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温带过渡区4种典型天然林土壤有机碳组分与碳库管理指数变化特征

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摘 要 探究温带过渡区典型天然林土壤有机碳组分与碳(C)库管理指数变化特征及其影响因素, 对提升土壤C储量和林地质量并制定合理有效的营林管护措施具有十分重要的现实意义。以山西庞泉沟国家级自然保护区境内的白桦(*Betula platyphylla*)林(BP)、青杆(*Picea wilsonii*) +华北落叶松(*Larix gmelinii* var. *principis-rupprechtii*) +桦树(*Betula*)针阔混交林(PLB)、白杆(*Picea meyeri*) +青杆针叶混交林(PP)和华北落叶松林(LP)等4种林型为对象, 以灌草地为对照(CK), 采集0–20 cm土层土壤样品, 分析了土壤有机碳(SOC)、可溶性有机碳(DOC)、易氧化有机碳(EOC)、微生物生物量碳(MBC)和惰性有机碳(ROC)含量以及C库管理指数(CPMI)对林型变化的响应及其影响因素。发现: (1) SOC含量为PP > PLB > BP > LP, 较CK分别增加了74.22%、41.62%、39.05%和3.01%; 4种天然林林型的DOC、EOC、MBC和ROC含量变化趋势与SOC相似, 但DOC和MBC含量变化不显著。(2) DOC:SOC和ROC:SOC受林型显著影响, LP的DOC:SOC和BP的ROC:SOC分别显著高于和低于其他3种天然林; 其余C组分含量对SOC含量的贡献未见显著变化, 均表现为PP中最低和LP中最高。(3) CPMI受林型显著影响, 其变化趋势与SOC含量相似。冗余分析和随机森林分析显示: 全氮和硝态氮含量是影响C组分含量和CPMI的主导因素, 其次是土壤含水量、有效钾含量和pH值。总体上, 混交林尤其是针叶混交林提高了土壤C组分含量和CPMI, 改善了土壤质量, 有助于土壤C储存; 土壤氮含量、水分含量及土壤酸碱度在预测温带过渡区森林生态系统土壤C库变化中起着关键的作用。因此, 适当增加土壤氮含量和改善物种多样性可能是提高温带过渡区天然林土壤C固存的有效手段。

关键词 林型; 土壤有机碳; 土壤有机碳组分; 土壤碳库管理指数; 温带过渡区

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Characteristics of soil organic carbon fractions and carbon pool management index in four typical natural forests in temperature-transition zone

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Abstract

Aims The present study aimed to quantify the characteristics of soil organic carbon (SOC) fractions and the carbon (C) pool management index (CPMI) in the topsoil (0–20 cm) of the four different natural forest types in the temperate climate-transition area in Pangquangou National Nature Reserve, Shanxi Province. The study's findings may offer a potential valuable reference and significant insight into enhancing soil C storage and the forestland quality, as well as the sustainable forest management within native woodlands in the future.

Methods A total of four forest types, which were characterized by similar site conditions, were selected to investigate the variations and influencing factors of soil C fractions and the CPMI in the topsoil layer. Here, soil samples were collected from representative forestlands, including *Betula platyphylla* forest (BP), *Picea wilsonii* +

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Larix gmelinii var. *principis-rupprechtii* + *Betula* conifer-broadleaf mixed forests (PLB), *P. meyeri* + *P. wilsonii* conifer mixed forest (PP), *L. principis-rupprechtii* forest (LP) and scrub-grass land (CK), respectively. The contents of SOC and its fractions were measured, and CPMI was calculated. Pearson correlation and redundancy analysis (RDA) were used to examine the relationships between soil environmental factors and carbon pool characteristics. Random forest analysis (RFA) was used to identify the soil properties significantly affecting the soil C fractions and CPMI.

Important findings The buildup of SOC and its fractions, as well as soil C pool index (CPI) and CPMI, was influenced by the distinct species composition and forest structure of different forest types. First, the contents of SOC were as follows: PP > PLB > BP > LP, which increased by 74.22%, 41.62%, 39.05% and 3.01% respectively in the topsoil layer compared to CK. For soil C components, dissolved organic carbon (DOC), easily oxidizable organic carbon (EOC), microbial biomass carbon (MBC) and recalcitrant organic carbon (ROC) contents from the different forest types followed similar trends to the concentration of SOC at the surface layer where PP recorded the maximum concentration. Here we show that MBC and DOC contents did not vary significantly among different forest types. Second, our data clearly evidenced that the DOC:SOC and ROC:SOC were significantly higher and lower in LP and BP, respectively, in comparison to the other three forest types. Conversely, the EOC:SOC, MBC:SOC and AOC:SOC remained consistent, and no significant differences were observed among the four forest types, with the PP exhibiting the lowest values. Third, the variation tendency of CPMI followed the same trend as SOC, while the CPMI in LP was significantly lower than that observed in other forest types. RDA revealed that TN and NO_3^--N contents play a prominent role in the variation characteristics of soil C pools in the natural forests in the temperate climate-transition zone. Furthermore, we observed that soil water content and available potassium had a significant impact on soil C fractions, while the CPMI was significantly affected by soil water, pH and TP. Taken together, our findings demonstrate that both temperate mixed forests, especially coniferous mixed forests promoted SOC stock by increasing C pool fractions contents, which in turn promoted soil fertility and quality of the forest land in a temperate transition zone. The results of this study emphasize the key role of the interplay between soil nitrogen, soil water and soil pH in predicting soil C pool in temperate forests. Consequently, these results should be considered by the forestry sectors, and suggest that the forest ecological restoration should promote biodiversity especially conifer species in the context of improving C stock and soil quality in temperate forests. Thus, it is predicted that increasing soil nitrogen and species diversity may be an effective measure for improving soil C sequestration in natural forest ecosystems in the temperate climate-transition zone.

Key words forest type; soil organic carbon; soil organic carbon fractions; soil carbon pool management index; temperate-transition zone

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森林土壤作为陆地碳(C)汇的重要组分, 储存了陆地生态系统中约50%的土壤有机碳(SOC) (Mayer et al., 2020), 其微弱变化会对全球C循环和气候变化产生重要影响(de Deyn et al., 2008; Hao et al., 2021)。SOC有助于维持土壤质量和森林物种多样性(Arias et al., 2005; Zarafshar et al., 2024), 其含量常被作为评价土壤质量与肥力以及土地生产力的指标(Jiang & Xu, 2006; Yao et al., 2023)。亦有研究认为, SOC含量只是有机质输入速率和分解速率的平衡结果, 不能反映SOC质量的变化(Yang et al., 2018), 且在短期内不易被监测, 对环境变化的响应速度不及活性有机碳(AOC)组分(Chen et al., 2014), 不能很好地表征土壤C库以及土壤质量的变化(Kara & Bolat, 2008; Yang et al., 2018)。大量研究表明, 来源于腐殖质、凋落物分解、根系分泌物、土壤微生物及其代谢产物的AOC, 不仅是植物和土壤微生物生长的营养及能量, 也是根系分泌物和微生物代谢产物的重要组分(Li et al., 2018); 因AOC容易被矿化、分解和氧化, 对生境变化的敏感性高于SOC, 能及时反映土壤C库的变化, 被认为是衡量土壤C库和土壤质量变化的敏感指标(Fang et al., 2014; 贾匡迪等, 2024; Zarafshar et al., 2024)。来源于动植物残体及其腐解产物、微生物残体以及碎屑物质的稳态有机碳(以惰性有机碳表征, ROC), 具有理化性质稳

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定、难分解、周转时间长(徐嘉晖等, 2018)、不易被微生物分解以及C矿化效率较低等特点(陈宗定等, 2019; Zhou et al., 2023), 可助力土壤C的长期封存(Yang et al., 2018; Xu et al., 2020), 被认为是土壤固C潜力的可靠指标和对环境长期变化的响应指标(Knorr et al., 2005; Dong et al., 2022; Zhou et al., 2023)。因此, 综合评价AOC和ROC在土壤中的分布情况, 能更全面地反映林型变化对SOC的影响(Pang et al., 2019; 滕秋梅等, 2020)。

