

# 长白山阔叶红松林和杨桦次生林土壤有机碳氮的协同积累特征

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**摘 要** 次生演替是森林土壤有机碳、氮库变化的重要驱动因素.本研究以长白山原始阔叶红松林和杨桦次生林为例,通过成对样地途径,研究了森林土壤有机碳、氮的数量分布及其协同积累特征,探讨了次生演替导致的温带森林土壤碳库和碳汇效应变化及其碳氮耦合机制.结果表明:杨桦次生林比原始阔叶红松林在土壤表层和亚表层(0~20 cm)积累了更多的有机碳和氮,其土壤 C/N 值也显著低于阔叶红松林;相对于阔叶红松林,杨桦次生林土壤(0~20 cm)有机碳储量平均增加了  $14.7 \text{ t} \cdot \text{hm}^{-2}$ ,相当于  $29.4 \text{ g} \cdot \text{m}^{-2} \cdot \text{a}^{-1}$  的土壤碳汇增益.土壤有机碳和全氮在不同林型的不同土层中均表现为极显著正相关,二者具有明显的协同积累特征.与阔叶红松林生态系统相比,相对富氮的杨桦次生林生态系统的上部土层中氮对有机碳的决定系数明显高于阔叶红松林,说明杨桦次生林土壤有机碳的积累在更大程度上依赖含氮有机质积累.在有机质最丰富的表层(0~10 cm),两种林型间轻组有机碳、氮储量无显著差异,但杨桦次生林重组有机碳、氮的含量、储量及分配比例均显著高于阔叶红松林,其中,重组有机碳储量平均增加了  $8.5 \text{ t} \cdot \text{hm}^{-2}$ ,表明次生演替过程中土壤有机碳、氮库的增加主要在于矿物质结合态稳定性土壤有机碳、氮库的增容.凋落物分解和稳定性土壤有机质形成中的碳氮耦合机制是次生演替过程中土壤有机碳、氮库变化的重要驱动机制.

**关键词** 次生演替; 森林土壤; 有机碳; 全氮; 碳氮耦合

**Co-accumulation characters of soil organic carbon and nitrogen under broadleaved Korean pine and *Betula platyphylla* secondary forests in Changbai Mountain, China.** ZHAO Hua-chen, GAO Fei, LI Si-wen, GAO Lei, WANG Ming-zhe, CUI Xiao-yang\* (College of Forestry, Northeast Forestry University, Harbin 150040, China).

**Abstract:** The retrogressive succession is an important driver for dynamics of soil organic carbon (SOC) and total nitrogen (TN). We studied the quantitative distribution and synergistic accumulation characteristics of soil organic carbon and nitrogen in the primary broadleaved Korean pine (KP) forest and *Betula platyphylla* (BP) secondary forest in Changbai Mountain through paired plot approach. Further, we analyzed the changes of carbon pool and carbon sink effect in temperate forest soil caused by secondary succession and their carbon-nitrogen coupling mechanism. The results showed that the BP forest accumulated more organic carbon and nitrogen in the surface and subsurface soil (0–20 cm) than the KP forest, with relatively low soil C/N. Compared with KP forest, soil organic carbon storage in BP forest (0–20 cm) was higher by  $14.7 \text{ t} \cdot \text{hm}^{-2}$ , equivalent to a soil carbon sink gain of  $29.4 \text{ g} \cdot \text{m}^{-2} \cdot \text{a}^{-1}$ . SOC and TN concentrations were positively correlated in each soil layer of all forest types, causing a co-accumulative relationship between SOC and TN. The coefficient of determination ( $R^2$ ) between SOC and TN in the upper soil layers of BP forest was significantly higher than that of the KP forest, indicating that SOC accumulation under the relatively N-rich BP forest was more dependent on the accumulation of organic nitrogen. In the upper soil lay-

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ers (0–10 cm) where organic matter concentrated, there was no significant difference in light fraction organic carbon and nitrogen stock between the two forest types, whereas the content, stock, and allocation percentage of heavy fraction organic carbon and nitrogen of BP forest were all significantly higher than that of the KP forest, with an average increment of  $8.5 \text{ t} \cdot \text{hm}^{-2}$  in heavy fraction organic carbon stock. Those results indicated that the increase of soil organic carbon and nitrogen during secondary succession was mainly due to the increases of soil organic carbon and nitrogen pools in mineral-bound stability. The carbon-nitrogen coupling mechanisms in litter decomposition and soil organic matter formation was an important driving mechanisms underlying the changes of soil organic carbon and nitrogen pools during secondary succession.

**Key words:** secondary succession; forest soil; organic carbon; total nitrogen; carbon and nitrogen coupling.

森林土壤学者历来重视土壤有机碳、氮,因其往往是决定土壤肥力的主要变量<sup>[1]</sup>.近几十年来,土壤碳源、汇功能在大气  $\text{CO}_2$  浓度变化估算中的重要性凸显<sup>[2]</sup>,使土壤有机碳库倍受关注.据估计,森林生态系统中大约蕴含了陆地生态系统碳库的一半 ( $1146 \times 10^{15} \text{ g}$ ),而其  $2/3$  ( $787 \times 10^{15} \text{ g}$ ) 又储存于森林土壤中<sup>[3]</sup>.因此,研究森林土壤碳库的变化与稳定性对深刻理解陆地生态系统的碳收支和长期固碳潜力具有重要意义<sup>[4]</sup>.

