在每条采样线上间隔5 m设置了6个50 cm × 50 cm的样方. 首先要去除表层的凋落物和有机层，然后采集矿质土壤上层15 cm范围内并且直径小于2 mm的附着土壤的细根[32]，然后利用“抖根法”仔细收集根际土壤. 具体地，轻轻抖掉细根表面的一些大块土壤，随后收集黏附在根表面的土壤，即定义为根际土[33]. 未黏附在根表面的土壤被认为是非根际土壤. 根际和非根际土壤收集完成后，将同一条采样线上的根际和非根际土壤样品分别合并为一个混合样品. 然后低温保存运至实验室进行后续指标分析.

1.3 室内分析

SOC含量采用元素分析仪燃烧的方法[34]测定. 具体步骤如下：使用1 mol/L的HCl溶液去除土壤样品中的无机碳，然后用超纯水冲洗土壤样品3次，待烘干土壤样品后用TOC分析仪（Multi N/C 2100，Analytik-Jena，Germany）测定SOC含量[32].

土壤碳官能团采用傅里叶变换红外吸收光谱法[35-36]测定. 相关操作如下：将过100目筛的干燥土壤样品与干燥的KBr以1:80的比例将样品在玛瑙研钵中研磨至粉末状（粒度小于2 μm），用手动压片机将粉末状的土壤样品压成透明薄片，然后立即用傅里叶变换红外光谱仪（Spectrum 100；PerkinElmer，MA，USA）扫描并记录其光谱数据. 根据文献调研，确定了与本研究相关的4个波峰区域：alkyl-C（2 985-2 820 cm^{-1}）、aromatic C=C（1 800-1 525 cm^{-1}）、O-alkyl-C（1 185-915 cm^{-1}）和aromatic CH（855-740 cm^{-1}）. 然后借助Omnic 8.3软件（Thermo Nicolet Corporation，USA）分析4个波峰区域的峰面积并计算峰面积比. 进一步计算脂肪族性（aliphatic，alkyl-C/O-Alkyl-C）、芳香性（aromaticity，aromatic-C/O-Alkyl-C）和组合指数（combination index，芳香性和脂肪族性之和）去表征SOM的稳定性[35].

土壤金属有机复合体中结合态铁和铝离子含量根据Keiluweit等描述的方法[18]进行测定. 具体地，将2 g鲜土与40 mL pH = 10的0.1 mol/L焦磷酸钠溶液混合，并在黑暗条件下使用200 r/min的速度在摇床上均匀振荡4 h. 随后，使用12 000 r/min的离心机离心样品15 min. 离心后，使用0.22 μm的乙酸纤维滤膜过滤上清液. 最后，利用电感耦合等离子体发射光谱仪（ICP-OES，Optima 8300，Perkin Elmer， USA）来测定滤液中的铁和铝离子含量[16].

土壤颗粒有机碳（POC）和矿物结合态有机碳（MAOC）采用湿筛法[10, 37]测定. 方法简述如下：将20 g预先风干并过筛的土壤（2 mm）分散在250 mL的锥形瓶中，加入100 mL 5%的六偏磷酸钠（NaHMP）摇动20 h以获得充分分散. 用去离子水在53 μm筛网上冲洗分散的土壤，直至通过筛网的水流清澈. 筛子上保留的部分为POM，而通过筛子的较细部分为MAOM. 将分离得到的POM和MAOM在65 ℃下干燥48 h，称重，研磨（100目）后测定各组分的C含量. POC（mg/g）、MAOC（mg/g）计算公式如下.

$$\text{Mass recovery} = (\text{MassPOM} + \text{MassMAOM})/\text{Mass} \times 100\% \quad (1)$$

$$\text{POC} = (\text{MassPOM} \times \text{OCPOM})/(\text{Masssoil} \times \text{Mass recovery}/100) \quad (2)$$

$$\text{MAOC} = (\text{MassMAOM} \times \text{OCMAOM})/(\text{Masssoil} \times \text{Mass recovery}/100) \quad (3)$$

式中，Masssoil是用于湿筛样品的土壤质量（g）；MassPOM和MassMAOM是湿筛后回收的POM和MAOM组分的质量（g）；Mass recovery是土壤质量的回收率；OCPOM、OCMAOC是POM和MAOC组分中各自测得的碳浓度（mg/g）.

