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黄土高原次生林演替过程土壤有机碳库及其化学组成响应特征

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摘要:为探明黄土高原次生林演替过程中土壤有机碳库及其化学组成演化特征, 选取陕北黄土高原黄龙山林区次生林演替初级阶段(山杨林)、过渡阶段(山杨、辽东栎混交林)和顶级阶段(辽东栎林)样地为研究对象, 分析不同土层深度(0~10、10~20、20~30、30~50和50~100 cm)土壤有机碳含量、储量和化学组成变化特征。结果表明:①土壤有机碳含量和储量随次生林演替过程显著增加($P < 0.05$), 土壤有机碳含量随土层深度增加显著降低, 土壤有机碳储量从初级阶段的 $64.8 \text{ Mg} \cdot \text{hm}^{-2}$ 增加至顶级阶段的 $129.2 \text{ Mg} \cdot \text{hm}^{-2}$, 增加了 99%。②次生林演替过程中, 表层(0~30 cm)土壤有机碳中结构简单、相对易分解的脂肪族碳组分相对含量减少, 结构复杂、相对难分解的芳香族碳组分相对含量增加, 表明表层土壤有机碳化学组成稳定性随次生林演替过程显著提高, 而深层(30~100 cm)土壤有机碳化学组成稳定性表现为先增加后降低, 即过渡阶段 > 顶级阶段 > 初级阶段。③次生林演替过程中, 初级阶段和过渡阶段土壤有机碳化学组成稳定性随土层深度增加显著增加, 顶级阶段整体上趋于稳定, 深层土壤碳稳定性略有降低。④Pearson 相关性分析表明, 次生林演替过程中, 土壤有机碳储量、化学组成稳定性均与土壤全磷含量呈显著负相关。总的来说, 次生林演替过程中 0~100 cm 土壤有机碳含量及储量均显著提升, 扮演了“碳汇”的角色, 且随次生演替过程, 表层(0~30 cm)土壤有机碳化学组成稳定性显著增加, 深层(30~100 cm)土壤有机碳化学组成稳定性先增加后降低。

关键词:黄土高原; 次生林演替; 土壤有机碳化学组成; 傅里叶红外光谱技术(FTIR); 土壤有机碳库

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Response Characteristics of Soil Organic Carbon Pool and Its Chemical Composition During Secondary Forest Succession in the Loess Plateau

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Abstract: In order to explore the characteristics of the soil organic carbon (SOC) pool and its chemical composition during the succession of secondary forests in the Loess Plateau, samples of the primary stage (*Populus davidiana* forest), transition stage (*Populus davidiana* and *Quercus wutaishansea* mixed forest), and top stage (*Quercus wutaishansea* forest) of secondary forest succession in the Huanglong Mountain forest area of the Loess Plateau in Northern Shaanxi were selected as the research object. The variation characteristics of SOC content, storage, and its chemical composition at different soil depths (0-10, 10-20, 20-30, 30-50, and 50-100 cm) were analyzed. The results showed that: ① the contents and storage of SOC increased significantly with the secondary forest succession process ($P < 0.05$). The content of SOC decreased significantly with the increase in soil depth, and the storage of SOC increased from $64.8 \text{ Mg} \cdot \text{hm}^{-2}$ in the primary stage to $129.2 \text{ Mg} \cdot \text{hm}^{-2}$ in the top stage, with an increase of 99%. ② During the succession of secondary forests, in the surface (0-30 cm) soil organic carbon, the relative content of aliphatic carbon components that have a simple structure and can be decomposed more easily decreased, and the relative content of aromatic carbon components that have a complex structure and cannot be decomposed easily increased, indicating that the chemical composition of organic carbon stability of surface-layer soil increased significantly with the process of secondary forest succession. However, the stability of the chemical composition of SOC in the deep layer (30-100 cm) first increased and then decreased, that is, the transition stage > the top stage > the primary stage. ③ In the process of secondary forest succession, the stability of SOC chemical composition in the primary stage and transition stage increased significantly with the increase in soil depth. The top stage tended to be stable, and the deep soil carbon stability decreased slightly. ④ Pearson correlation analysis showed that during the secondary forest succession process, SOC storage and chemical composition stability were significantly negatively correlated with soil total phosphorus content. In general, the content and storage of SOC in the 0-100 cm soil increased significantly during the secondary forest succession, playing the role of a “carbon sink.” The stability of the chemical composition of SOC in the surface layer (0-30 cm) increased significantly, but in the deep layer (30-100 cm), it increased first and then decreased.