生态学界日益认识到生态系统中氮循环对碳循环的影响<sup>[5–7]</sup>,尤其是土壤有机氮 (SON) 和土壤有机碳 (SOC) 通过生物质的生产与分解过程而产生紧密的耦合关系<sup>[8–9]</sup>.这种耦合关系不仅表现为土壤有机碳、氮的数量相关<sup>[10–11]</sup>,而且包含着从凋落物分解到稳定性土壤有机质形成的多种耦合机制<sup>[5,9]</sup>.通常来说,凋落物基质质量(如 C/N、木质素含量)在很大程度上控制着其分解速率<sup>[12–15]</sup>,而凋落物分解是森林土壤有机质和氮最重要的来源,决定了土壤有机碳和氮库的大小<sup>[13,16]</sup>;在土壤内部,尚存在着另类“稳定性有机质积累的碳氮耦合机制”,即有机氮易被选择性地保存在土壤中,构成难分解有机质的重要组成部分<sup>[9,17]</sup>,影响整个 SOC 库的数量和周转率;氮库大小和 C/N 甚至被看作是衡量土壤固碳潜力的指标<sup>[13,17–19]</sup>.

森林土壤有机碳、氮库的变化受很多因素影响.人为因素包括树种选择<sup>[13,15,20–22]</sup>、经营措施(如采伐和整地)<sup>[17]</sup>、大气沉降<sup>[23]</sup>和  $\text{CO}_2$  浓度升高<sup>[24]</sup>;自然因素包括自然演替、病虫害,以及因土壤水热条件和基质质量变化所致的微生物活性变化<sup>[25–26]</sup>.尤其是不同森林类型组成的差异将直接影响土壤凋落物输入的数量、质量和方式,从而导致土壤微生物群落结构、活性及分解产物差异,进而影响土壤有机碳和氮的积累过程<sup>[16,27–28]</sup>.20 世纪 50—80 年代,长白山

林区原始红松针阔混交林遭受大规模集中采伐,现已大部分转变为阔叶次生林.在次生演替过程中,森林类型和生境条件发生动态变化,由此必然影响森林生态系统的碳、氮循环过程,并导致土壤有机碳、氮库大小和质量的变化.尽管长白山不同森林类型或不同演替阶段土壤有机碳、氮储量变化已受到国内学界关注<sup>[29–31]</sup>,但因未顾及立地条件控制,所得结果并不一致.长白山作为中国温带典型林区和全球气候变化高度敏感区,从原始红松针阔混交林转变为现阶段典型阔叶次生林后,其土壤有机碳、氮库发生了哪些变化? 土壤碳源、汇功能又是如何变化的? 变化的机理是什么? 这些科学问题均尚需解答.本文通过严格的成对样地途径,系统研究了长白山原始阔叶红松林和典型杨桦次生林下土壤有机碳、氮库的大小、分布与组分稳定性,以及土壤有机碳、氮之间的数量关系.以期回答上述科学问题提供参考,并探讨土壤有机碳库变化的碳氮耦合机理.

## 1 研究地区与研究方法

### 1.1 研究区域和样地描述

研究区位于长白山自然保护区及毗邻区(涉及白河和露水河两个林业局),地理坐标范围为  $42.3193^\circ$ — $42.4978^\circ \text{ N}$ 、 $127.8332^\circ$ — $128.1319^\circ \text{ E}$ (图 1).该区为典型的玄武岩台地地貌,地势较为平缓,地形微有起伏,坡度一般在  $0 \sim 5^\circ$ ,海拔在 700~750 m.属温带湿润季风气候,年降水量在 700~900 mm,年平均气温在  $0.9 \sim 2.5^\circ \text{ C}$ ,无霜期约为 100 d.该区属于长白植物区系,森林生态系统的保存较为完整.地带性植被为以红松为优势树种的针阔混交林(简称阔叶红松林),乔木层针叶树种主要为红松(*Pinus koraiensis*),还有沙松(*Abies holophylla*)、红皮云杉(*Picea koraiensis*)、鱼鳞云杉(*Picea jezoensis*)等;阔叶树种有蒙古栎(*Quercus mongolica*)、水曲柳(*Fraxinus*

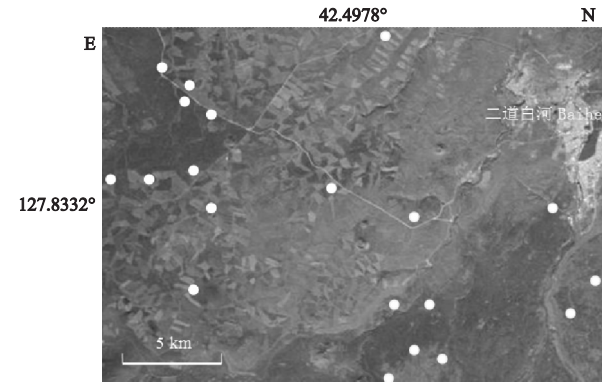


图 1 研究样地分布图  
Fig.1 Location of the sampling plots.  
白色圆点表示 20 对样地位置 White dots indicated 20 pairs of sampling plots.

*mandshurica*)、色木槭 (*Acer mono*)、春榆 (*Ulmus pumila*) 等.由于人为干扰,本区原始林面积已大幅减少,阔叶次生林面积不断增加,其中较典型的是以白桦 (*Betula platyphylla*)、山杨 (*Populus davidiana*) 为主的杨桦次生林.研究区主要土壤类型为在玄武岩台地上发育的白浆土或白浆化暗棕壤(漂白冷凉淋溶土, CST),系经过白浆化等成土过程形成具有

暗色腐殖质表层、灰白色亚表层(白浆层)的土壤,其成土母质比较黏重.