1.4 数据处理与分析

采用SPSS 22.0软件（SPSS Inc.，Chicago，Illinois，USA）中的配对样本*t*检验（Paired *t*-test）分别比较不同林地内根际和非根际土壤之间SOC含量、POC和MAOC百分比、脂肪族性、芳香性、组合指数以及金属有机复合体中结合态铁和铝离子含量的差异显著性. 采用线性混合效应模型，分析根际和非根际土壤的SOC含量、POC和MAOC百分比、脂肪族性、芳香性、组合指数以及金属有机复合体中结合态铁和铝离子含量的显著性，其中将土壤位置（根际/非根际）作为固定效应，4个林地以及5个重复作为随机效应. 线性混合效应模型分析采用R 3.4.2 ‘nlme’ 软件包中的 ‘lme’ 完成. 采用线性回归模型分析根际土壤有机碳含量与官能团特征以及结合态铁和铝离子含量的相关性. 数据在分析前检验正态性和方差齐性，必要时进行对数转换，显著性水平设置为P < 0.05. 数据图全部采用Origin 2021b绘制，表采用Microsoft Excel 2010绘制.

2 结果与分析

2.1 根际/非根际SOC及其组分含量差异

在所选择的4个云杉人工林内，根际和非根际土壤对SOC含量以及组分的影响存在差异. 根际SOC有机碳含量均显著高于非根际土壤（图1）. 具体地，在4个林地内，根际平均SOC含量为77.95 mg/g，而非根际SOC含量仅为56.96 mg/g. 根际平均SOC含量约为非根际土壤的1.4倍. 根际土壤中MAOC的比例显著高于非根际土壤（表2）. 而POC的百分比则呈现相反的趋势.

2.2 根际/非根际土壤C官能团与金属结合态铁、铝离子含量差异

在所有观测的林地内，根际土壤碳官能团中alkyl-C和aromatic C=C的比例显著高于非根际土壤，而O-alkyl-C的比例显著低于非根际土壤（表3）. 基于4种官能团的相对比例计算的脂肪族性、芳香性和组

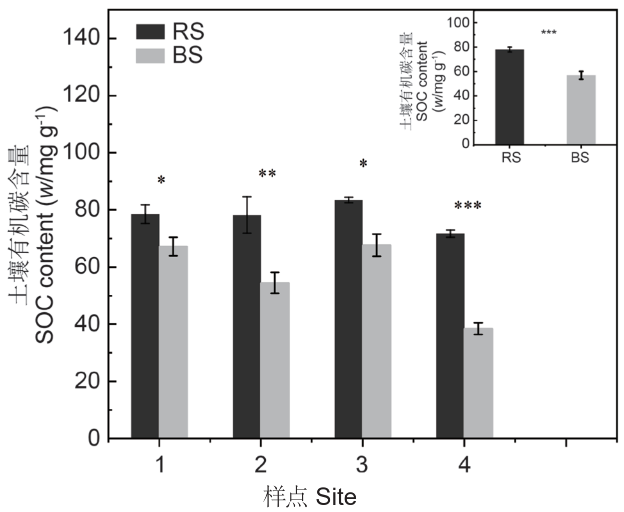

图1 4个样点根际和非根际土壤有机碳含量变化. RS：根际土壤；BS：非根际土壤. *、**、***分别表示根际和非根际土壤有机碳含量在P < 0.05、P < 0.01、P < 0.001水平上差异显著. 右上角图中星号表示线性混合效应模型中将林地和重复作为随机因子后，土壤位置（根际和非根际土壤）的影响. *** P < 0.001.

Fig. 1 Changes in organic carbon content in rhizosphere and bulk soils at the four sites. SOC: Soil organic carbon. RS: Rhizosphere soil; BS: Bulk soil. The symbols *, ** and *** indicate significant differences in organic carbon content between rhizosphere and bulk soils at the 0.05, 0.01, and 0.001 levels, respectively. The asterisk in the upper right corner of the figure represents the effect of soil position (rhizosphere and bulk soils) in a linear mixed effects model with forest land and repetition as random factors (*** P < 0.001).