一般认为, 阔叶林或混交林的SOC及其活性组分含量高于针叶林(Liang et al., 2021; Lee et al., 2024), 但也有相悖结论(Shi et al., 2023; 张金硕等, 2024), 说明林型对SOC及其组分的影响各不相同(李书杨等, 2018; Chen et al., 2021), 主要源于不同林型的地表凋落物数量和质量及其分解速率、根系结构及其分泌物、微生物以及优势物种功能性状存在差异, 使得C输入的成分不同(Chen et al., 2021; Lee et al., 2024), 进而改变了C输入和C损失的平衡态(Mayer et al., 2020), 最终导致SOC形成及其组分含量和C库稳定性的变化(辜翔等, 2016; Mayer et al., 2020; Liang et al., 2021)。最近有研究表明, 输入土壤的活性C会通过微生物同化或物化保护, 将其部分转化为SOC (Zhao et al., 2024); SOC含量的增加主要受进入土壤的新C质量或植物生物量限制, 而不受现存土壤C分解的限制(Lange et al., 2015)。可见, 林型对C组分的影响较复杂, 迄今尚未达成共识。

基于SOC和易氧化有机碳(EOC)建立的碳库管理指数(CPMI), 是C库活度指数与C库指数的乘积(Blair et al., 1995), 已成为表征森林生态系统土壤C库质量和C稳定性的敏感性指标(Blair et al., 1995; Shi et al., 2023; 王磊等, 2023), 是土壤质量评价的有用参数(蔡华等, 2023; Wang et al., 2024), 也是研究土壤C库的一个关键内容。有研究表明, CPMI与SOC和AOC含量呈显著正相关关系(滕秋梅等, 2020; Shi et al., 2023); 亦有研究显示, CPMI与SOC和AOC含量分别表现为相关性不显著和显著正相关(毛馨月等, 2025), 以及CPMI与SOC及其活性组分含量负相关(王磊等, 2023)。这些结果说明, CPMI作为指示土壤C库的变化及其稳定性的表征指标有待商榷。从已有研究看, 以前对CPMI的探究多集中在土地管理实践、植被更新恢复以及亚热带森林生态系统等方面(Vieira et al., 2007; 闫丽娟等, 2019; 蔡华等, 2023; Wang et al., 2024)。相比之下, 对温带地区尤其是中温带-暖温带过渡区不同天然森林类型间的CPMI呈现何种变化特征的了解较为欠缺, 这就限制了人们对该区域森林生态系统土壤C库的质量及其稳定性机制的深入了解。因此, 明确CPMI对林型变化的响应特征, 对预测该区域土壤C固存具有重要意义。

温带森林约占全球森林面积的25% (周广胜等, 2002), 其土壤C储量约占全球森林土壤C储量的18% (Pan et al., 2011; Mayer et al., 2020)。我国温带森林面积占全国森林总面积的35.3%, 其土壤C含量的变化在一定程度上影响着我国乃至世界的C储量估算。然而人们对该区域尤其是中-暖温带过渡区不同林型土壤C组分和CPMI变化特征及其主要影响因素了解不足。探究土壤C组分及CPMI对林型变化的响应特征及其控制因素, 可深入了解该区域SOC固存机制及其影响因素, 对有关部门制定应对气候变化的区域策略和实现“碳中和”战略目标具有重要的理论指导和现实意义。为此, 在山西庞泉沟国家级自然保护区选取4种典型天然林分类型, 以灌草地为对照(CK); 测定土壤基本理化性质、SOC及其活性组分含量等指标, 旨在: (1)揭示土壤C组分含量及CPMI对林型变化的响应变化特征; (2)探讨影响C组分含量与CPMI变化的主要因素, 并指出何种C组分能很好地表征SOC含量的变化。我们假设: (1)混交林SOC及其组分含量高于阔叶或针叶林; (2) ROC比活性C组分更能反映SOC的长期积累。旨在为提升温带过渡区森林土壤C储量和林地质量的评估提供理论依据, 亦可为该区域森林生态系统制定合理有效的营林管护措施提供参考。

1 材料和方法

1.1 研究区概况

庞泉沟国家级自然保护区位于山西省吕梁市交城县、方山县和娄烦县交界处(111.37°–111.55° E, 37.75°–37.92° N), 主要受温带大陆性季风气候影响, 具有半湿润气候特点, 是中温带到暖温带过渡区。保护区内主要分布有温性落叶阔叶林及其混交林、寒温性针阔混交林和针叶混交林等植被类型, 森林覆盖率86%, 是我国华北落叶松(*Larix gmelinii* var. *principis-rupprechtii*)天然原始林和次生林集中分布

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地带, 拥有“华北落叶松之乡” “华北绿肺”以及黄土高原“绿色明珠”的美誉。保护区内多年平均气温为4.3 ℃; 年降水量约820 mm, 降雨主要集中在7–9月, 约占全年降水量的83.0%。土壤以山地褐土和山地棕壤为主。实验地主要物种有华北落叶松、白杆(*Picea meyeri*)、青杆(*P. wilsonii*)、云杉(*P. asperata*)、白桦(*Betula platyphylla*)、红桦(*B. albosinensis*)、花楸树(*Sorbus pohuashanensis*)、辽东栎(*Quercus wutaishanica*)、山杨(*Populus davidiana*)、毛榛(*Corylus mandshurica*)、白榆(*Ulmus pumila*)、沙棘(*Hippophae rhamnoides*)等; 草本物种主要有披针薹草(*Carex lancifolia*)、东方草莓(*Fragaria orientalis*)、欧洲唐松草(*Thalictrum aquilegifolium*)等。

1.2 样地设置与土壤样品采集

2023年8月上中旬, 经实地探勘, 根据地形特征相似性原则, 选择文峪河上游4种典型林分类型, 即白桦落叶阔叶林(BP, 阔叶林)、青杆+华北落叶松+桦木针阔混交林(PLB, 针阔混交林)、白杆+青杆针叶混交林(PP, 针叶混交林)和华北落叶松针叶林(LP, 针叶林) 4种天然林为对象, 以孝文山林场的灌草丛为对照(CK)。每种林型随机布设相距≥30 m的6个20 m × 20 m标准样方, 并进行植物群落调查, 记录物种名、胸径、树高、郁闭度、凋落物厚度等(表1); 在每个样方内按照“梅花五点”法布设5个1 m × 1 m小样方, 记录草本物种名称、数量、高度和盖度等。

在每个标准样方内再按照“田”字形划分4个10 m × 10 m亚样方, 在每个亚样方内按“梅花五点”法布设取样点, 去除地表凋落物后, 用不锈钢土钻采集0–20 cm土壤样品, 将其20个取样点土壤样品捡去植物残体、细根等并充分混匀后, 按四分法取两份混合样, 一份装入无菌塑料自封袋室温保存; 另一份装入无菌塑料自封袋放入泡沫保温箱(内置冰袋)运至实验室。过2 mm筛后, 分别放置于室内自然风干和–40 ℃冰箱中保存, 直至后续实验处理。

1.3 指标测定

土壤容重(BD)用环刀法测定; 土壤含水量(SW)用烘干法测定; 土壤pH用赛多里斯PB-10型pH计测定; 土壤全氮(TN)含量用凯氏定氮法测定; 铵态氮(NH_4^+-N)和硝态氮(NO_3^--N)含量用靛酚蓝比色法, 利用UV-2450紫外分光光度计测定; 土壤全磷(TP)和土壤有效磷(AP)含量用钼锑抗比色法, 利用UV-2450紫外分光光度计测定; 土壤全钾(TK)、速效钾(AK)含量用火焰光度计法测定。SOC含量用重铬酸钾氧化外加热法测定。

EOC含量用高锰酸钾氧化法测定: 称取2 g风干土样并加入25 mL的333 mmol·L^{-1}高锰酸钾氧化,

表1 不同林型样地的基本特征(平均值±标准误)
Table 1 Basic characteristics of the studied sample plots (mean ± *SE*)

林型 Forest type	海拔 Mean altitude (m)	坡度 Mean slop (°)	平均郁闭度 Mean canopy density (%)	平均林分密度 Mean stand density (stems·hm^{-2})	平均胸径 Mean DBH (cm)	乔木层平均树高 Tree layer mean tree height (m)
BP	2 027	26	73.50 ± 1.38^{b}	2 637 ± 400^{a}	17.57 ± 1.21^{c}	15.88 ± 0.56^{b}
PLB	2 036	28	79.33 ± 2.34^{a}	1 554 ± 693^{b}	23.91 ± 2.76^{b}	16.39 ± 1.42^{b}
PP	2 157	28	76.00 ± 1.79^{ab}	1 166 ± 281^{b}	27.97 ± 2.00^{a}	21.48 ± 0.43^{a}
LP	1 974	25	75.83 ± 2.14^{b}	1 662 ± 279^{b}	25.88 ± 2.87^{ab}	18.61 ± 0.91^{b}
CK	2 017	33	–	–	–	–