Key words: Loess Plateau; secondary forest succession; soil organic carbon stability; Fourier transform infrared spectroscopy (FTIR); SOC pool

土壤在全球碳循环中扮演了重要角色^[1], 陆地生态系统土壤碳储量大约是植物碳储量的 3 倍和大气碳储量的 2 倍^[2]. 在全球范围, 0~30 cm 土层土壤碳储量超过 684 Pg, 而 0~100 cm 土层土壤碳储量超过 1 642 Pg^[3]. 巨大的碳储量较小的变幅即能影响全球碳收支平衡, 导致大气二氧化碳浓度较大

波动. 因此, 土壤作为碳汇已然成为全球气候变化下

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的研究热点^[4],特别是森林生态系统维持着约 73% 的陆地土壤有机碳库,因此,深入理解森林土壤有机碳库的演变与分布特征,对保持陆地生态系统碳平衡和长期固碳潜力具有重要意义。

植被演替使得植被群落结构发生变化,进而影响土壤碳库和微生物群落结构,在中国生态环境脆弱的黄土高原要恢复退化土壤^[5,6],次生林演替对该区域的生态系统服务功能发挥和生态环境保护起着重要作用。近些年来,越来越多学者就黄土高原次生林演替过程地上植被变化、土壤养分和土壤碳储量^[7-9]等方面进行了研究,结果都表明黄土高原次生林演替对表层土壤有机碳、土壤养分和土壤微生物等均有显著影响,土壤有机碳含量、储量不断增加^[10],但就次生林演替过程土壤有机碳库稳定性如何变化的研究还较少。

傅里叶红外光谱技术(Fourier transform infrared spectroscopy, FTIR)可以通过测定土壤有机碳的化学官能团,反映土壤化学组成、结构变化等多方面的信息^[11]。Tiver 等^[12]对热带和亚热带农田和自然植被土壤剖面有机碳化学组成进行了研究,发现其有机碳稳定性存在显著差异,郝翔翔等^[13]在中国黑土区,探讨了自然草地及恢复前农田土壤有机质官能团的差异,发现土壤有机碳化学组成稳定性差异较大。研究表明,土壤脂肪族碳官能团相对吸收峰面积与土壤活性组分的有机碳含量呈显著正相关关系,可反映土壤中活性有机碳含量,芳香族官能团相对吸收峰面积可反映土壤中稳定有机碳含量。

总的来讲,目前就黄土高原次生林演替过程土壤碳库的研究,主要集中在含量和储量等方面,对不同土层土壤有机碳化学组成及其性质还认识不足。

因此,本研究从土壤有机碳化学组成的角度,探究次生林演替过程中不同土层土壤有机碳化学组成的响应特征,以期深入认识黄土高原次生林演替过程土壤有机碳化学组成稳定性提供科学依据。

1 材料与方法

1.1 研究区概况

黄龙山次生林自然保护区(109°38'~110°12'E, 35°28'~36°02'N)位于陕北黄土高原南部黄龙县境内的黄龙林区,是黄土高原保存较好的一块天然植被区,森林覆盖率约为 84.6%。属于半湿润温带大陆性气候,年平均温度为 8.6℃,年降雨量约 611.8 mm,主要集中在 7~9 月,年蒸发量为 856.5 mm^[14],海拔 962.6~1 783.5 m。主要土地利用类型为暖温带落叶阔叶林、针叶林和农田,经过长期的人为破坏和自然演替,形成了以油松、辽东栎、山杨和白桦等为主要类型的天然次生林^[15]。

1.2 样地选取与样品采集

2021 年 7 月进行样地调查,并确定初级阶段为山杨林(*Populus davidiana*, PD),过渡阶段为山杨及辽东栎混交林(*Populus davidiana* mixed *Quercus wutaishansea*, PQ)和顶级阶段辽东栎林(*Quercus wutaishansea*, QW),样地主要物种组成、经纬度和海拔如表 1 所示。在每个森林群落中选择 3 块 20 m×20 m 的地块,每个地块选择 5 个采样点,小心除去地表凋落物后,用土钻按照 0~10、10~20、20~30、30~50 和 50~100 cm 分层采集土壤,将每个样方中各层土壤混合均匀,采用四分法取一定量土壤作为一个样品,置于冰盒带回实验室,每森林类型共 15 个样品。风干后过 1 mm 筛,4℃冰箱中保存备用。

表 1 样地基本情况

Table 1 General information of experimental sampling sites

演替阶段	初级阶段	过渡阶段	顶级阶段
物种组成	山杨	山杨和辽东栎	辽东栎
主要灌草	苔草和绣线菊	杜梨和绣线菊	南蛇藤和野山楂
位置	35.49°N, 109.44°E	35.49°N, 109.44°E	35.45°N, 109.53°E
海拔/m	1 280	1 230	1 590

1.3 土壤理化性质测定

对所选取的 3 个样地挖取剖面,通过环刀法测定容重(BD),烘干法测定土壤含水率(SWC),使用重铬酸钾氧化-外加热法测定土壤有机碳(SOC),凯氏法测定土壤全氮(TN),氯化钾浸提法测定土壤硝态氮(NO₃⁻-N)和铵态氮(NH₄⁺-N),硫酸-高氯酸消解法测定土壤全磷(TP),碳酸氢钠浸提-钼锑抗比色法测定土壤速效磷(AP)^[16]。

1.4 土壤有机碳化学组成特征分析

土壤有机碳化学组成采集使用傅里叶变换红外光谱仪,将过 0.05 mm 筛的自然风干土放入红外光谱仪,采用 ATR 法进行测定。为消除大气背景干扰,首先测定大气背景值,即空气的反射光谱,后续将样品反射光谱减去空气反射光谱获得样品的真实反射光谱。参数设定:光谱范围设置为 400~4 000 cm⁻¹,分辨率为 4 cm⁻¹,扫描频次为 32 次。