表2 根际和非根际土壤中颗粒有机碳（POC）和矿物结合态有机碳（MAOC）的百分比

Table 2 Percentage of particulate ogranic carbon (POC) and mineral-associated organic carbon (MAOC) in the rhizosphere and bulk soil

样点 Site	土壤位置 Soil compartment	MAOC (P/%)	POC (P/%)
1	RS	67.00(1.75)a	33.00(1.75)b
	BS	43.74(0.38)b	56.26(0.38)a
2	RS	57.54(0.68)a	42.46(0.68)b
	BS	48.14(1.17)b	51.86(1.17)a
3	RS	56.60(0.78)a	43.40(0.78)b
	BS	49.84(0.99)b	50.16(0.99)a
4	RS	57.37(2.03)a	42.63(2.03)b
	BS	42.51(0.79)b	57.48(0.79)a

RS：根际土壤；BS：非根际土壤. 表中数据表示平均值（标准误）. 同一列内不同小写字母表示根际和非根际土壤在P < 0.05水平上差异显著.

RS: Rhizosphere soil; BS: Bulk soil. Values are means with SE. Different lowercase letters within a column denote significant differences between rhizosphere and bulk soils (P < 0.05).

合指数在根际土壤中分别为0.10、0.13和0.23，在非根际土壤中分别为0.06、0.09和0.15，根际土壤均显著高于非根际土壤（图2）. 相似地，根际土壤金属有机复合体中结合态铁和铝离子的浓度分别为3.42和1.84 mg/g，平均分别比非根际土壤高 51.15%和34.27%，且均达到显著水平（图3）.

2.3 土壤SOC含量与稳定性的关系

相关性分析表明，SOC的化学保护强烈影响了根际SOC含量. 根际SOC含量随土壤SOC化学保护程度的增强而增加（图4）. 具体而言，根际SOC含量与

表3 根际和非根际土壤有机碳官能团特征

Table 3 Functional group characteristics of soil organic carbon in the rhizosphere and bulk soil

样点 Site	土壤位置 Soil compartment	Alkyl-C	Aromatic C=C	O-Alkyl-C	Aromatic CH
1	RS	7.43(0.29)[a]	10.45(0.34)[a]	77.65(0.34)[b]	4.46(0.18)[b]
	BS	5.23(0.37)[b]	7.40(1.08)[b]	82.19(0.91)[a]	5.18(0.18)[a]
2	RS	7.28(0.86)[a]	9.82(0.59)[a]	76.83(1.21)[b]	6.07(0.36)[a]
	BS	4.59(0.28)[b]	7.95(0.46)[b]	81.67(0.47)[a]	5.79(0.20)[a]
3	RS	8.50(0.26)[a]	11.85(0.33)[a]	74.64(0.29)[b]	5.01(0.36)[a]
	BS	5.64(0.68)[b]	7.29(0.66)[b]	81.33(1.12)[a]	5.74(0.36)[a]
4	RS	7.43(0.24)[a]	9.08(0.23)[a]	78.05(0.40)[b]	5.45(0.21)[a]
	BS	5.60(0.50)[b]	6.48(0.92)[b]	82.11(1.59)[a]	5.36(0.30)[a]

RS：根际土壤；BS：非根际土壤. 表中数据表示平均值（标准误）. 同一列内不同小写字母表示根际与非根际之间各指标在P < 0.05水平上差异显著.

RS: Rhizosphere soil; BS: Bulk soil. Values are means with SE. Different lowercase letters within a column denote significant differences between rhizosphere and bulk soils (P < 0.05).