林型 Forest type	灌木层平均盖度 Shrub layer mean coverage (%)	灌木层平均高度 Shrub layer mean height (m)	草本平均盖度 Herbaceous mean coverage (%)	草本平均高度 Herb layer mean height (cm)	苔藓层平均盖度 Moss layer mean coverage (%)	凋落物平均厚度 Litter mean thickness (cm)
BP	13.03 ± 2.11^{b}	5.27 ± 0.99^{b}	41.65 ± 3.61^{a}	8.35 ± 0.56^{a}	–	2.41 ± 0.94^{a}
PLB	22.62 ± 12.22^{a}	7.76 ± 1.63^{b}	31.80 ± 3.88^{b}	7.95 ± 2.29^{a}	7.78 ± 2.16^{b}	1.64 ± 0.25^{b}
PP	4.70 ± 4.14^{b}	11.97 ± 3.71^{a}	31.00 ± 3.28^{b}	7.27 ± 0.81^{a}	38.85 ± 7.88^{a}	1.74 ± 0.45^{ab}
LP	18.61 ± 2.24^{b}	7.73 ± 0.50^{b}	28.22 ± 2.72^{b}	6.91 ± 0.78^{a}	8.95 ± 7.35^{b}	1.86 ± 0.40^{ab}
CK	–	1.00 ± 0.28	66.50 ± 13.98	4.60 ± 5.70	–	–

BP, 白桦林; CK, 灌草丛; LP, 华北落叶松林; PLB, 青杆+华北落叶松+桦木针阔混交林; PP, 白杆+青杆针叶混交林。不同小写字母表示林型间差异显著($p < 0.05$)。
BP, *Betula platyphylla* forest; CK, scrub-grassland; LP, *Larix gmelinii* var. *principis-rupprechtii* forest; PLB, *Picea wilsonii* + *Larix gmelinii* var. *principis-rupprechtii* + *B. platyphylla* mixed conifer-broadleaf forest; PP, *P. meyeri* + *P. wilsonii* mixed conifer forest. Different lowercase letters indicate significant differences between different forest types ($p < 0.05$).

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振荡1 h (250 r·min^{-1})后, 离心5 min (4 000 r·min^{-1}), 取上清液稀释250倍后, 使用紫外分光光度计在565 nm波长比色测定, 根据$KMnO_4$浓度的变化计算EOC含量。可溶性有机碳(DOC)用超纯冷水浸提法测定: 浸提水土质量比4:1 (20 mL超纯水, 5 g鲜土), 25 ℃ 250 r·min^{-1}条件下恒温振荡30 min后, 离心10 min (4 000 r·min^{-1}), 使用0.45 μm滤膜对上清液进行抽滤, 用岛津TOC-L CPH分析仪(Shimadzu, Kyoto, Japan)测定含量。微生物生物量碳(MBC)用氯仿熏蒸-直接浸提法: 称取5 g鲜土两份, 一份氯仿熏蒸处理, 另一份未熏蒸处理。抽真空至氯仿沸腾后保持5 min后将其置于黑暗中静置24 h, 取出土壤样品加入20 mL 0.5 mol·L^{-1} K_2SO_4, 振荡浸提30 min, 使用0.45 μm滤膜过滤后, 将滤液稀释20倍后, 立即用日本岛津TOC-L CPH分析仪测定全碳含量, 利用提取碳计算MBC含量: MBC (mg·kg^{-1}) = (熏蒸C–未熏蒸C)/0.45 (Vance et al., 1987; Zhou et al., 2023)。惰性有机碳(ROC)用酸水解法提取: 称取2 g风干土置于消煮管中, 加入5 mL 6 mol·L^{-1} HCl摇匀, 125 ℃下消煮16 h, 待样品冷却后使用蒸馏水将其洗至中性, 再于55 ℃下烘干, 研磨过180 μm筛, 用重铬酸钾氧化外加热法测定含量。

1.4 数据计算

1.4.1 土壤碳组分对有机碳的贡献

土壤C组分对有机碳的贡献用各C组分含量占SOC含量的百分比表示, 即为土壤C组分含量/SOC含量×100%; AOC含量用DOC、EOC和MBC含量的总和表示。此外, 利用AOC含量的几何平均值(GMC)表征土壤C库稳定性(Yu et al., 2022), 数值越低, 说明SOC越稳定, 统计公式如下:

$$GMC = \sqrt[3]{DOC + EOC + MBC} \quad (1)$$

1.4.2 土壤碳库管理指数

以灌草丛土壤为CK, 计算前述4种林型的土壤C库活度(CPA)、C库活度指数(CAI)、C库指数(CPI)和CPMI (Blair et al., 1995), 以反映SOC含量和质量的变化, 亦可表征C库稳性和SOC质量的变化。CAI主要是综合EOC和稳态碳含量两个指数, 其数值越高, 土壤C库质量越高, C库稳定性越低(Pang et al., 2019; 蔡华等, 2023); CPMI用CAI和CPI的乘积表示, 其数值越大, 表示外源有机物对CPA和CPI质量的促进作用就越强, 越能反映C库的稳定性, 而土壤C库质量也会越高(Lange et al., 2015)。计算公式如下:

$$C_{SS} = SOC - EOC \quad (2)$$

$$CPA = EOC/C_{SS} \quad (3)$$

$$CAI = CPA_{sam}/CPA_{ref} \quad (4)$$

$$CPI = SOC_{sam}/SOC_{ref} \quad (5)$$

$$CPMI = CAI \times CPI \times 100 \quad (6)$$

式中, Css为土壤稳态C含量, CPA_{sam}为样品C库活度, CPA_{ref}为CK土壤C库活度; SOC_{sam}为样品SOC含量, SOC_{ref}为CK的SOC含量。

1.5 数据统计分析

用SPSS 28.0软件进行单因素方差分析和邓肯多重比较, 检验4种林型SOC含量、土壤C组分含量及其占SOC百分比、CPI和CPMI的显著性差异($p < 0.05$); 利用独立样本t检验揭示天然林型与对照间的土壤理化性质以及C组分含量及其占SOC百分比的显著性差异($p < 0.05$)。用RStudio软件中的“linkET”进行Pearson分析和mantel检验, 以确定土壤CPI和CPMI与土壤理化因子和物种多样性之间的关系, 并利用“ggplot 2”包制作图片。用冗余分析(RDA)确定土壤理化性质对土壤C组分和CPMI总体变化的相对贡献。进一步采用随机森林(RStudio软件中的“rfPermute”包)分析方法确定显著影响SOC及其组分含量和CPMI变化的环境因子, 并利用“randomForest”包对其进行相对重要性排序。此外, 利用Origin 2021软件制作均值图。文中数据为平均值±标准误。

2 结果和分析

2.1 土壤有机碳及其组分含量的变化特征

林型对SOC含量有显著影响(表2), 表现为PP > PLB > BP > LP, 较CK分别高出74.22%、41.62%、39.05%和3.01%, 其中PP的SOC含量显著高于LP (高69.13%), 而与BP (高25.30%)和PLB (高23.02%)差异不显著; 虽然BP和PLB较LP高出34.98%和37.47%, 但差异不显著。4种林型SOC含量极显著高于CK (高出39.47%)。此外, 从表2可看出, DOC、EOC和MBC含量的变化趋势与SOC含量一致, 其中EOC含量受到林型变化的影响极显著, 而DOC含量则接近显著性水平, 但MBC含量变化不显著。PP的DOC含量显著高于BP、PLB和LP, 分别高出20.61%、14.85%和16.73%, 相较于CK高出25.28%, 4种林型DOC含量的均值略高出CK的11.39%。4种林型的EOC和MBC平均含量极显著或显著高于CK,

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表2 不同林型土壤理化性质(平均值±标准误)
Table 2 Selected physical-chemical properties of soil at different forest types (mean ± *SE*)