2017 年至 2018 年 8 月中旬,在设定的研究区内选设 20 对典型原始阔叶红松林样地及毗邻的杨桦次生林样地 (30 m×30 m) (图 1).样地选择的原则是:林相整齐,郁闭度 0.7 以上;阔叶红松林未曾受过择伐干扰,主林层红松盖度占 6 成以上;杨桦次生林林龄 40 年以上,林木生长良好(即所谓“现阶段典型阔叶次生林”).成对样地间的边界距离严格控制在 10~20 m 范围内,以确保其立地条件的一致性,同时又避开不同林型的边际效应.样地的其他一些林分特征和土壤性状分别见表 1 和表 2.

1.2 样品采集和制备

采用多点混合采样法采集土壤样品.每个样地随机选取 5 个采样点,小心去除地表有机层后,分别按照 0~5、5~10、10~20、20~40、40~60 cm 深度采集土芯样品;每块样地的同层 5 个土样充分混合,组成 1 个代表该样地的混合样.待风干后,利用四分法分别制成过 2、0.25 mm 筛的土样,部分样品研磨过 100 目筛,编号备用.

表 1 阔叶红松林和杨桦次生林样地的部分林分特征  
Table 1 Stand characters of the broadleaved Korean pine forest and *Betula platyphylla* secondary forest

林型 Forest type	林分 Stand				凋落物 Forest litter <sup>1)</sup>			地表有机层 Forest floor <sup>2)</sup>	
	林龄 Stand age	郁闭度 Closure	树高 Tree height (m) <sup>1)</sup>	树干断面积 Basal area (m <sup>2</sup> ·hm <sup>-2</sup> ) <sup>1)</sup>	输入量 Input (t·hm <sup>-2</sup> ·a <sup>-1</sup> )	C/N	pH (H <sub>2</sub> O)	厚度 Thicknees (cm)	现存量 Stock (t·hm <sup>-2</sup> )
阔叶红松林 Broadleaved Korean pine forest	>250	0.70~0.85	31.3a	81.6a	4.12a	55.5a	4.32b	7.2a	11.51a
杨桦次生林 <i>Betula platyphylla</i> secondary forest	40~60	0.70~0.80	25.7b	44.5b	3.78b	36.6b	5.47a	3.4b	5.60b

1) 6 对样地的调查、观测结果平均值 The mean of 6 paired forest blocks; 2) 全部 20 对样地在 8 月中旬的调查结果平均值 The mean of total 20 paired forest blocks, which were determined in mid-August. 不同小写字母表示不同林型间差异显著 ( $P<0.05$ ) Different lowercase letters indicated significant differences between forest types at 0.05 level.

表 2 阔叶红松林和杨桦次生林样地土壤剖面的一些重要性状  
Table 2 Selected soil properties in the broadleaved Korean pine forest and *Betula platyphylla* secondary forest

林型 Forest type	发生层 Soil horizon	向下部土层过渡情况 TCU	土层厚度 Thicknees (cm)	容重 BD (g·cm <sup>-3</sup> )	粉粒 Silt (%)	黏粒 Clay (%)	pH (H <sub>2</sub> O)	有机质 OM (%)	全氮 TN (%)	C/N
阔叶红松林	A	截然过渡 D	10.2b	0.88b	34.5a	25.6a	5.21b	12.1a	0.49b	14.6a
KP	E	逐渐过渡 G	14.7a	1.19a	46.3a	12.5a	5.18a	1.8b	0.12b	10.1a
	B	逐渐过渡 G	42.3a	1.41a	23.6a	40.2a	5.32a	1.1a	0.08	7.8a
杨桦次生林	A	截然 D/逐渐 G	13.1a	0.92a	33.7a	26.1a	5.67a	11.6a	0.56a	12.5b
BP	E	逐渐过渡 G	12.3b	1.18a	45.3a	12.6a	5.22a	2.2a	0.14a	10.2a
	B	逐渐过渡 G	43.1a	1.41a	22.9a	39.7a	5.32a	1.1a	0.08	7.8a

A: 腐殖质淋溶层 Humus eluvial horizon; E: 漂白淋溶层(即白浆化层) Albic eluvial horizon; B: 淀积层 Illuvial horizon. TCU: Transition characters to the underneath horizon; D: Distinct; G: Gradual; BD: Bulk density; OM: Organic matter; TN: Total nitrogen. KP: Broadleaved Korean pine forest; BP: *Betula platyphylla* secondary forest. 下同 The same below. 数据为全部 20 对样地中心剖面的测定结果平均值 All the data were means of the central soil profiles of 20 paired forest blocks. 不同小写字母表示相同发生层不同林型间差异显著 ( $P<0.05$ ) Different lowercase letters indicated significant differences between forest types under the same soil horizon at 0.05 level.



### 1.3 样品分析

土壤总碳和全氮含量用自动 CN 分析仪 (Heraeus Elementar Vario EL, Hanau) 直接测定。鉴于长白山森林土壤中不含碳酸钙, 所以测得的土壤总碳均为有机碳; 同时, 由于土壤全氮的绝大部分为有机态<sup>[32]</sup>, 所以亦可作为有机氮的替代指标<sup>[15]</sup>。