本研究土壤样品的吸收峰主要包括位于 $1\,520\text{ cm}^{-1}$ 和 $1\,645\text{ cm}^{-1}$ 处的芳香族化合物或酰胺组分,位于 $2\,935\text{ cm}^{-1}$ 和 $2\,980\text{ cm}^{-1}$ 处的脂肪族甲基和亚甲基.选取特征峰 $1\,520$ 、 $1\,645$ 、 $2\,935$ 和 $2\,980\text{ cm}^{-1}$,在其吸收峰波长范围内进行积分,将得到的各特征峰面积相加,分别计算芳香族碳(aromatic-C)和脂肪族碳(aliphatic-C)特征峰面积的相对比例(即吸收峰相对面积)^[17].有研究表明,土壤有机碳中芳香族碳结构复杂、相对稳定,其含量增加,则有机碳稳定化学组分增加,脂肪族碳则反之,同时,芳香族碳组分和脂肪族碳特征峰相对面积比值与土壤有机碳稳定性成正比,可以作为指示土壤有机碳化学组成稳定性的指标,其比值越大,土壤有机碳化学结构越稳定^[18].

1.5 数据处理

数据结果采用 Excel 2019 进行记录整理,使用 SPSS 26 进行方差分析及相关性分析,数据以平均值±标准差表示,差异显著性水平为 $P<0.05$.红外光谱图使用 OMNIC 9.0 软件进行基线校正和平滑处理,后通过 Origin 2020b 对范围内吸收峰进行积分,将得到的各吸收峰面积总和相加,最后计算各峰面积的百分比(即吸收峰相对面积).文中所有图使

用 Origin 2020b 软件完成.

2 结果与分析

2.1 次生林演替过程中土壤理化性质变化

在次生林演替的 3 个典型阶段(表 2),土壤 $\omega(\text{TN})$ 分别为 $0.43\sim1.93$ 、 $0.46\sim2.03$ 和 $0.56\sim2.13\text{ g}\cdot\text{kg}^{-1}$,表现为随次生林演替增加,随土层深度增加而减少,顶级阶段的各土层含量均最大;土壤 $\omega(\text{NO}_3^-\text{-N})$ 分别为 $0.05\sim2.98$ 、 $0.10\sim3.51$ 和 $0.18\sim3.73\text{ mg}\cdot\text{kg}^{-1}$, $\omega(\text{NH}_4^+\text{-N})$ 分别为 $1.45\sim13.74$ 、 $1.55\sim14.45$ 和 $1.60\sim15.60\text{ mg}\cdot\text{kg}^{-1}$, $\omega(\text{AP})$ 分别为 $0.57\sim2.77$ 、 $0.97\sim2.83$ 和 $1.16\sim2.94\text{ mg}\cdot\text{kg}^{-1}$,3 种速效养分变化趋势均与土壤全氮相似,均为顶级阶段的各土层含量最大;而土壤 $\omega(\text{TP})$ 分别为 $1.29\sim1.44$ 、 $1.00\sim1.31$ 和 $0.87\sim1.25\text{ g}\cdot\text{kg}^{-1}$,表现为随次生林演替而减少,垂直方向上随土层深度增加而减少.总的来说,土壤 TN、 $\text{NO}_3^-\text{-N}$ 、 $\text{NH}_4^+\text{-N}$ 和 AP 含量呈现出相似的分布特征,且随次生林演替过程增加.对于土壤含水量和容重,则均随次生林演替过程增加,前者随土层深度增加而降低,后者随土层深度增加而增加,均表现为顶级阶段的各土层数值最大.

表 2 不同演替阶段及土层深度土壤理化性质的差异¹⁾
Table 2 Differences in soil physical and chemical properties in different succession stages and different soil depths