土壤理化性质 Soil physical-chemical property	BP	PLB	PP	LP	CK	Sig. (*p*)
土壤容重 Soil bulk density (g·cm^{-3})	1.13 ± 0.04^{a}	1.05 ± 0.08^{a}	0.98 ± 0.10^{a}	1.11 ± 0.04^{a}	1.14 ± 0.07^{ns}	0.434
含水量 Water content (%)	20.32 ± 2.31^{b}	24.56 ± 3.07^{ab}	30.13 ± 3.22^{a}	21.45 ± 1.07^{b}	28.90 ± 2.36^{ns}	0.058
pH	6.49 ± 0.05^{a}	6.08 ± 0.07^{b}	6.44 ± 0.05^{a}	5.89 ± 0.09^{b}	5.80 ± 0.08**	<0.001
土壤有机碳含量 Soil organic carbon content (g·kg^{-1})	52.12 ± 16.22^{ab}	53.08 ± 12.64^{ab}	65.31 ± 11.30^{a}	38.61 ± 15.75^{b}	37.48 ± 4.75***	0.032
可溶性有机碳含量 Dissolved organic carbon content (mg·kg^{-1})	251.55 ± 23.68^{b}	264.18 ± 29.54^{b}	303.40 ± 22.77^{a}	259.92 ± 46.61^{b}	242.17 ± 20.60^{ns}	0.051
易氧化有机碳含量 Easily oxidizable organic carbon content (g·kg^{-1})	7.80 ± 0.82^{b}	8.28 ± 0.39^{ab}	8.80 ± 0.84^{a}	5.83 ± 0.74^{c}	4.11 ± 1.94***	<0.001
微生物生物量碳含量 Microbial biomass carbon content (mg·kg^{-1})	729.79 ± 45.50^{a}	742.33 ± 65.93^{a}	808.69 ± 53.86^{a}	652.63 ± 62.90^{a}	569.45 ± 36.25*	0.324
惰性有机碳含量 Recalcitrant organic carbon content (g·kg^{-1})	32.73 ± 8.01^{b}	42.20 ± 10.18^{ab}	53.06 ± 9.31^{a}	35.33 ± 15.15^{b}	31.85 ± 11.05*	0.021
活性有机碳含量 Active organic carbon content (g·kg^{-1})	8.78 ± 0.36^{b}	9.28 ± 0.21^{ab}	9.92 ± 0.37^{a}	6.75 ± 0.37^{c}	4.93 ± 10.79***	<0.001

BP, 白桦林; CK, 灌草丛; LP, 华北落叶松林; PLB, 青杆+华北落叶松+桦木针阔混交林; PP, 白杆+青杆针叶混交林。不同小写字母表示林型间差异显著($p < 0.05$)。ns表示不同天然林型与CK之间没有显著性差异($p > 0.05$); *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$。Sig. 是指采用单因素方差分析以检验不同指标在4种林型之间的显著差异($\alpha = 0.05$)。

BP, *Betula platyphylla* forest; CK, scrub-grassland; LP, *Larix gmelinii* var. *principis-rupprechtii* forest; PLB, *Picea wilsonii* + *Larix gmelinii* var. *principis-rupprechtii* + *B. platyphylla* mixed conifer-broadleaf forest; PP, *P. meyeri* + *P. wilsonii* mixed conifer forest. Different lowercase letters indicate significant differences between different forest types ($p < 0.05$). ns imply no significant differences between natural forest types and CK in the table ($p > 0.05$); *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$. Sig. in the table refers than the physical-chemical properties and soil carbon fractions content across four forest types use the least significant difference of one-way ANOVA testing at the 0.05 level.

分别高出了86.64%和28.78%, 其中EOC含量在PP和PLB之间以及BP和PLB之间差异不显著, 而MBC含量在不同林型间未见显著差异。

林型对ROC含量影响显著, 其变化与SOC含量变化趋势一致(表2), 其中PP和PLB之间以及BP、PLB和LP之间未见显著性差异, 4种林型ROC含量的均值较CK显著高出了28.20%; AOC含量的变化趋势与ROC含量一致, 且受到林型的极显著影响, 表现为PP与PLB及PLB与BP间的差异不显著, 但均显著高于LP, 4种林型AOC的平均含量极显著高于CK, 达到了76.12%。

2.2 土壤碳组分对有机碳的相对贡献

土壤C组分对SOC的相对贡献表现为: ROC > EOC > MBC > DOC, 分别介于64.86%–90.86%、13.66%–16.57%、1.26%–1.82%和0.48%–0.72% (图1)。从图1可看出, 林型对DOC:SOC和ROC:SOC影响显著(图1A、1D), 对MBC:SOC影响接近显著水平(图1C), 而对EOC:SOC和AOC:SOC未产生显著影响(图1B、1E)。具体表现为: 4种林型中, LP的DOC:SOC最高, 显著高于BP、PP和LP, 且均值与CK差异不显著(图1A); 不同林型的EOC:SOC未见显著差异, 但均显著高于CK (图1B); LP的MBC:SOC显著高于PP, 略高于BP和PLB (图1C), 4种林型的MBC:SOC均值与CK差异显著。4种林型ROC:SOC表现为LP最高(90.86%), 显著高于BP (64.86%), 但与PLB (79.80%)和PP (81.55%)无显著差异(图1D)。AOC:SOC较低, 变幅为15.39%–19.10%, 与EOC:SOC变化一致且差异不显著, 其均值显著高于CK (图1E)。图1F显示, 4种林型的GMC变幅为0.99–1.29, 对林型变化响应极为敏感, 其中PLB和PP、BP和PLB以及BP和LP之间未见显著差异, 但PLB和PP均显著高于LP。4种林型的GMC均值极显著高于CK。

2.3 土壤碳库管理指数的变化特征

4种林型C_{SS}含量接近显著水平(表3), 表现为LP的C_{SS}含量显著低于PP, 而与BP和PLB差异不显著, 其平均含量较CK高了33.66%, 说明研究区天然林的土壤C稳定性极显著高于CK。以灌草地土壤为参照(CK), 4种林型CPA和CAI变幅分别为0.16–0.20和1.25–1.59, 对林型变化响应不敏感(表3), 但均高于CK。CPI和CPMI在不同类型间差异显著, 均表现为PP > PLB > BP > LP, 且数值均大于1.00和100% (表3), 即PP的CPI最高, 但与BP和PLB差异不显著, 而较LP显著高了69.13%, 较BP和PLB分别增加了25.30%和23.02%。此外, LP的CPMI显著低于BP、PLB和PP, 分别低了24.40%、29.13%和31.33%, 且

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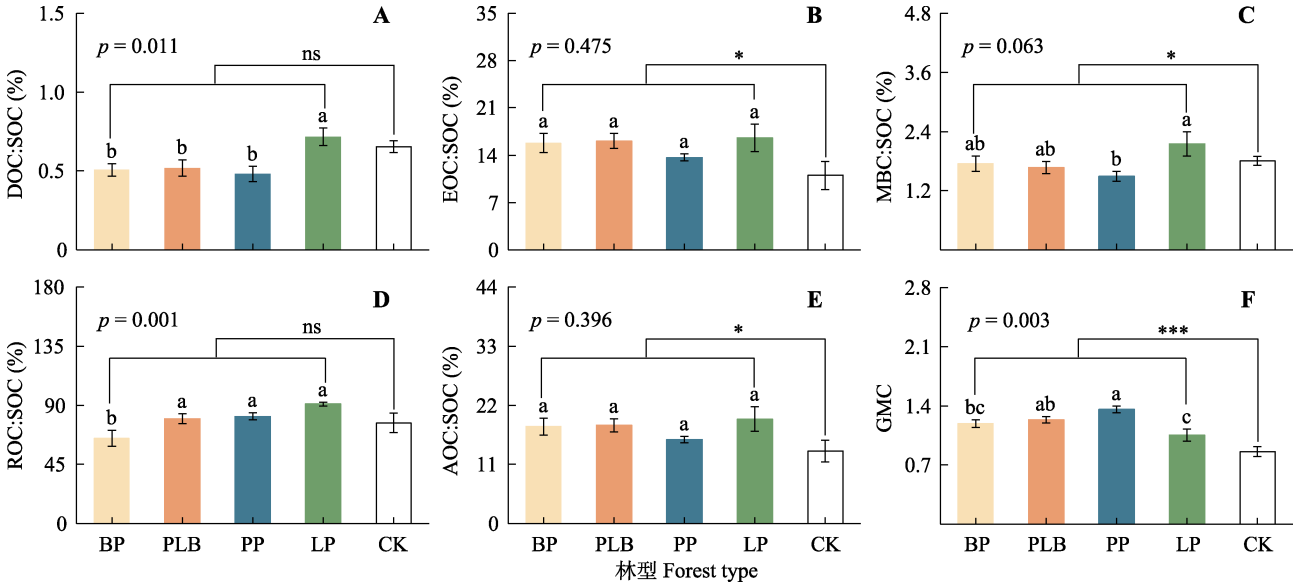