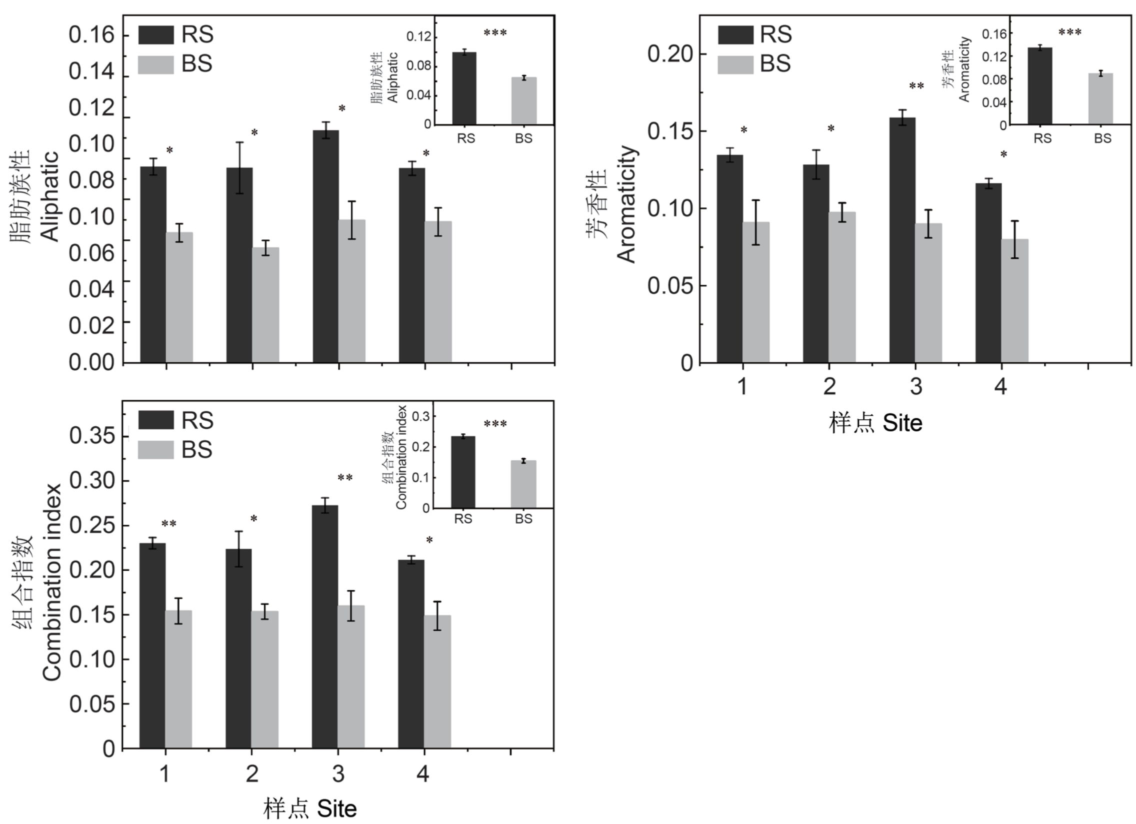

图2 4个样点根际和非根际土壤官能团指数变化. RS：根际土壤；BS：非根际土壤. *和**表示根际和非根际土壤官能团指数在P < 0.05和P < 0.01水平上差异显著. 右上角图中星号表示线性混合效应模型中将林地和重复作为随机因子后，土壤位置（根际和非根际土壤）的影响（*** P < 0.001）.

Fig. 2 Functional group index changes in rhizosphere and bulk soils at the four sites. RS: Rhizosphere soil; BS: Bulk soil. * and ** indicate significant differences in functional group indices between rhizosphere and bulk soils at the 0.05 and 0.01 levels, respectively. The asterisk in the upper right corner of the figure represents the effect of soil position (rhizosphere and bulk soils) in a linear mixed effects model with forest land and repetition as random factors (*** P < 0.001).

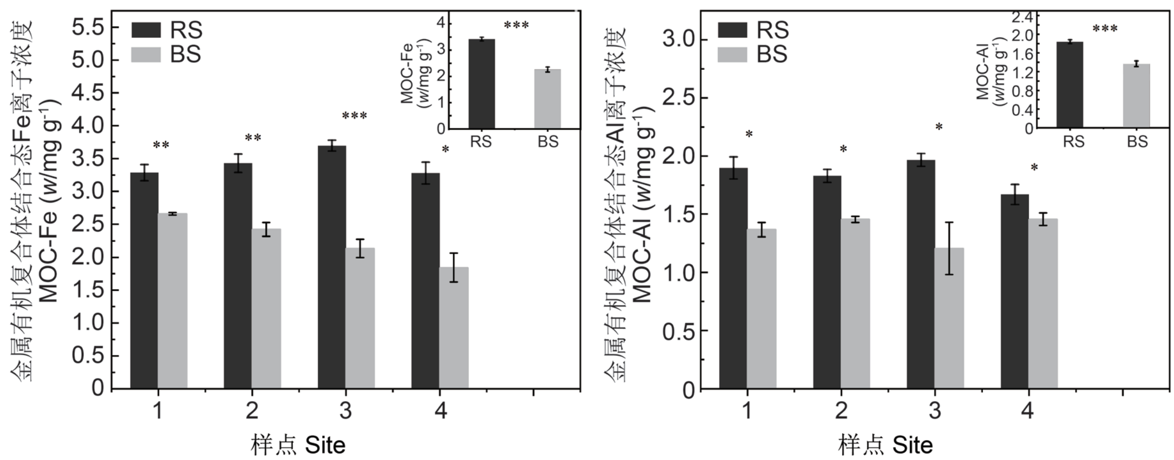

图3 4个样点根际和非根际土壤金属有机复合体中结合态Fe离子和Al离子浓度变化. RS：根际土壤；BS：非根际土壤. *、**、***分别表示根际和非根际土壤金属有机复合体中结合态Fe离子和Al离子浓度在P < 0.05、P < 0.01、P < 0.001水平上差异显著. 右上角图中星号表示线性混合效应模型中将林地和重复作为随机因子后，土壤位置（根际和非根际土壤）的影响（*** P < 0.001）.