演替阶段	土层深度 / cm	含水率	容重 / $\text{g}\cdot\text{cm}^{-3}$	$\omega(\text{TN})$ / $\text{g}\cdot\text{kg}^{-1}$	$\omega(\text{NO}_3^-\text{-N})$ / $\text{mg}\cdot\text{kg}^{-1}$	$\omega(\text{NH}_4^+\text{-N})$ / $\text{mg}\cdot\text{kg}^{-1}$	$\omega(\text{TP})$ / $\text{g}\cdot\text{kg}^{-1}$	$\omega(\text{AP})$ / $\text{mg}\cdot\text{kg}^{-1}$
PD	0~10	$0.22\pm0.01\text{a}$	$0.93\pm0.01\text{c}$	$1.93\pm0.01\text{a}$	$2.98\pm0.08\text{a}$	$13.74\pm0.18\text{a}$	$1.44\pm0.01\text{a}$	$2.77\pm0.01\text{a}$
	10~20	$0.12\pm0.01\text{b}$	$1.01\pm0.02\text{bc}$	$1.27\pm0.02\text{b}$	$2.01\pm0.08\text{b}$	$5.21\pm0.27\text{b}$	$1.40\pm0.01\text{ab}$	$1.80\pm0.04\text{b}$
	20~30	$0.10\pm0.01\text{bc}$	$1.11\pm0.02\text{ab}$	$0.91\pm0.02\text{c}$	$0.73\pm0.01\text{c}$	$4.16\pm0.16\text{c}$	$1.38\pm0.03\text{bc}$	$1.08\pm0.05\text{c}$
	30~50	$0.09\pm0.01\text{c}$	$1.16\pm0.05\text{a}$	$0.56\pm0.02\text{d}$	$0.16\pm0.05\text{d}$	$2.48\pm0.20\text{d}$	$1.34\pm0.01\text{c}$	$0.97\pm0.06\text{c}$
	50~100	$0.08\pm0.01\text{c}$	$1.20\pm0.06\text{a}$	$0.43\pm0.01\text{e}$	$0.05\pm0.02\text{d}$	$1.45\pm0.01\text{e}$	$1.29\pm0.02\text{d}$	$0.57\pm0.01\text{d}$
PQ	0~10	$0.23\pm0.01\text{a}$	$0.96\pm0.03\text{c}$	$2.03\pm0.01\text{a}$	$3.51\pm0.32\text{a}$	$14.45\pm0.23\text{a}$	$1.31\pm0.05\text{a}$	$2.83\pm0.01\text{a}$
	10~20	$0.14\pm0.01\text{b}$	$1.11\pm0.03\text{b}$	$1.34\pm0.01\text{b}$	$2.16\pm0.04\text{b}$	$5.58\pm0.07\text{b}$	$1.17\pm0.03\text{b}$	$1.92\pm0.03\text{b}$
	20~30	$0.12\pm0.01\text{c}$	$1.17\pm0.03\text{ab}$	$0.92\pm0.01\text{c}$	$0.82\pm0.02\text{c}$	$4.53\pm0.04\text{c}$	$1.11\pm0.02\text{b}$	$1.21\pm0.04\text{c}$
	30~50	$0.11\pm0.01\text{d}$	$1.19\pm0.01\text{ab}$	$0.64\pm0.03\text{d}$	$0.21\pm0.03\text{d}$	$2.89\pm0.02\text{d}$	$1.07\pm0.02\text{bc}$	$1.17\pm0.04\text{c}$
	50~100	$0.10\pm0.01\text{d}$	$1.23\pm0.03\text{a}$	$0.46\pm0.03\text{e}$	$0.10\pm0.01\text{d}$	$1.55\pm0.04\text{e}$	$1.00\pm0.03\text{c}$	$0.97\pm0.01\text{d}$
QW	0~10	$0.24\pm0.01\text{a}$	$1.12\pm0.02\text{d}$	$2.13\pm0.01\text{a}$	$3.73\pm0.01\text{a}$	$15.60\pm0.17\text{a}$	$1.25\pm0.02\text{a}$	$2.94\pm0.02\text{a}$
	10~20	$0.15\pm0.01\text{b}$	$1.13\pm0.02\text{d}$	$1.45\pm0.01\text{b}$	$2.23\pm0.03\text{b}$	$5.85\pm0.08\text{b}$	$1.08\pm0.03\text{b}$	$2.12\pm0.07\text{b}$
	20~30	$0.13\pm0.01\text{bc}$	$1.28\pm0.02\text{c}$	$0.95\pm0.02\text{c}$	$0.97\pm0.01\text{c}$	$4.90\pm0.09\text{c}$	$0.98\pm0.01\text{c}$	$1.51\pm0.08\text{c}$
	30~50	$0.12\pm0.01\text{c}$	$1.48\pm0.02\text{b}$	$0.77\pm0.01\text{d}$	$0.32\pm0.01\text{d}$	$3.07\pm0.04\text{d}$	$0.91\pm0.01\text{d}$	$1.44\pm0.01\text{c}$
	50~100	$0.11\pm0.01\text{c}$	$1.60\pm0.02\text{a}$	$0.56\pm0.03\text{e}$	$0.18\pm0.02\text{e}$	$1.60\pm0.05\text{e}$	$0.87\pm0.02\text{d}$	$1.16\pm0.06\text{d}$

1) 不同小写字母表示差异显著($P<0.05$)

2.2 次生林演替过程中土壤有机碳含量及储量变化

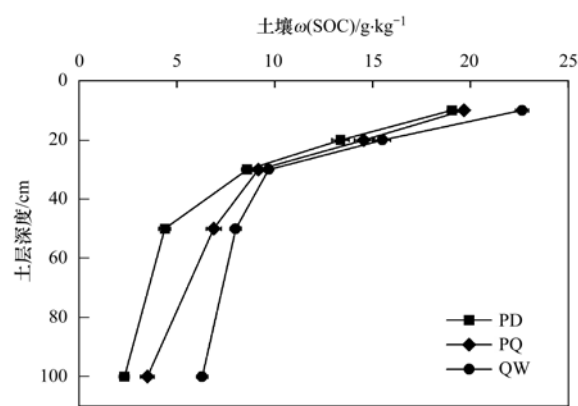
次生林演替过程中,土壤 $\omega(\text{SOC})$ 在初级、过渡和顶级阶段分别 $2.31\sim19.05$ 、 $3.49\sim19.66$ 和 $6.28\sim22.62\text{ g}\cdot\text{kg}^{-1}$,如图 1 所示,土壤 SOC 含量随次生林演替过程显著增加,但随土层深度增加显著降低,顶级阶段各土层土壤 SOC 含量均最大.