图1 不同林型土壤碳组分含量占有机碳百分比的变化特征(平均值±标准误)。BP, 白桦林; CK, 灌草丛; LP, 华北落叶松林; PLB, 青杆+华北落叶松+桦木针阔混交林; PP, 白杆+青杆针叶混交林。AOC:SOC, 活性有机碳含量: 土壤有机碳含量; DOC:SOC, 可溶性有机碳含量:土壤有机碳含量; EOC:SOC, 易氧化有机碳含量:土壤有机碳含量; GMC, 几何平均值; MBC:SOC, 微生物生物量有机碳含量:土壤有机碳含量; ROC:SOC, 惰性有机碳含量:土壤有机碳含量。图中不同小写字母表示不同林型间差异显著($p < 0.05$)。ns表示天然林型与CK之间没有显著差异($p > 0.05$); p值是指采用单因素方差分析检验不同指标在4种林型之间的差异显著性($\alpha = 0.05$); *, $p < 0.05$; ***, $p < 0.001$。

Fig. 1 Variation characteristics of the percent of soil C pool fractions in soil organic carbon content from the different forest types (mean ± *SE*). BP, *Betula platyphylla* forest; CK, scrub-grassland; LP, *Larix gmelinii* var. *principis-rupprechtii* forest; PLB, *Picea wilsonii* + *Larix gmelinii* var. *principis-rupprechtii* + *B. platyphylla* mixed conifer-broadleaf forest; PP, *P. meyeri* + *P. wilsonii* mixed conifer forest. AOC:SOC, ratio of active organic carbon contents to soil organic carbon contents; DOC:SOC, ratio of dissolved organic carbon contents to soil organic carbon contents; EOC:SOC, ratio of easily oxidizable organic carbon contents to soil organic carbon contents; GMC, geometric means of active organic carbon; MBC:SOC, ratio of microbial biomass carbon contents to soil organic carbon contents; ROC:SOC, ratio of recalcitrant organic carbon contents to soil organic carbon contents. Different lowercase letters indicate significant differences between different forest types in the figure ($p < 0.05$). ns imply no significant differences between natural forest types and CK in the figure ($p > 0.05$); p values refer to the significant differences in the percentages of each soil carbon pool component to total soil organic carbon among the four forest types, using one-way ANOVA testing at the 0.05 level; *, $p < 0.05$; ***, $p < 0.001$.

表3 不同林型土壤有机碳稳定性与土壤碳库管理指数(平均值±标准误)

Table 3 Lability of soil organic carbon and carbon (C) pool management indexes in different forest types (mean ± *SE*)

林型 Forest type	稳态碳含量 Soil steady-state C content (C_{SS}, g·kg^{-1})	碳库活度 C pool active degree (CPA)	碳库活度指数 C pool active indexes (CAI)	碳库指数 C pool indexes (CPI)	碳库管理指数 C pool management indexes (CPMI)
BP	44.32 ± 6.36^{ab}	0.19 ± 0.02^{a}	1.49 ± 0.16^{a}	1.39 ± 0.18^{ab}	194.05 ± 7.14^{a}
PLB	44.81 ± 5.08^{ab}	0.19 ± 0.02^{a}	1.52 ± 0.12^{a}	1.42 ± 0.14^{ab}	207.01 ± 4.04^{a}
PP	56.50 ± 4.30^{a}	0.16 ± 0.01^{a}	1.25 ± 0.06^{a}	1.74 ± 0.12^{a}	213.64 ± 7.53^{a}
LP	32.78 ± 6.21^{b}	0.20 ± 0.03^{a}	1.59 ± 0.24^{a}	1.03 ± 0.17^{b}	146.71 ± 6.98^{b}
CK	33.37 ± 4.80**	0.13 ± 0.03^{ns}	1.00	1.00	100.00
Sig. (p)	0.053	0.523	0.462	0.033	<0.001

BP, 白桦林; CK, 灌草丛; LP, 华北落叶松林; PLB, 青杆+华北落叶松+桦木针阔混交林; PP, 白杆+青杆针叶混交林;。表中不同小写字母表示不同林型间的差异显著($p < 0.05$)。ns表示不同天然林型与CK之间没有显著性差异($p > 0.05$); **, $p < 0.01$。Sig. 是指采用单因素方差分析以检验不同指标在4种林型之间的显著差异($\alpha = 0.05$)。

BP, *Betula platyphylla* forest; CK, scrub-grassland; LP, *Larix gmelinii* var. *principis-rupprechtii* forest; PLB, *Picea wilsonii* + *Larix gmelinii* var. *principis-rupprechtii* + *B. platyphylla* mixed conifer-broadleaf forest; PP, *P. meyeri* + *P. wilsonii* mixed conifer forest. Different lowercase letters indicate significant differences between different forest types ($p < 0.05$). ns imply no significant differences between natural forest types and CK in the table ($p > 0.05$); **, $p < 0.01$. Sig. in the table refers than the physical-chemical properties and soil carbon fractions content across four forest types use the least significant difference of one-way ANOVA testing at the 0.05 level.

BP、PLB和PP差异不显著。

2.4 土壤碳组分及管理指数与理化性质的相关性

Pearson相关分析(图2)显示, SOC含量与土壤碳组分均表现为极显著正相关关系, 相关系数依次为ROC > EOC > MBC > DOC; 除了DOC与EOC、MBC和AOC含量之间未见显著性相关, 其余指标

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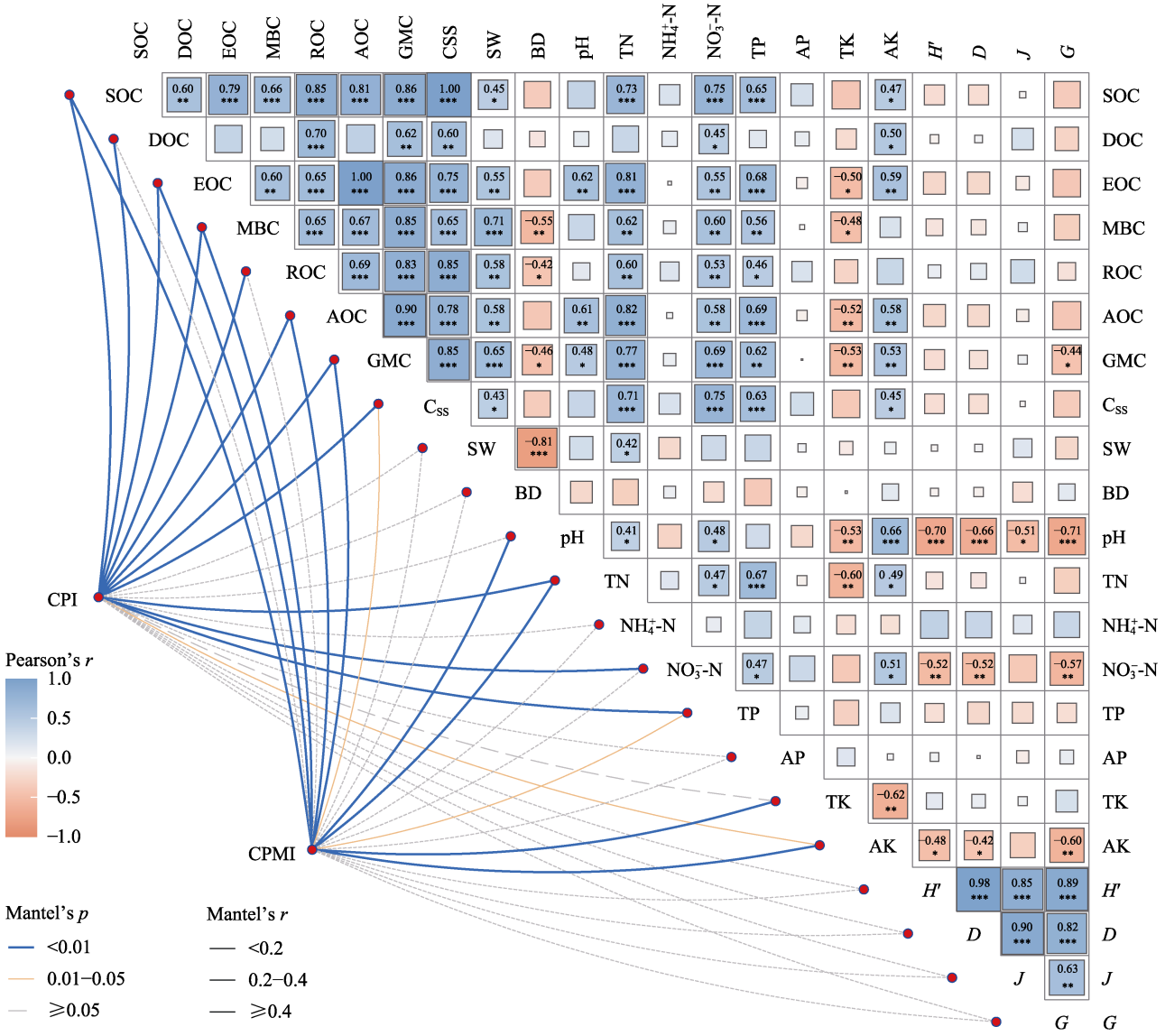