土壤轻组和重组的分离, 在 Janzen 等<sup>[33]</sup> 提出的分离方法基础上加以改进: 1) 称取过 2 mm 筛的风干土样 25.0 g 于 100 mL 离心管中, 加入 50 mL NaI 重液 (密度  $1.80 \text{ g} \cdot \text{cm}^{-3}$ ), 振荡 1 h ( $200 \text{ r} \cdot \text{min}^{-1}$ ), 期间超声分散 3 min ( $400 \text{ J} \cdot \text{mL}^{-1}$ ), 然后在  $4000 \text{ r} \cdot \text{min}^{-1}$  条件下离心 20 min (如果悬液浑浊则加大离心机的转速或增加离心时间), 表面悬浮的轻组有机物连同上清液轻轻倒入装有  $0.45 \mu\text{m}$  尼龙滤膜的砂芯过滤装置中抽气过滤; 2) 重复上述过程 2~3 次, 直至没有可见的轻组有机物质, 最后用去离子水冲洗轻组有机物至重液被淋洗干净, 将收集的轻组用 75 mL  $0.01 \text{ mol} \cdot \text{L}^{-1}$  的  $\text{CaCl}_2$  进行滤洗, 再用去离子水滤洗 3 次, 滤纸上的轻组有机物洗到预先称量的器皿中, 在  $60^\circ\text{C}$  下烘干 72 h, 称量, 这一组分为轻组; 3) 上述离心管内沉淀加 50 mL 蒸馏水, 震荡  $0.5 \text{ h}$  ( $200 \text{ r} \cdot \text{min}^{-1}$ ), 然后在  $4000 \text{ r} \cdot \text{min}^{-1}$  条件下离心 20 min, 弃去上清液, 重复洗涤 3 次, 管内沉淀用 95% 乙醇反复洗涤至无色, 洗出, 烘干、称量, 这一组分为重组; 4) 以上组分用玛瑙研钵研磨, 过 100 目筛后装入半微量样品管备用。轻组、重组组分的有机碳、氮含量测定同上。本研究从 20 对样地中随机抽取 10 对样地 0~5 和 5~10 cm 两个土层的样品进行密度组分分析。

土壤有机碳、氮储量按以下公式计算:

$$S = C \times BD \times T \times (1 - RF) \times 10^{-1} \quad (1)$$

式中:  $S$  为某层土壤的总有机碳、氮或密度组分有机碳、氮储量 ( $\text{t} \cdot \text{hm}^{-2}$ );  $C$  为该层土壤的总有机碳、氮或密度组分有机碳、氮含量 ( $\text{g} \cdot \text{kg}^{-1}$ );  $BD$ 、 $T$ 、 $RF$  分别为该层土壤的容重 ( $\text{g} \cdot \text{cm}^{-3}$ )、土层厚度 (cm) 及  $>2 \text{ mm}$  石砾含量百分比。

### 1.4 数据处理

采用 SPSS 19.0 软件进行统计分析, 两种林型间的差异采用成对数据  $t$  检验, 不同土层间的差异采用单因素方差分析 Duncan 法检验; 利用线性回归评估土壤有机碳、氮间的关系。利用 SigmaPlot (12.0) 软件作图。

## 2 结果与分析

### 2.1 土壤总有机碳、氮及其剖面分布

土壤有机碳含量在表层最高, 随土层深度而显著递减。0~5 cm 土层有机碳含量中位值高达  $100 \text{ g} \cdot \text{kg}^{-1}$  以上, 5~10 cm 土层有机碳中位值也高达  $50 \text{ g} \cdot \text{kg}^{-1}$  以上, 0~10 cm 是有机碳的主要聚集层。在 0~5、5~10、10~20 cm 土层, 杨桦次生林土壤有机碳含量分别比阔叶红松林高 5.0%、15.7%、53.6%, 土壤有机碳储量分别比阔叶红松林高 8.2%、14.5%、51.1%, 差异均达显著或极显著水平。在 0~20 cm 土层, 杨桦次生林的有机碳储量均值比红松阔叶林提高  $14.7 \text{ t} \cdot \text{hm}^{-2}$ 。20 cm 以下土层, 两种林型土壤有机碳含量和储量均无显著差异 (图 2), 表明林型或次生演替对研究区土壤有机碳的影响主要限于表层或亚表层。

土壤全氮含量的剖面分布与总有机碳相似。0~5 cm 土层全氮含量中位值高达  $6.0 \sim 7.0 \text{ g} \cdot \text{kg}^{-1}$ , 5~10 cm 土层全氮含量中位值也高达  $4.0 \sim 5.0 \text{ g} \cdot \text{kg}^{-1}$ , 0~10 cm 也是全氮的主要聚集层。在 0~5、5~10、10~20 cm 土层, 杨桦次生林土壤全氮含量分别比阔叶红松林高 17.2%、30.3%、58.8%, 土壤全氮储量则分别比阔叶红松林高 20.8%、28.9%、56.2%, 差异均达极显著水平。在 20 cm 以下土层, 两种林型土壤全氮含量和储量无显著差异 (图 2), 表明林型或次生演替对研究区土壤全氮的影响也主要限于表层或亚表层。

土壤 C/N 值同样在表层最高, 随土层深度而显著递减。在 0~5、5~10 cm 土层, 杨桦次生林土壤 C/N 值显著低于阔叶红松林 (图 2)。在 10 cm 以下土层, 两种林型土壤 C/N 值无显著差异。

### 2.2 土壤总有机碳、氮的协同积累

在不同森林类型的不同土层中, 土壤总有机碳和全氮均表现为极显著的正相关关系 (图 3), 即二者是协同积累的 (co-accumulation)<sup>[34]</sup>。考虑到东北森林土壤有机氮占全氮的绝大部分<sup>[32]</sup>, 所以, 我们认为土壤含氮有机质积累是有机碳和全氮协同积累的根本原因。

在 0~10 cm 土层, 杨桦次生林土壤全氮对总有机碳的决定系数 ( $R^2$ ) 明显高于原始阔叶红松林 (图 3), 说明与相对贫氮的原始阔叶红松林生态系统相比 (表 1、表 2、图 2), 相对富氮的杨桦次生林生态系统表层土壤有机碳的积累在更大程度上依赖氮 (含氮有机质) 积累, 这一指向与杨桦次生林表层土壤