次生林演替过程中,0~100 cm 深土壤 SOC 储

量显著增加,表现为:顶级阶段>过渡阶段>初级阶段,如图 2 所示,初级、过渡和顶级阶段 0~100 cm 土壤 SOC 储量分别为 64.8、83.4 和 129.2 $\text{Mg}\cdot\text{hm}^{-2}$,较初级阶段,顶级阶段土壤 SOC 储量增加 99%.

2.3 次生林演替过程中土壤有机碳化学组成稳定性

如图 3 所示,从已检测出的主要红外特征峰中,



PD 为初级演替阶段山杨林,PW 为过渡演替阶段山杨及
辽东栎混交林,QW 为顶级演替阶段辽东栎林,下同
图 1 不同演替阶段和土层深度土壤 SOC 含量分布

Fig. 1 Distribution of soil organic carbon content
in different succession stages and soil depths

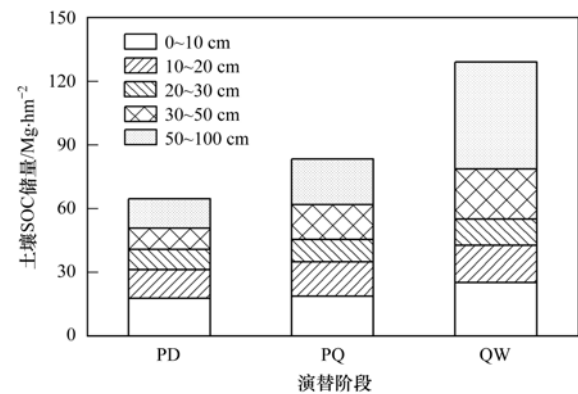


图 2 不同演替阶段和土层深度土壤 SOC 储量分布

Fig. 2 Distribution of soil organic carbon storage
in different succession stages and soil depths

选取分别代表芳香族碳组分和脂肪族碳组分的特征峰,并分别计算芳香族碳组分和脂肪族碳组分的相对峰面积,以表示其质量分数.

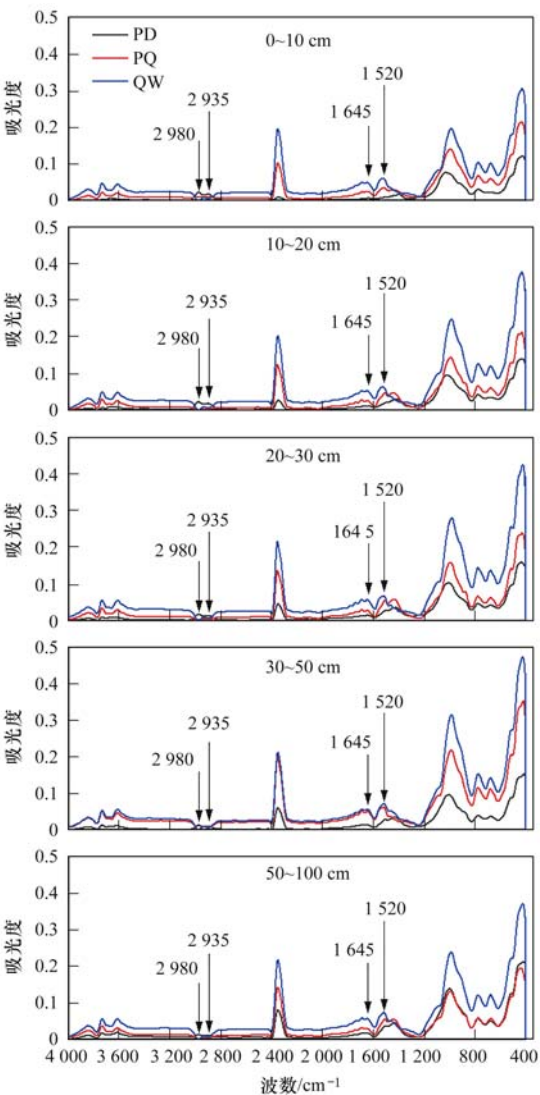


图 3 不同演替阶段和土层深度土壤 SOC 中红外光谱图

Fig. 3 Mid-infrared spectroscopy patterns of soil organic
carbon in different succession stages and soil depths

整体上看,演替阶段和土层深度对所选的土壤
红外特征峰指标均影响显著(表 3).