图2 土壤碳库管理指数与环境变量之间的关系(n = 24)。AK, 有效钾含量; AOC, 活性有机碳含量; AP, 有效磷; BD, 土壤容重; C_{SS}, 土壤稳态碳含量; CPI, 碳库指数; CPMI, 碳库管理指数; *D*, Simpson指数; DOC, 可溶性有机碳含量; EOC, 易氧化有机碳含量; *G*, Gleason指数; GMC, 活性有机碳含量的几何平均值; *H*′, Shannon-Wiener指数; *J*, Pielou均匀度指数; MBC, 微生物量碳含量; NH_4^+-N, 铵态氮含量; NO_3^--N, 硝态氮含量; ROC, 惰性有机碳含量; SOC, 土壤有机碳含量; SW, 土壤含水量; TK, 全钾含量; TN, 总氮含量; TP, 总磷含量。不同颜色表示相关类型及Pearson相关系数, 实线和虚线分别表示显著和不显著相关。*, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$。

Fig. 2 Relationship between the carbon (C) pool management indexes and environmental variables under different forest types based on the Pearson correlation and mantel test analysis (n = 24). AK, available potassium content; AOC, active organic carbon content; AP, available phosphorus content; BD, soil bulk density; C_{SS}, soil stable carbon content; CPI, carbon pool index; CPMI, carbon pool management index; *D*, Simpson index; DOC, dissolved organic carbon content; EOC, easily oxidizable organic carbon content; *G*, Gleason index; GMC, geometric mean value of active organic carbon content; *H*′, Shannon-Wiener index; *J*, Pielou evenness index; MBC, soil microbial biomass carbon content; NH_4^+-N, ammonium nitrogen content; NO_3^--N, nitrate nitrogen content; ROC, recalcitrant organic carbon content; SOC, soil organic carbon content; SW, soil water content; TK, total potassium content; TN, total nitrogen content; TP, total phosphorus content. Different colors indicate the corresponding types and Pearson correlation coefficients, and solid lines and dashed lines represent significant and insignificant correlations, respectively. *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$.

间均呈极显著正相关关系。SOC含量与SW、TN、NO_3^--N、TP和AK含量呈极显著或显著正相关关系; DOC含量与NO_3^--N、AK含量显著正相关; EOC、MBC、AOC、C_{SS}和GMC含量分别与SW、TN、NO_3^--N、TP含量极显著或显著正相关, 而与TK含量极显著或显著负相关, 其中MBC含量和GMC还受

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到BD的极显著或显著负向影响; ROC含量与SW、TN、NO_3^--N、TP含量极显著或显著正相关, 而与BD显著负相关; AK含量与EOC、AOC、C_{SS}含量和GMC极显著或显著正相关; pH对EOC、AOC含量和GMC有极显著或显著正向效应。此外, 物种多样性两两之间极显著相关。

Mentel检验结果(图2)显示, CPI受TN、NO_3^--N、TP和AK含量极显著或显著影响; CPMI与pH、TN、TP、TK和AK含量极显著或显著相关。进一步选用与C组分含量与CPI和CPMI相关性较强的指标进行RDA分析, 发现轴1和轴2分别解释了C组分含量的62.93%和11.71% (图3A)和土壤C库(CPI和CPMI)特征的64.20%和18.62% (图3B), 其总变化累计解释率分别为74.64%和82.82%。从图3还可看出, C组分含量和CPMI主要受到TN、NO_3^--N含量的极显著影响, 其中C组分含量还受到Pielou均匀度指数、SW和AK含量显著影响; CPMI受到pH的显著影响。此外, 可看出TN、NO_3^--N、SW、AK含量、Pielou均匀度指数与C组分含量呈正相关关系; TN、NO_3^--N含量和pH与CAI呈负相关关系, 而与CPMI和CPI正相关。

随机森林分析(图4)表明, 土壤NO_3^--N、TN和TP含量是SOC含量和CPI最强预测因子; AK含量对DOC含量有显著影响; TN含量、TP含量、SW和BD对EOC含量有极显著或显著预测作用; MBC含量受TN、NO_3^--N含量和SW的极显著影响; ROC含量受BD、SW和TN含量的显著影响; AOC含量受到TN、TP含量和SW的显著影响。此外, TN和TP含量对CPI和CPMI有极显著或者显著预测作用，其中CPMI受到pH显著影响。

3 讨论

3.1 林型对土壤有机碳含量的影响

SOC含量变化常与地表凋落物分解路径、根系分泌物、微生物活性以及树种密度等因素有关(Blair et al., 1995; Kooch et al., 2019; Whalen et al., 2021; Zarafshar et al., 2024), 亦受到地上和地下有机质输入与分解或C矿化的交互作用过程的影响(Liu et al., 2021; Wang et al., 2024)。本研究发现, 林型对SOC含量影响显著, 表现为PP的SOC含量显著高于LP, 而其余林型间SOC含量差异不显著, 这可能是其凋落物分解速率较低的结果(Lin et al., 2017)。总体上, 混交林的SOC含量高于纯林(表2), 与已有研究结果(Zhang et al., 2011; 王棣等, 2015; Lee et al., 2024)部分类似, 究其原因: 一方面源于苔藓层和地表凋落物等地上残余物数量和质量不同(表1), 阔叶树种凋落物和混合凋落物的分解速度高于针叶树种, 然而混合凋落物分解速率与针叶树种所占比例相关, 即针叶树种占比越高, 凋落物分解速率越慢(赵喆等, 2016; Xiao et al., 2019), 向土壤释放的C源量不尽相同, 这与“微生物效率-基质稳定”假说认为的高质量凋落物有利于SOC积累的观点相悖; 另一方面, 林分物种混交后, 改善了土壤微环境和微生物活性(Lee et al., 2024), 提高了土壤养分总量和有效性, 促进了SOC的积累(Guo et al., 2023); 此外, 地下根

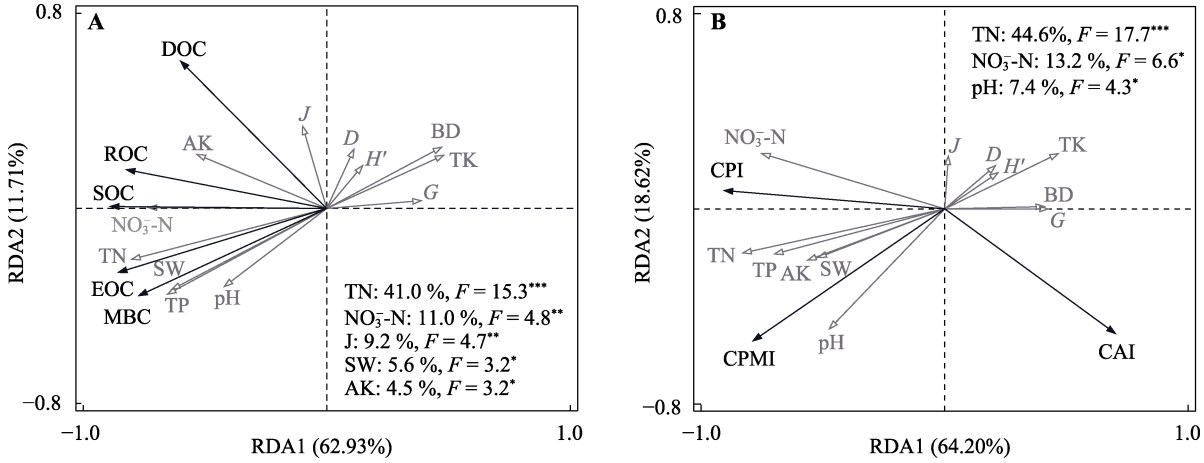


图3 土壤碳组分(**A**)和土壤碳库管理指数(**B**)与土壤环境因子的冗余分析(RDA)。指标同图2。*, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$。

Fig. 3 Redundancy analysis (RDA) of soil carbon (C) pool fractions (**A**) and C pool management indexes (**B**) and soil environment factors. Index see Fig. 2. *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$.