Fig. 3 Changes in the concentration of bound Fe and Al ions in metal-organic complexes (MOC) in rhizosphere and bulk soils at the four sites. RS: Rhizosphere soil; BS: Bulk soil. The symbols of *, **, and *** indicate significant differences in the concentration of bound Fe and Al ions in MOC between rhizosphere and bulk soils at the 0.05, 0.01, and 0.001 levels, respectively. The asterisk in the upper right corner of the figure represents the effect of soil position (rhizosphere and bulk soils) in a linear mixed effects model with forest land and repetition as random factors (*** P < 0.001).

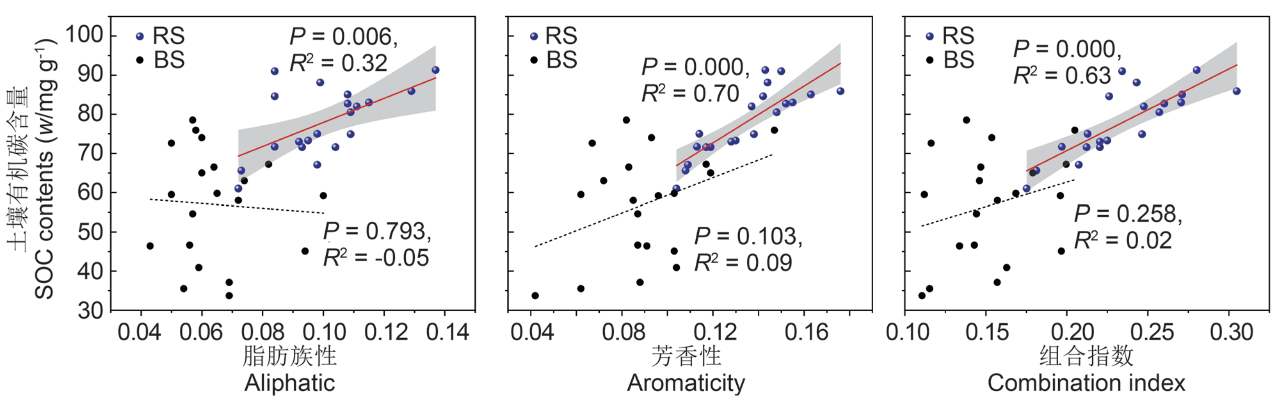

图4 4个样点根际和非根际土壤的脂肪族性、芳香性以及组合指数与土壤有机碳含量的线性回归分析.

Fig. 4 Linear regression analysis of the aliphatic, aromaticity, and combined index of rhizosphere and bulk soils with soil organic carbon (SOC) content at the four sites.

SOC的脂肪族性、芳香性和组合指数呈显著正相关关系. 相似地，根际SOC含量与金属有机复合体中结合态铁离子和铝离子浓度也表现出显著的正相关关系. 但在非根际，SOC含量并未与SOC的化学保护特性之间表现出显著相关关系（图5），表明根际SOC的积累与其较高的SOC稳定性密切关联.

3 讨论

根际SOC的周转和储存受到根源碳输入的强烈影响，导致SOC动态与非根际土壤存在显著差异，但目前对根际和非根际SOC储量和稳定性差异的认识仍存在诸多不确定性，这一知识差距严重限制了我们对陆地生态系统碳储量和动态及其对未来环境变化响应的准确评估和预测. 本研究通过多点采样并分析结果后发现，在亚高山云杉人工林中，与非根际土壤相比，根际具有更高的SOC含量，这一发现主要归因于根系诱导了较强的SOC的物理和化学保护作用（表现为MAOC和稳定性碳官能团的比例以及金属有机复合体含量更高）. 这些结果表明，根系介导的SOC储存在决定森林土壤碳储量中发挥关键作用，而且根际SOC含量的大小与SOC的物理和化学保护机制密切相关.