表 3 演替阶段和土层深度对土壤中红外光谱特征峰相对峰面积的影响(F 值)¹⁾

Table 3 Effects of succession stage and soil depth on selected peak area determined by mid-infrared spectroscopy (F value)

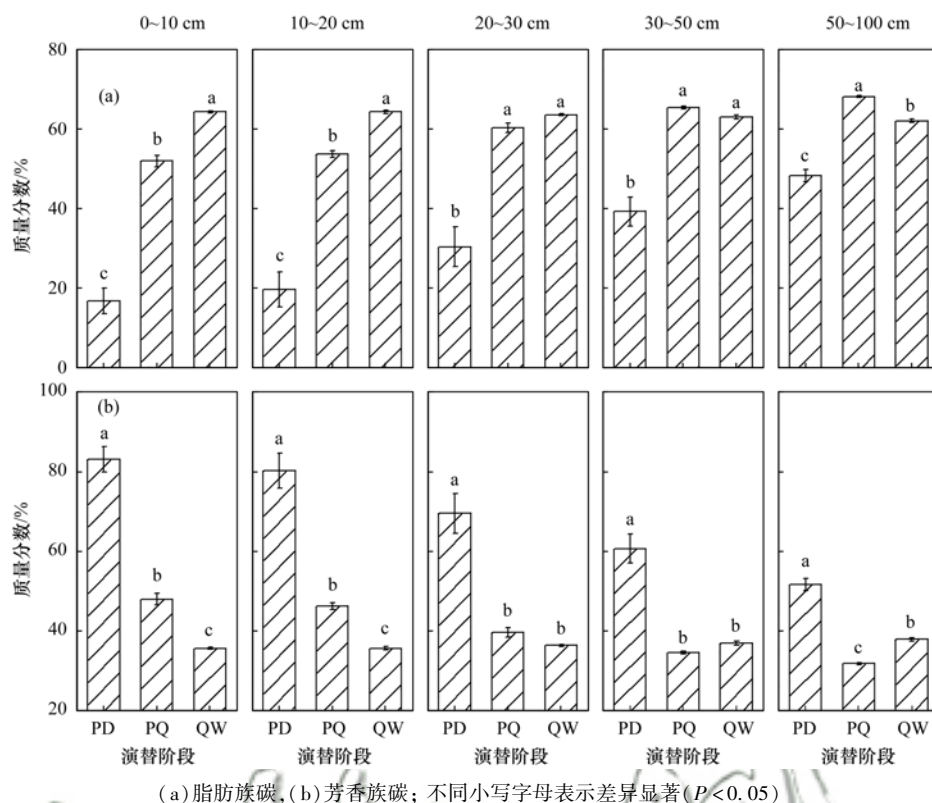
变量	演替阶段	土层深度	演替阶段 $\times$ 土层深度
脂肪族碳	316.405 **	24.826 **	10.139 **
芳香族碳	316.405 **	24.826 **	10.139 **
芳香族碳/脂肪族碳	699.567 **	49.152 **	23.008 **

1) ** 表示该指标影响极显著($P < 0.01$),芳香族碳/脂肪族碳表示土壤芳香族碳组分与脂肪族碳组分相对峰面积的比值

从图 4 可以看出,在次生林演替过程中,不同演替阶段,土壤有机碳的脂肪族碳组分和芳香族碳组分质量分数差异显著,具体表现为表层(0~30 cm)土壤随次生林演替过程土壤中结构较为简单的脂肪族 C—H 结构有机碳组分含量显著减少,较为稳定的芳香族 C=C 结构有机碳组分含量显著增加,而深层(30~100 cm)土壤表现为随次生林演替过程土

壤中脂肪族碳组分含量先减少后增加,芳香族碳组分含量先增加后减少.

通过使用土壤芳香族碳组分与脂肪族碳组分相对峰面积的比值来指示土壤有机碳化学组成稳定性,从图 5 可以看出,表层(0~30 cm)土壤有机碳化学组成稳定性随次生林演替过程显著增加,深层(30~100 cm)土壤有机碳化学组成稳定性则表现



(a) 脂肪族碳, (b) 芳香族碳; 不同小写字母表示差异显著 ($P < 0.05$)

图4 不同演替阶段和土层深度土壤脂肪族碳和芳香族碳特征峰质量分数

Fig. 4 FTIR mass fraction of characteristic peaks of soil aliphatic carbon and aromatic carbon in different succession stages and soil depths

为先增加后减小,即过渡阶段 > 顶级阶段 > 初级阶段.同时,在初级阶段和过渡阶段,土壤有机碳化学组成稳定性随土层深度增加而显著增加,顶级阶段则表现为随土层深度增加略有下降,整体上差异不显著.

2.4 次生林演替过程土壤有机碳化学组成稳定性影响因素分析

如图6所示, Pearson相关性分析表明,在次生林演替过程中,土壤有机碳储量、土壤有机碳化学组成稳定性均与土壤全磷含量呈显著负相关,土壤有机碳化学组成稳定性与土壤容重呈显著正相关.