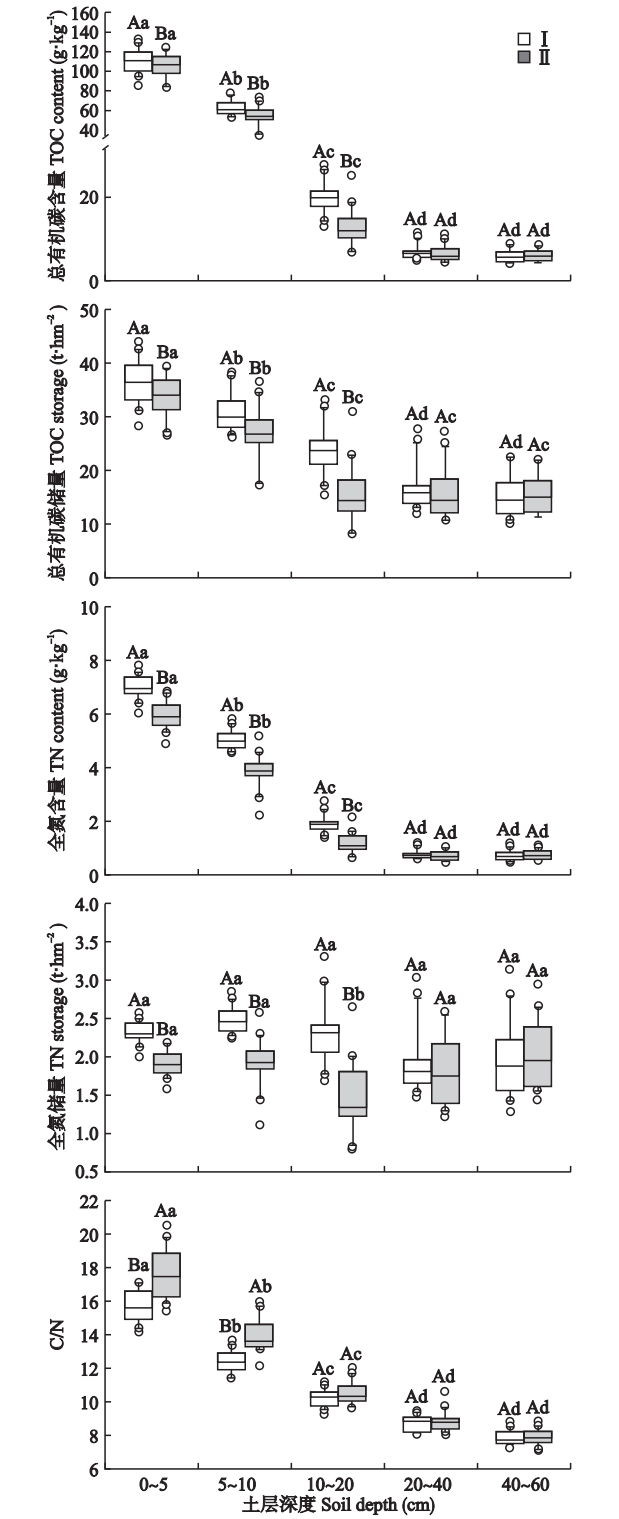


图2 土壤总有机碳、全氮及C/N的剖面分布

**Fig.2** Distribution of total organic carbon, total N, and C/N ratio in soil profile ( $n=20$ ).

不同小写字母表示同一林型不同土层间差异显著, 不同大写字母表示相同土层不同林型间差异显著 ( $P<0.05$ ) Different lowercase letters indicated significant differences between different soil layers of the same forest type, and different uppercase letters indicated significant differences between different forest types in the same soil layer at 0.05 level.

I: 杨桦次生林 *Betula platyphylla* secondary forest; II: 阔叶红松林 Broadleaved Korean pine forest. 下同 The same below.