基于对根际土壤碳过程根际效应的全球数据分析结果表明，根际SOC含量大约比非根际土壤高52.6% [11]，在本研究中我们也检测到了类似的结果，根际SOC含量约为非根际土壤的1.4倍（图1），表明根际土壤碳固持能力在维持森林土壤碳汇潜力中发挥着

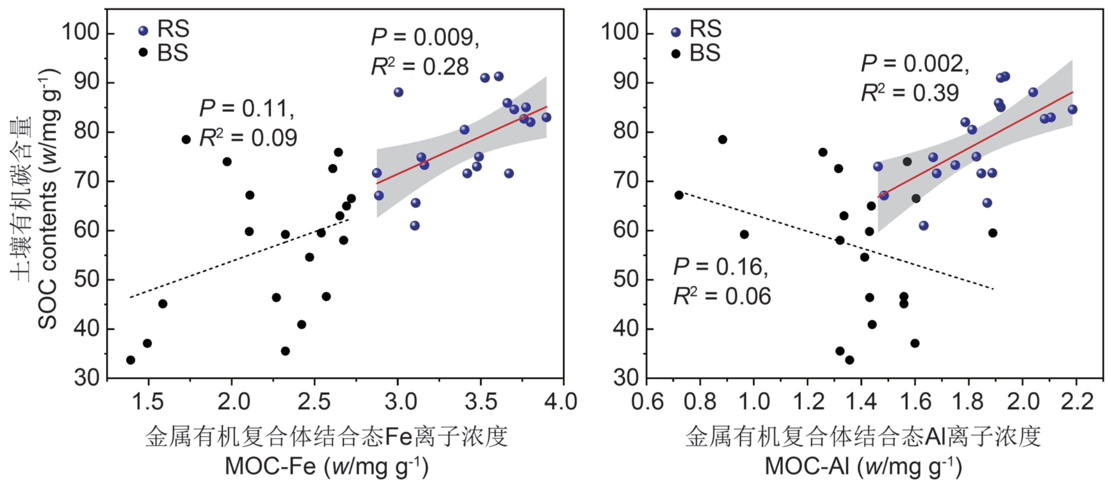

图5　4个样点根际和非根际土壤的金属有机复合体中结合态Fe离子和Al离子浓度与土壤有机碳含量的线性回归分析.
Fig. 5　Linear regression analysis of the concentrations of bound Fe and Al ions in metal organic complexes and soil organic carbon (SOC) content in rhizosphere and bulk soils at the four sites.

十分重要的作用. 根据以往的研究, 根源碳输入不仅能够导致根际土壤碳分解的激发效应, 同时也可以通过提高土壤有机碳的稳定性而导致碳积累, 二者的相对作用强度最终决定了土壤碳源/汇功能的转变[14]. 本研究对象为亚高山针叶林, 独特的生态学特征(例如低温)导致微生物对土壤有机质分解的速率较为缓慢[27-28], 同时也更加有利于土壤有机质的矿物吸附和团聚体的形成, 这些过程对SOC带来的较强的物理化学保护效应可能超过了微生物对有机质的分解效应, 而最终导致SOC的积累. 尽管这个推测已经在个别研究中得到了验证, 但这种决定根际土壤碳汇功能大小的重要非生物机制的普适性研究在未来仍需进一步开展. 此外, 近年来, 微生物源碳在稳定SOC形成中的重要作用被广泛关注. 微生物经过内部周转(合成代谢过程)的产物(主要是微生物坏死体)对SOM的长期固存和累积的意义更加重大, 因为它们能够在土壤中长期储存, 周转时间也远远长于腐殖质[38-40], 也是到目前为止发现的微生物贡献于稳定SOC库的主要形式[41-43]. 在不同的土壤微生物热点地区, 根际是一个独特的土壤区域, 由来自植物根系的充足且高质量的稳定碳输入(例如根沉积物)形成, 并拥有丰富多样性的微生物[44]. 根际微生物丰度高, 通过根源碳输入的顺序同化、合成和周转, 促进微生物副产物的形成[45-46]. 因此, 微生物生长和残体迭代积累的能力在根际可能比在非根际土壤中更大[47], 从而导致更大的SOC积累.