3 讨论

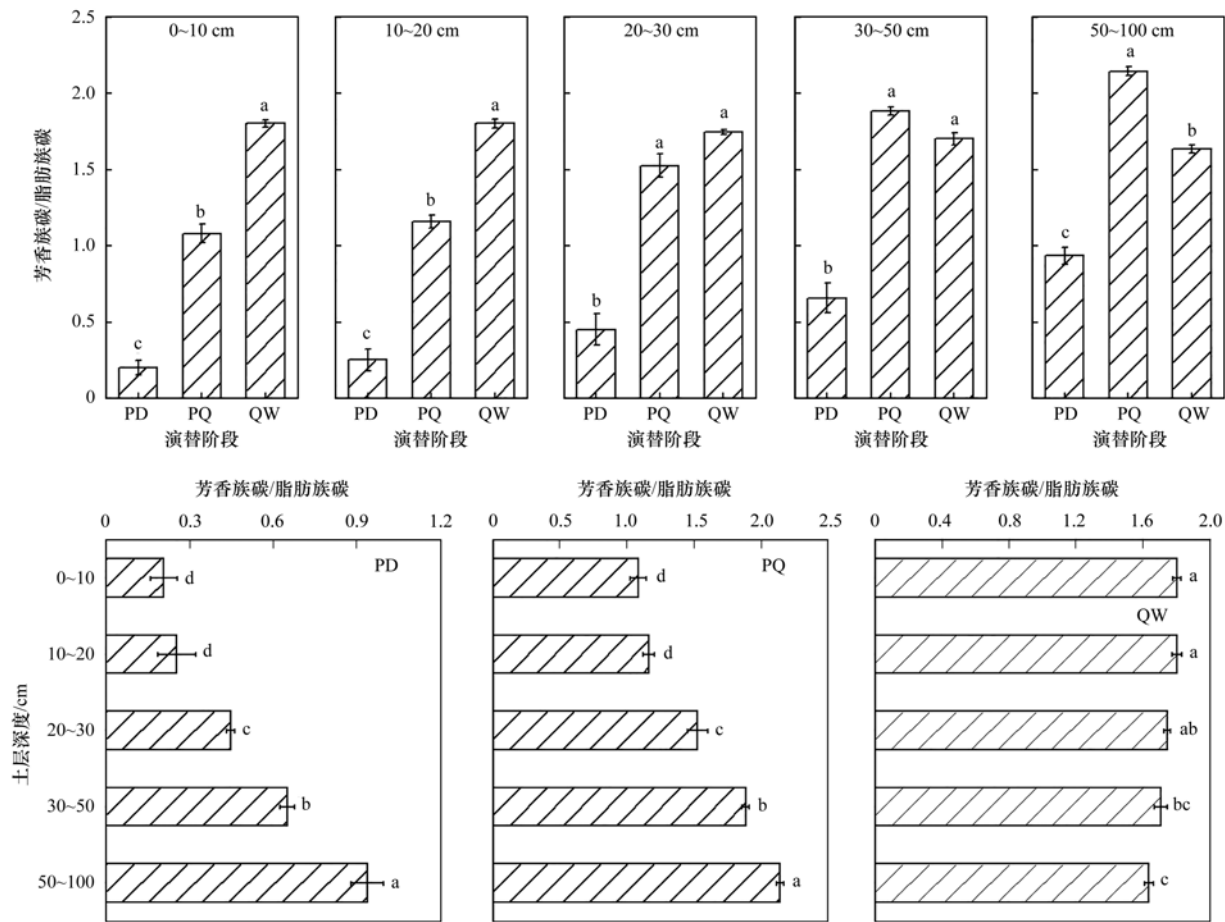
3.1 次生林演替过程中土壤有机碳库的动态变化

植被是土壤有机碳含量及储量的重要影响因素^[19]. 本研究结果表明,与次生林演替初级阶段相比,过渡阶段和顶级阶段土壤各层有机碳含量和储量显著增加 ($P < 0.05$). 这与潘英杰等^[20]和黄艳章等^[21]在子午岭和蔡家川林区森林演替土壤碳库变化研究的结果一致,且数值上均表现出次生林演替生态恢复土壤“碳汇”效益较人工生态林、经济林和草地等要好. 这主要是由于植物凋落物是影响土壤有机碳周转与形成的重要因素^[22],随着演替进行系统内植物物种丰富度增加,凋落物及根系分泌物随

之增加,影响了土壤理化性质及微生物活性,进而对土壤有机碳含量和储量变化产生影响^[23,24],同时,由于天然次生林具有完整的群落结构,且微生物的多样性指数和丰度均高于人工林^[25],生态系统碳循环相对稳定,有利于有机碳的积累.

3.2 次生林演替过程中土壤有机碳化学组成稳定性变化

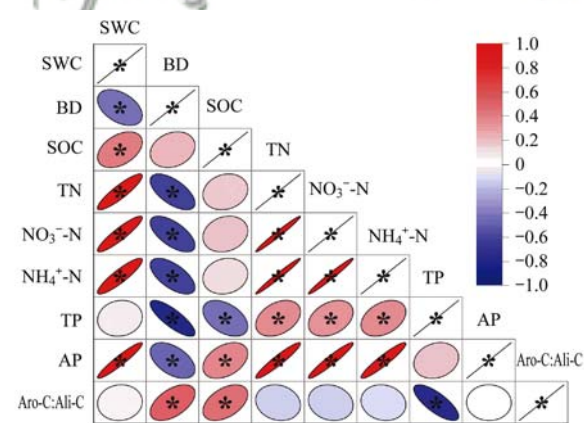
本研究采用红外光谱方法分析了在次生林演替过程中,不同土层深度土壤有机碳化学组成稳定性的差异,结果表明演替阶段和土层深度均显著影响土壤有机碳化学组成稳定性. 在表层(0~30 cm)土壤中,土壤有机碳化学组成稳定性随次生林演替过程显著增加,这主要是由于在次生林演替过程中,土壤有机碳库易受到植被覆盖类型、凋落物和土壤环境条件的影响,凋落物的输入是表层土壤有机碳变化的主要原因^[26],随着演替进行,凋落物质量不断增加,因此,表层土壤有机碳化学组成稳定性不断增加. 在深层(30~100 cm)土壤中,土壤有机碳化学组成稳定性先增加后减小,即过渡阶段 > 顶级阶段 > 初级阶段,根系和微生物活动是深层土壤有机碳形成和稳定的主要原因^[27,28],土壤微生物碳泵理论假设通过微生物代谢特性调控土壤有机碳的化学组成^[29,30],在次生林演替过程中,过渡阶段地上植物多样性及地下根系的量均最大,亦提高了微生物多