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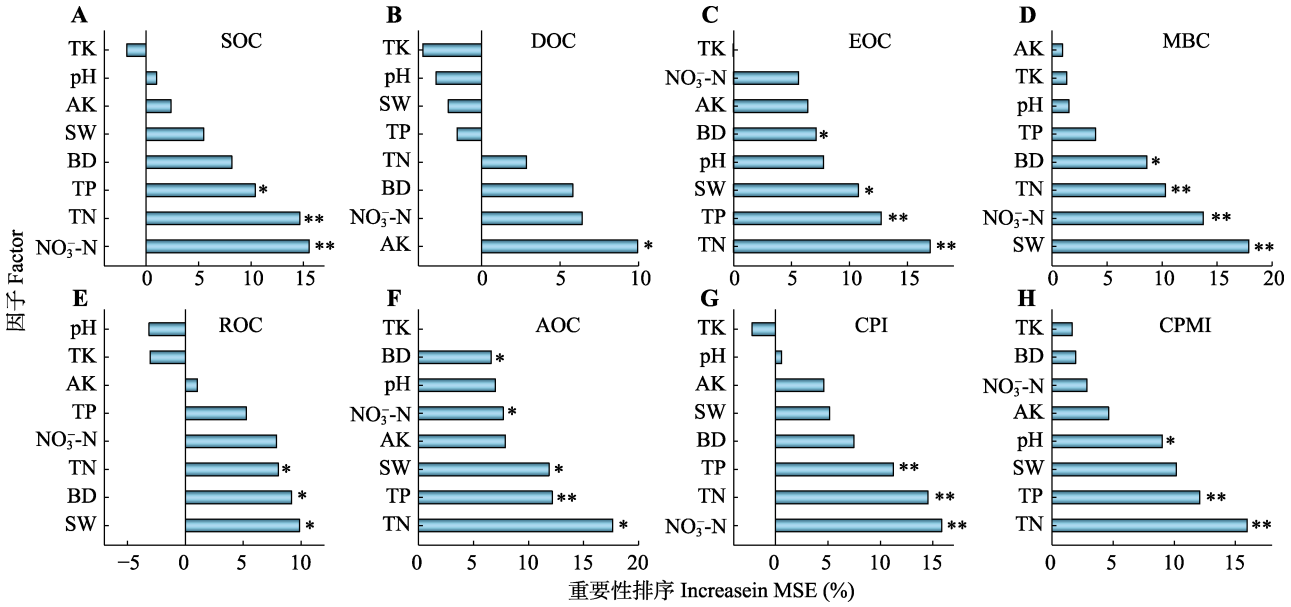


图4 随机森林分析检测土壤环境因子对土壤碳(C)组分含量和C库管理指数变化的相对重要性。*, $p < 0.05$; **, $p < 0.01$。指标同图2。

Fig. 4 Random forest analysis indicating the effects of soil environmental variables on the contents of soil organic carbon (C) and C pool fractions, and soil carbon pool management indexes. * and ** correspond to $p < 0.05$ and 0.01, respectively. Index see Fig. 2.

系生物量、质量和分解速率以及树种获取和消耗C源的能力不同(Augusto et al., 2015), 进而影响到C源的生物降解(Zarafshar et al., 2024), 最终使得SOC含量在不同林型间表现不一。本研究结果显示, 地上高生物量水平的林型(表1)对SOC含量具有正向效应, 与已有研究结果(Augusto & Boča, 2022; Lee et al., 2024)一致, 即地上生物量越大, 树木坏死物含量越高(Hynynen et al., 2011), 通过根际沉降和根系死亡向土壤输送更多有机质, 进而增加了SOC含量(Jackson et al., 2017)。此外, 本研究发现4种林型SOC含量均高于CK, 说明该区域通过对华北落叶松林以及灌草地进行保护性生态修复(如针叶树种或针阔树种混交), 可提高土壤SOC的储量, 进而提升林地土壤质量。

3.2 林型对土壤有机碳组分及有机碳贡献率的影响

3.2.1 对土壤有机碳组分的影响

通常认为, DOC、EOC和MBC含量可表征C库稳定性以及土壤质量(Zhang et al., 2011; Yang et al., 2018)。本研究中, DOC、EOC、MBC和ROC含量均与SOC含量呈极显著相关关系(图2), 且呈同步增加趋势, 说明土壤C组分含量在很大程度上依赖于SOC的含量水平(Anderson & Domsch, 1989), 也表明地上或地下C输入的数量和质量也会导致活性C组分含量变化不一, 具体影响因素有待进一步研究证实。另外, 土壤养分及SOC的供给提高了植被生物量, 刺激了SOC的活化, 促进土壤中SOC向DOC的转化, 使得AOC含量在PP中相对较高。

DOC作为动植物和微生物自身生长及分解过程中的主要物质和能量来源, 在C固存中起着关键作用(Jones & Willett, 2006), 可表征土壤质量敏感性及土壤C库稳定性(Gunapala & Scow, 1998; Yuan et al., 2018)。本研究发现, DOC含量与SOC含量显著正相关(图2), 说明DOC含量在很大程度上取决于SOC总量(Wu et al., 2022; Huang et al., 2024)。有研究显示, 混合凋落物中的养分从含量高的物种向含量低的物种发生转移的过程中, 分解者(土壤动物、微生物等)优先利用高质量的凋落物, 提升了低质量凋落物的养分有效性(Briones & Ineson, 1996), 导致低质量凋落物分解加快并最终使混合凋落物整体分解速率加快(Hättenschwiler et al., 2005), 提升了土壤C含量, 导致DOC含量升高(图2)。因此, PP的DOC含量相对较高, 而其余林型间未见显著性差异。未来需进一步从分解者的物种组成结构角度探究其影响机制。

EOC是土壤养分的潜在来源以及土壤微生物活动的重要能源, 可灵敏地反映SOC含量的变化, 常被用作判定土壤质量优劣的指标(Weil et al., 2003;

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Zou et al., 2005)。本研究发现, EOC含量对林型变化响应极为敏感, 与已有研究结果(Zhang et al., 2011; 李书杨等, 2018)类似, 与Sheng等(2015)的研究结论不一致, 一方面因为高锰酸钾氧化法对木质素或木质素类化合物较为敏感, 而对纤维素不敏感(Skjemstad et al., 2006), 增加的EOC含量可能主要来源于木质素部分的氧化分解; 另一方面与不同植物输入的蛋白质、纤维素和木质素等的比例、养分释放速率以及土壤酶活性不同有关(李书杨等, 2018; Tian et al., 2024), 还可能与土壤C矿化速率和机械组成等因素有关(Dong et al., 2022)。

一般认为, 林型对MBC含量具有直接或间接的影响, 主要源于微生物活动所需C源(如凋落物、根系分泌物等)以及生存环境不一(李宜浓等, 2016; Tian et al., 2024), 使得微生物活性和数量发生改变, 进而引起MBC含量的变化。亦有研究认为, 温带森林MBC含量可能主要存在于土壤物理组分中, 导致MBC含量变化不显著(Gartzia-Bengoetxea et al., 2009)。Fang等(2016)研究显示, 云杉人工林和白桦林的MBC含量差异不显著; Lin等(2017)发现, 丛枝菌根(AM)和外生菌根(ECM)林间MBC含量无显著差异, 本研究结果与之相似。