根际和非根际SOC的化学抗性差异可能是导致二者间SOC含量差异的一个重要原因. 以往的研究表明, 较高含量的SOC惰性组分能够促进土壤碳的固存和稳定性[7-8]. 基于官能团相对比例计算的脂肪族性(alkyl-C/O-alkyl-C ratio)、芳香性(aromatic-C/O-alkyl-C ratio)和组合指数((aromatic-C + alkyl-C)/O-alkyl-C ratio)被认为可以综合表征土壤有机质的稳定性[35-36, 48]. 与此一致的是, 在本研究中, 基于傅里叶变换红外吸收光谱分析, 我们发现根际土壤中alkyl-C和aromatic C=C官能团的比例显著高于非根际土壤(表2), 从而提高了根际SOC抵抗微生物分解的能力. 同时, 根际SOC官能团的脂肪族性、芳香性和组合指数均显著高于非根际土壤(表2), 进一步表明根际比非根际具有更高的土壤有机质稳定性. 通常, 来自根系的凋落物比叶片的凋落物更具有化学抗性[49], 尤其会在低氧和低温的土壤环境(例如北极和高山生态系统)中累积, 从碳来源角度解释了根际比非根际具有较高的惰性碳官能团比例. 最终, 根际较高的SOC稳定性驱动了根际SOC的积累并导致其含量显著高于非根际土壤(图2).

有研究发现, 土壤SOC库稳定性随土壤不同组分碳比例变化, 也是土壤碳源/汇功能的重要体现[50]. 惰性组分碳比例越大, 碳稳定性越强, 碳汇功能增强; 反之, 活性组分碳比例越大, 碳稳定性越差, 碳汇功能削弱[51]. MAOC与SOC之间有正相关关系也进一步表明SOC的积累可能归因于MAOC的变化, 而不是快速循环的POC [52]. 本研究发现根际MAOC比例显著高于非根际, POC则呈现相反趋势, 这表明根际土壤的稳定性大于非根际, 这种差异可能是因为来自根际的大量不稳定碳输入强烈刺激了根际土壤的微生物活动, 导致增加的微生物生物量对不稳定碳的快速利用和同化. 因此, 积累在根际的微生物合成代谢产物(主要是微生物残留物)会大量增加, 并可被输送到矿物相关的有机碳库, 从而提高了根际土壤碳的稳定性[53-54].

随着研究方法和手段的不断创新，大多数有机复合物与活性金属或矿物颗粒结合形成物理化学特性稳定的矿物/金属-有机复合体的现象在矿质土壤中被发现并逐渐受到重视[55-56]，因为这种结合产物大大限制了微生物和胞外酶对SOM的分解作用而抑制了土壤碳循环过程[57]，被认为是维持SOC长期固存和持久稳定的最重要途径[7]. 据估算，根源输入对矿物结合态碳的贡献约为地上输入的1.5-10倍，约占总SOC的75% [58]. 在本研究中，我们发现根际土壤金属有机复合体中结合态铁/铝离子含量显著高于非根际土壤（图3），并与根际SOC含量的变化显著正相关（图5）. 根际土壤结合态铁/铝离子含量较高的原因可能是由于根系分泌物中的有机酸会导致pH值降低，促进土壤中铁/铝离子的溶解，使其更容易形成结合态离子[59]. 此外，云杉人工林独特的菌根共生也可能是导致根际SOC含量和稳定性较高的原因之一. 菌根菌丝是除根系之外植物光合产物的另一个重要传输者，甚至超过了根系的传输量[60]. 外生菌根真菌的分泌物中芳香族代谢物的比例超过10%，能显著增强矿物表面有机物的吸附[20]. 同时菌丝还能通过缠绕作用和释放黏液等生理过程提高团聚体和矿物有机复合体的形成速率[61]，从而增强根际SOC的稳定性. 因此，根系活动驱动的较强的土壤金属离子与有机质的结合能力是导致根际SOC含量显著高于非根际土壤的一个关键过程. 云杉人工林的4个样地，每个样地背景值有所差异，但是都印证了根际土壤的SOC的积累和稳定性更强这一结论，使得我们的研究结果更具有普适性.

4　结论

与非根际相比，根际SOC含量显著升高，这主要是由于根际SOC的物理和化学保护程度更高，能够更大程度地抵抗微生物分解. 具体表现为根际SOC具有更大比例的惰性碳组分（MAOC）和官能团以及更高含量的金属有机复合体. 本研究结果强调了根际在调控土壤碳积累和稳定中发挥着不可忽视的关键作用. 相应地，将根际和非根际土壤碳储量差异整合到陆地生态系统土壤碳循环模型将有助于更加准确地评估和预测陆地生态系统土壤碳源/汇功能.

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