不同小写字母表示差异显著 ($P < 0.05$), 芳香族碳/脂肪族碳表示土壤芳香族碳组分与脂肪族碳组分相对峰面积的比值

图5 不同演替阶段和土层深度土壤芳香族碳组分与脂肪族碳组分特征峰相对峰面积比值差异

Fig. 5 Difference in relative peak area ratio of aromatic and aliphatic carbon components in different succession stages and soil depths



SWC 为土壤含水率, BD 为容重, SOC 为土壤有机碳储量, TN 为全氮, NO_3^- -N 为硝态氮, NH_4^+ -N 为铵态氮, TP 为全磷, AP 为速效磷, Aro-C: Ali-C 为土壤芳香族碳组分与脂肪族碳组分相对峰面积的比值, 表示土壤有机碳化学组成稳定性; * 表示 $P < 0.05$, 说明两指标间影响显著, 红色和蓝色分别表示正相关和负相关, 椭圆大小表示相关系数大小

图6 次生林演替过程土壤有机碳化学组成稳定性与影响因素间的相关分析

Fig. 6 Correlation analysis between chemical composition stability of soil organic carbon and influencing factors in the secondary forest succession process

样性及代谢能力,使其通过体内周转形成了更多的相对稳定的土壤碳组分.

在次生林演替初级阶段和过渡阶段,土壤有机碳化学组成稳定性随土层深度增加而显著增加,这与 Tivet 等^[12]在热带和亚热带获得的 FTIR 结果一致.这主要是由于土壤中的脂肪族碳组分主要是来源于纤维素和半纤维素等糖类^[31],属于容易降解的化合物,主要来源于植物残体,在表层土壤中较多;而深层土壤有机碳主要是根系木质素^[32]和微生物体内周转合成产物^[33]等惰性较强、结构较为稳定的碳组分,因此,表现为土壤有机碳化学组成稳定性随土层深度的增加而显著增加.在次生林演替的顶级阶段,土壤有机碳化学组成稳定性在剖面上整体差异不大,这主要是由于在演替初级阶段到过渡阶段,土壤养分含量显著增加,微生物生物量、活性均随着演替而增加;当到达演替后期,微生物群落与土壤环境达到平衡,微生物 C 循环基因减少^[34],生态系统养分循环达到相对稳定的状态.同时,深层土壤微生物受到土壤养分和水分等因素的限制,尤其是由于磷与大气没有交换,而次生林演替过程中需要吸

收磷作为能源^[35],结合 Odum 生态学能量理论,由于磷元素的显著减少,土壤微生物能量来源减少,因此其生长速率和碳利用效率等特性减弱,有利于有机碳的储存,但不利于形成相对稳定的微生物源碳^[36]。同时,本研究结果表明,土壤有机碳稳定性、有机碳储量均与土壤全磷呈显著负相关,这也就是说,土壤磷含量可能成为森林演替后期土壤固碳及碳稳定性的限制因素。

总的来说,随着次生林演替过程中植被生长,促进了植物生物量的输入,改变了土壤养分及环境,减少了土壤侵蚀^[37,38],整体上增加了 0~100 cm 土壤有机碳储量,使黄土高原地区次生林演替扮演了“碳汇”的角色。但次生演替过程中表层(0~30 cm)和深层(30~100 cm)土壤有机碳化学组成稳定性表现不同,表层土壤有机碳化学组成稳定性随次生林演替过程显著增加,但深层土壤有机碳化学组成稳定性表现为:过渡阶段>顶级阶段>初级阶段,顶级阶段深层土壤有机碳的稳定机制还有待进一步探究。

4 结论

(1)黄土高原从初级阶段山杨林到顶级阶段辽东栎林的次生林演替过程中,0~100 cm 各土层土壤有机碳含量、储量均随演替过程显著增加,扮演了“碳汇”的角色。

(2)在初级阶段和过渡阶段土壤有机碳化学组成稳定性随土层深度增加而显著增加,顶级阶段则表现为整体上趋于稳定,深层有机碳化学组成稳定性略有降低。

(3)随着次生林演替,表层(0~30 cm)土壤有机碳化学组成稳定性显著增加,深层(30~100 cm)土壤有机碳化学组成稳定性先增加后降低。

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