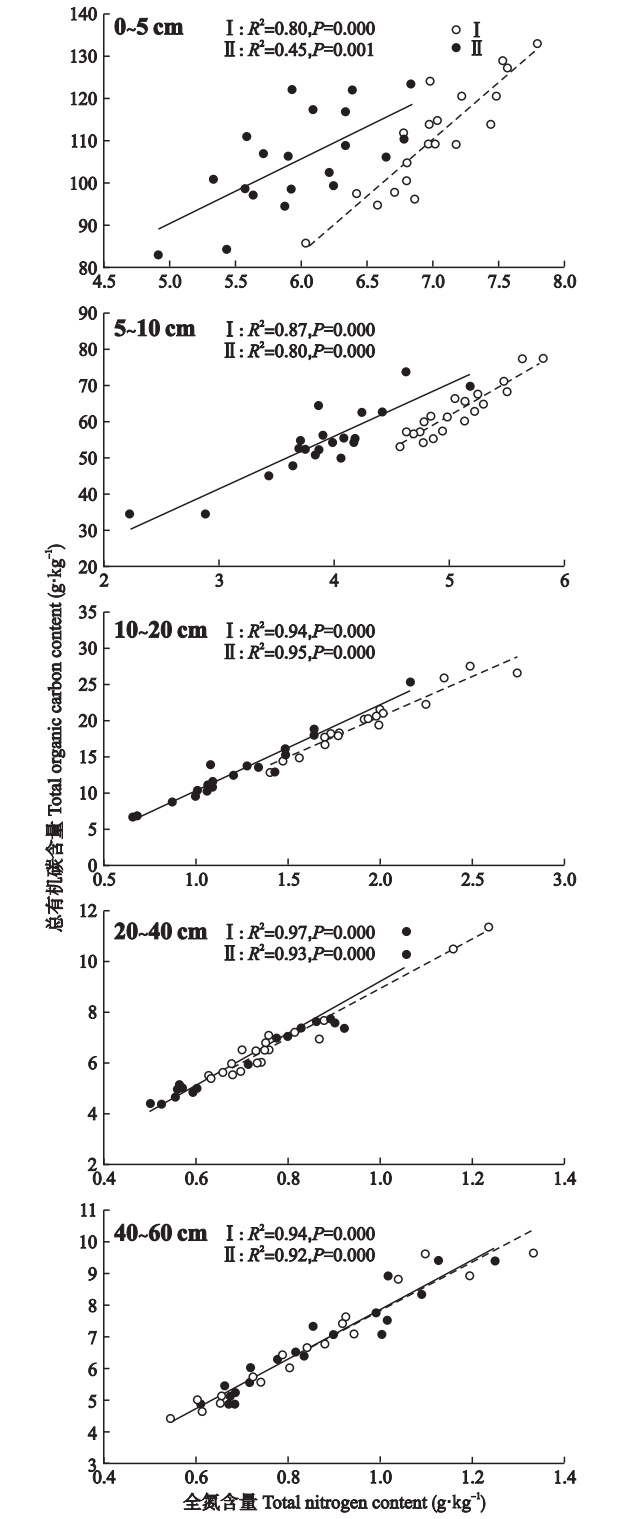


图3 不同土层总有机碳与全氮含量的相关性

**Fig.3** Correlation between total organic carbon and total nitrogen in different soil layers.

C/N 低于阔叶红松林相符(图2);此外,线性回归曲线斜率也反映出杨桦次生林表层土壤中氮积累更有利于促进碳的积累.两种林型 10~20、20~40、40~60 cm 土层的碳、氮关系差异不大(图3),说明林型或

表 3 土壤密度组分中有机碳、氮及其相关性  
Table 3 Organic carbon and nitrogen in soil density fractions and the C, N correlations (n=10)

林型 Forest type	土层 Soil layer (cm)	轻组 Light fraction							重组 Heavy fraction								
		有机碳 OC			氮 N			C/N	R <sup>2</sup>	有机碳 OC			氮 N			C/N	R <sup>2</sup>
		含量 (g· kg <sup>-1</sup> )	储量 (t· hm <sup>-2</sup> )	LOC/ SOC (%)	含量 (g· kg <sup>-1</sup> )	储量 (t· hm <sup>-2</sup> )	N/TN (%)			含量 (g· kg <sup>-1</sup> )	储量 (t· hm <sup>-2</sup> )	HOC/ SOC (%)	含量 (g· kg <sup>-1</sup> )	储量 (t· hm <sup>-2</sup> )	N/TN (%)		
阔叶	0~5	54.3Aa	17.4Aa	51.5Aa	1.41Aa	0.46Aa	23.4Aa	38.8Aa	0.43 *	44.4Ba	14.2Ba	43.1Bb	4.18Ba	1.34Ba	69.8Bb	10.6Aa	0.92 * *
红松林 KP	5~10	17.7Ab	8.7Ab	32.5Ab	0.44Ab	0.22Ab	11.3Ab	40.2Aa	0.48 * *	32.7Bb	16.4Ba	60.3Ba	3.30Bb	1.67Ba	84.8Ba	9.9Ab	0.96 * *
	合计 Total	-	26.0A	-	-	0.66A	-	-	-	-	30.7B	-	-	3.01B	-	-	-
杨桦次	0~5	50.6Ba	16.7Aa	45.7Ba	1.50Aa	0.49Aa	21.5Aa	33.5Ba	0.66 * *	54.9Aa	18.1Aa	49.6Ab	5.28Aa	1.74Aa	75.3Ab	10.4Aa	0.95 * *
生林 BP	5~10	16.5Ab	8.1Ab	26.2Bb	0.43Ab	0.21Ab	8.5Bb	38.8Aa	0.64 * *	42.9Ab	21.1Aa	68.3Aa	4.47Ab	2.20Aa	88.4Aa	9.6Ab	0.96 * *
	合计 Total	-	24.9A	-	-	0.71A	-	-	-	-	39.2A	-	-	3.93A	-	-	-

表中数据为 10 对样地测定结果的平均值 All the data were means of 10 paired forest blocks. R<sup>2</sup>: 决定系数 Coefficient of determination. LOC: 轻组有机碳 Organic carbon in light fraction; HOC: 重组有机碳 Organic carbon in heavy fraction. 不同大写字母表示相同土层不同林型间差异显著,不同小写字母表示相同林型不同土层间差异显著 (P<0.05) Different capital letters indicated significant differences between forest types under the same soil layer at 0.05 level, and different lowercase letters indicated significant differences between soil layers within a forest type at 0.05 level. \* P<0.05; \* \* P<0.01.