ROC主要来源于植物根部输入和地下碎屑, 对陆地生态系统的C汇的影响强烈(Shi et al., 2023)。本研究中, ROC含量受到林型显著影响, 且不同林型的ROC含量显著高于AOC含量, 说明不同林型的SOC以稳定性C为主, 与已有研究结论 (贾匡迪等, 2024) 相似。本研究发现, ROC含量变化趋势与DOC含量变化趋势一致(表2), 总体上表现为混交林高于纯林, 其原因可能源于植物C输入引起的活性C增加, 可能通过与土壤颗粒或矿物结合将部分AOC转化为稳态C (Jakšík et al., 2015; Xiang et al., 2022)。此外, ROC含量与SOC及其活性C组分含量显著正相关(图2), 表明研究区不同植被类型土壤中SOC和AOC含量的增加是表层土壤ROC含量增加的结果, 与已有研究观点(Xiang et al., 2022)相似。因此, 在评价研究区不同林型土壤C积累与稳定性的变化时, 应考虑土壤中ROC含量的变化。

3.2.2 对碳组分贡献率的影响

AOC:SOC可消除土壤有机碳含量对不同活性碳组分的影响, 以表征土壤C损失与C稳定性(Yu et al., 2022), 也能反映林型对土壤质量和C库变化的影响(王春燕等, 2016)。本研究中, 4种林型土壤C组分对SOC贡献率为ROC > EOC > MBC > DOC, 其中ROC占比变幅为64.84%–90.86% (均值79.27%)略高于CK (76.59%), 而AOC则为17.58%, 显著高于CK (图1D、1E), 可见该区域森林和CK土壤有机C库稳定性较好, 有利于SOC的累积。此外, 林型对DOC:SOC、GMC和ROC:SOC影响显著, 而对EOC:SOC、MBC:SOC和AOC:SOC影响不显著(图1A–1D), 表明林型变化并没有改变不稳定有机C组分(DOC除外)及其AOC占SOC的比例, 而在LP中GMC最低和ROC:SOC最高(图1D、1F), 说明该林型SOC稳定性相对较高。本研究亦发现, LP的DOC:SOC相较于其他3种林型高, 说明该林型凋落物中存在酚类化合物的累积不利于微生物的活动(Jílková et al., 2022), 导致DOC:SOC的比例显著提高(图1A); EOC:SOC介于15.77%–16.57%, 在已有研究(蔡华等, 2023)报道范围之内, 表明EOC是活性有机碳组分中贡献最大的组分; MBC:SOC变幅为1.2%–2.4%, 略低于在黑龙江帽儿山温带森林的研究结果(2%–4%) (刘爽和王传宽, 2010), 高于德国东北部温带森林(0.9%–1.5%) (Akinyede et al., 2022), 与全球温带森林(1.9%–2.2%)相当(Gao et al., 2024), 其差异可能源于采样土壤层次及时间不同。MBC:SOC作为土壤微生物熵, 反映了土壤微生物对SOC的贡献, 其值越高, 土壤C活性越大。本研究中, MBC:SOC高低排序为LP > BP > PLB > PP (p = 0.063), 与MBC含量变化趋势相悖, 说明混交林和阔叶林虽然在一定程度上增加了MBC的含量, 但降低了其比值, 减缓了C矿化, 有利于C的固存。因此, 在一定程度上促进了混交林尤其是针叶混交林的C固存及土壤质量改善(Shi et al., 2023)。此外, BP土壤中ROC:SOC显著低于其他3种林型, 与已有研究结果(Shi et al., 2023)相似, 可能源于白桦林土壤微生物功能多样性较高(程智超等, 2021), 菌根类群通过分解ROC获得必需的部分养分, 导致ROC:SOC相对较低。

3.3 林型对碳库管理指数的影响

CPMI能全面反映林型对土壤有机质数量和质量的影响(闫丽娟等, 2019; Wang et al., 2024), 数值越大表示外源有机质对CPMI和土壤质量的促进作用越强, C积累越好, 越能反映土壤有机C库的质量及其稳定性(Blair et al., 1995; Pang et al., 2019)。林

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型变化改变了土壤理化性质, 提高了土壤水分含量, 以及不同外源有机质的输入与微生物分解方式的改变, 有利于土壤C库积存与固持, 提高了土壤C库的质量和稳定性; 加之地上植物C输入是SOC的主要来源, 对表层土壤C稳定的相对重要性大于其他非生物因子(Chen et al., 2021)。本研究中, 林型并未对CPA和CAI产生显著影响, 与已有研究结果(贾匡迪等, 2024)相似, 这可能是因为不同天然林型土壤C库中活性部分增加的幅度趋于一种临界状态, 将多余活性C转化为稳态C (表3), 从而导致在C输入逐渐增加背景下的CPA和CAI无显著差异, 其影响因素需进一步研究。本研究亦发现, 林型变化对CPI和CPMI影响显著, 相较于CK, 4种林型的土壤质量和稳定性有所提高(CPI > 1, CPMI > 100%), 表明天然林地能够有效改善土壤质量和积累SOC。4种林型中, PP、PLB和BP的CPMI显著高于LP, 表现为PP > PLB > BP > LP (表3), 一方面说明阔叶林和混交林可以提供更多的新鲜有机质, 增加SOC的来源; 另一方面也说明了随着林型的变化, 地下植物根系木质化程度越来越高, 在提供根系分泌物和新鲜植物残体的同时, 增加了木质素和纤维素等难降解大分子物质, 导致ROC的增加(Prieto et al., 2016), 从而提高土壤C库稳定性及其质量。上述分析表明CPMI可用来表征阔叶林、混交林与针叶林土壤C库的质量及其稳定性特征。

3.4 影响有机碳组分及碳库管理指数的主要环境因子

林型物种组成不一或森林恢复更新会引起土壤基本理化性质的改变, 进而导致SOC及其组分含量发生变化(Liang et al., 2021)。本研究中, 相较于CK, 天然林通过改善土壤养分含量和土壤酸碱度, 提高了SOC和C组分的累积(表2)。TN和NO_3^--N含量与SOC及其组分含量之间存在较显著的正相关关系, 与已有研究结果(李书杨等, 2018; Yao et al., 2023)相似, 这是因为大部分的N素都储存于土壤中有机质中(Xie et al., 2020), 被土壤有机质吸附、固定, 减缓了有机质分解, 增加SOC固持率(张金硕等, 2024), 进而提高SOC及其组分的含量(Xu et al., 2020; Liu et al., 2021); 另外, 不同的NO_3^--N含量可以通过抑制或促进木质素降解酶活性来提高或降低DOC的输出(DeForest et al., 2005), 导致ROC含量也发生协同变化(Ågren et al., 2001)。这说明不同林型土壤C固持力受到TN和NO_3^--N含量的耦合协同影响(Shi et al., 2023), 同时也说明C稳定性主要取决于土壤N及其有效性(Li et al., 2023), 最终导致SOC和C组分(EOC和AOC)含量(表2)以及CPI和CPMI均呈现出PP > PLB > BP > LP的变化趋势(表3)。Lee等(2024)指出, 土壤pH越接近中性或土壤相对潮湿及其水分有效性相对较高的背景下, 有利于EOC、AOC和SOC的积累(王磊等, 2023), 进而提升了以EOC进行统计的CPI和CPMI, 本研究也发现了这一点; 同时NO_3^--N含量和TN与SOC及其C组分含量呈显著相关关系(图3, 图4), 这表明不同林型土壤中SOC和C组分的积累会受到N的限制, 这与Pang等(2019)的研究结果相似。此外, 本研究也发现物种多样性(Pielou均匀度指数)影响到SOC及其组分含量变化, 源于植物多样性通过根系碳输入有机物在土壤微生物介导下对C储量的正向影响(Lange et al., 2015), 加之地面凋落物多样性对活性组分和惰性组分的积极或消极影响(Wang et al., 2022), 使得C组分含量在不同林型中的差异显著, 具体驱动机制有待进一步研究。

4 结论

在保护区人为干扰较低的森林生态系统中, 森林群落优势物种组成和林分类型是影响SOC及其组分含量和CPMI的关键因素。4种林型SOC及C组分含量和CPMI均表现为PP > PLB > BP > LP, 总体上表现为混交林明显高于纯林, 其中EOC、ROC含量和GMC受林型变化影响显著, 可作为评估研究区SOC含量变化的指标。各林型土壤CPMI显著高于100%, 但LP的CPMI显著低于其他3种林型。因此, 通过混种云杉属物种或固氮树种, 以及适当增加土壤N含量可以改善温带过渡区针叶纯林和灌草地生态系统的土壤质量和功能, 提高SOC及其C组分累积量和C库稳定性, 实现“双碳”增汇目标。

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