次生演替对土壤碳氮关系的影响主要体现在表层。

0~5、5~10 cm 土层 (尤其前者) 中全氮对总有机碳的决定系数明显小于 10~20、20~40 cm 土层 (图 3), 即相对于上部土层, 下部土层有机碳的积累在更高程度上依赖氮积累; 这与 0~5、5~10 cm 土层 C/N 值及其相对变异程度明显高于下部土层相吻合 (图 2)。

2.3 土壤密度组分中的有机碳、氮及其协同积累

在 0~5 cm 土层, 土壤有机碳各有 45%~55% 分布在轻组或重组中; 而在 5~10 cm 土层, 分布在轻组中的有机碳比例下降到 30% 左右, 重组有机碳占比则升至 60%~70%。相较于有机碳, 氮的分布更倾向于重组组分。在 0~5 cm 土层, 约 20% 的土壤全氮分布在轻组, 约 70% 分布在重组; 5~10 cm 土层, 分布在轻组中的氮比例下降到 10% 左右, 重组氮占比则升至 80% 以上。轻组组分的 C/N 在 30~40, 重组组分的 C/N 则仅为 10 左右; 重组组分中氮对有机碳的决定系数 (0.92~0.96) 明显大于轻组 (0.48~0.71) (表 3)。表明相较于轻组, 重组有机碳 (有机质) 积累在更大程度上依赖含氮有机物积累。

尽管阔叶红松林比杨桦次生林趋于将较高比例的有机碳、氮分布在轻组组分中, 但林型间轻组有机碳、氮储量并无显著差异。杨桦次生林重组有机碳、氮的含量、储量及分配比例均显著高于阔叶红松林, 其 0~10 cm 土层重组有机碳、氮储量分别是阔叶红松林的 1.28、1.30 倍, 重组有机碳储量平均增加 8.5 t·hm<sup>-2</sup>。杨桦次生林轻组、重组组分的 C/N 值略低于阔叶红松林, 其轻组、重组 (尤其轻组) 组分中氮对有机碳的决定系数也比阔叶红松林高, 这可从表观上部分地解释上文中其相应土层“C/N 值较低 (图 2) 且全氮对总有机碳的决定系数较高 (图 3)”;

不过, 主要的表观解释可能不在此, 而是杨桦次生林在相对富氮的重组组分中分配了更高比例的有机碳、氮 (表 3)。

3 讨 论

3.1 次生演替与土壤有机碳、氮库变化

近年来, 长白山森林土壤有机碳储量变化颇受关注。有研究得出: 基于传统的样地调查和统计方法, 长白山森林土壤有机碳含量和密度随森林类型 (或演替阶段) 和林龄的变化并不显著<sup>[29,31]</sup>; 杨树天然林、阔叶混交天然林表层土壤有机碳、氮含量均不比红松天然林高, 甚至有低于后者的趋势<sup>[30]</sup>。本研究通过严格的成对样地途径, 得出长白山杨桦次生林下土壤有机碳、氮含量和密度均显著高于原始阔叶红松林 (图 2)。这一结果与前人截然不同, 提示对比样地立地条件和林分条件的控制至关重要。

从林分现状分析, 杨桦次生林与阔叶红松林的首要差异是树种组成。树种导致的森林土壤碳、氮储量差异首先表现在地表有机层或林褥层 (forest floor), 其次才是其下面的矿质土层<sup>[13,21,35-36]</sup>。针叶树主导的生态系统趋于在地表有机层中储存较大量的低分解植物有机碳、氮; 而阔叶林则趋于在矿质土层储存较多或较高比例的土壤有机碳、氮<sup>[13,15,20,37]</sup>。在欧洲或北美, 挪威云杉 (*Picea abies*) 等表现为较典型的“针叶树趋向”<sup>[13,20]</sup>, 欧洲白蜡 (*Fraxinus excelsior*)、槭 (*Acer pseudoplatanus*)、椴 (*Tilia cordata*) 则表现为较典型的“阔叶树趋向”<sup>[13,21-22,35-39]</sup>。在长白山地区, 尽管红松针阔混交林可能会减弱红松的“针叶树趋向”, 且杨桦次生林也不是单个阔叶树种的纯林, 但后者相对于前者的“阔叶树趋向”还是较明显的 (表 1、图 2)。就稳定性而言, 地表有机层中积



累的有机碳易因林火和其他干扰而迅速损失,而矿质土壤中固存的有机碳则因受保护而较少受短期气候变化和其他干扰的影响<sup>[37,40]</sup>;因此,从生态系统固碳角度鉴别和选择有利于在矿质土层(而非地表有机层)固存有机碳的树种尤为重要<sup>[13]</sup>.本研究表明,长白山原始红松针阔混交林转化为杨桦次生林后,随着林分发育至一定(中龄)阶段,其土壤层有机碳(尤其矿质结合的稳定性有机碳)固存量是增加的(图2、表3).根据0~20 cm土层中杨桦次生林有机碳储量比参照林型红松阔叶林提高14.7 t·hm<sup>-2</sup>,假设林分平均年龄为50年(表1),推算得知次生林土壤的平均固碳速率增量为29.4 g·m<sup>-2</sup>·a<sup>-1</sup>,这是一个相当可观的碳汇增益.鉴于我国东北温带森林次生演替的普遍性现状,这一结果有利于我国碳外交谈判.

从原始红松针阔混交林向阔叶次生林的转变主要是大面积采伐驱动的次生演替过程<sup>[41]</sup>,包括采伐迹地以及次生植被恢复中的未郁闭幼龄林、郁闭中幼龄林、郁闭成熟林等不同群落发育阶段.森林采伐后,因采伐剩余物分解和土壤有机质扰动<sup>[42-43]</sup>,往往能迅速观测到碳、氮的爆发性释放<sup>[44-45]</sup>.尽管采伐不可避免地导致生态系统内碳、氮的生物地球化学循环,但其对土壤有机碳、氮库的影响却因采伐方式、强度、频率及气候条件和立地质量而异<sup>[46]</sup>.Johnson等<sup>[47]</sup>通过Meta分析发现:针叶树采伐使A层土壤有机碳、氮显著增加,硬阔叶树采伐则使土壤有机碳趋于减少而氮趋于增加.在森林更新早期,由于地表有机层扰动、幼林郁闭前凋落物输入大幅减少及土壤有机质分解加速等原因,土壤有机碳、氮储量有所降低<sup>[48]</sup>,但30~40年后可恢复到其初始水平<sup>[49-52]</sup>,有些情况下恢复时间可能会更长<sup>[53]</sup>.在长白山林区,杨桦次生林一般是原始阔叶红松林高强度采伐(皆伐仅收获树干)后的产物,经历了早期采伐迹地小气候(水热条件)骤变、次生幼林凋落物锐减、土壤生物群落及活性变化、地表有机层和土壤有机质分解加速等一系列过程.这一过程中土壤有机碳、氮有无损失?损失的程度和组分?土壤有机碳源汇转化及土壤碳库恢复的大致年限等,均有待进一步研究.

### 3.2 土壤有机碳、氮库变化的驱动机制

不同树种地表有机层积累差异被认为是树种的分解行为所致<sup>[15]</sup>.主要是凋落物化学组成,包括木质素和钙含量<sup>[12,54]</sup>,尤其是C/N值或氮含量调控凋落物的分解与积累过程<sup>[15]</sup>.因植物残体氮主要是有

利于微生物分解的蛋白质类,故凋落物的C/N是地表有机层碳储量的良好指标,较低的凋落物C/N预示较快的分解速率和较低的地表有机层碳储量<sup>[13]</sup>.本研究中杨桦次生林凋落物的C/N值显著低于阔叶红松林,而其pH值又显著高于后者(表1);相应地,杨桦次生林应该具有较高的凋落物分解速率(本文未测),以及较低的地表有机层碳储量(表1).这一结果与国内外的概念框架相吻合,也与国内对长白山森林凋落物分解的有关研究相一致<sup>[55-56]</sup>.

尽管植物残体的低C/N值或高含氮量表征其易分解性,但对土壤有机质而言,低C/N值却意味着高分解度和高稳定性.近年来,土壤和生态学界已经认识到有机氮在稳定性土壤有机质的形成中具关键作用<sup>[9,17]</sup>.核磁共振波谱(NMR)分析表明,蛋白质(肽)类物质倾向于被选择性地保存在土壤中并构成SON库的主体<sup>[57-58]</sup>.土壤中固存肽类(氨基酸)或蛋白质类物质的可能机制包括:矿物质结合、蛋白质-单宁复合物、化学封闭作用、某些蛋白(如酶)的固有稳定性等<sup>[9]</sup>.肽类可被黏土矿物颗粒强烈吸附<sup>[59-60]</sup>,从而受到物理保护以抵抗酶的分解,且当这些小分子被吸附进入<10 nm的阻酶介孔时会受到更强的保护作用<sup>[61]</sup>.被吸附的肽类物质可在黏土矿物表面形成一个稳定的有机内层,这使其他弱极性有机物质更易在外层被吸着(即所谓onion-layer假说<sup>[62]</sup>).在森林生态系统中,产生富氮(蛋白质)高质量凋落物的树种,如欧洲白蜡、槭树、椴树等,其地表有机层的积累较少而矿质土壤中有机碳、氮积累较多且C/N值较低<sup>[13,20-22,35-39]</sup>.这可以从富氮凋落物的分解特性和蛋白质、肽类(氨基酸)在土壤中的固存机制得到很好的解释,尽管上述研究大都并未涉及到这一层次.本研究推测,相对富氮的杨桦次生林凋落物(包括细根)分解会产生比阔叶红松林更丰富的蛋白质和肽类(氨基酸)物质,更多含氮有机物在进入土壤后因不同机制而得到固存,从而在很大程度上导致次生林土壤总有机碳、氮积累量相对较高且C/N值较低(图2).长白山地区白浆土中富含黏土矿物(表2),较丰富肽类(氨基酸)的优先吸附保护机制可能进一步促成了杨桦次生林土壤中与矿质紧密结合的重组有机碳、氮积累显著高于阔叶红松林(表3);此外,无论杨桦次生林还是阔叶红松林,土壤重组组分的C/N值均远低于轻组,暗示有机氮与矿物结合在稳定性土壤有机质形成中的重要性,这与国外许多研究一致<sup>[62]</sup>.

在森林生态系统中,土壤动物是凋落物分解和

土壤有机质形成的一个独特驱动因素.尤其蚯蚓类,可将地表有机层中的植物残体混入深层土壤<sup>[63]</sup>,并能强烈影响土壤碳、氮动态<sup>[64]</sup>.本研究在采样过程中注意到,杨桦次生林地表有机层和土壤 A 层中有比阔叶红松林更丰富的蚯蚓和其他土壤动物,不过未对其进行量化.杨桦次生林下高质量凋落物所致的较强土壤动物活动可能是凋落物分解较快且土壤有机质(碳、氮)积累较多的重要附加因素.阔叶次生林上部土层有机碳、氮对下部土层有机碳、氮的决定系数( $R^2$ )高于阔叶红松林(数据未显示),提示上下土层间较强的混合作用,而这种混合作用的主要驱动力可能就是土壤动物.

树种根系在土壤剖面中的分布特征也会显著影响土壤有机碳、氮的积累,因为细根凋落物对土壤有机碳库的贡献可以与地上凋落物相当或更大<sup>[65-66]</sup>.在欧洲,挪威云杉倾向于将大量根系分布在地表有机层中<sup>[67]</sup>,因而主要增加对该层碳、氮积累的贡献;白蜡和椴树林下 15~30 cm 土层中较高的有机碳、氮积累可归因于较高的细根凋落物输入量<sup>[13]</sup>.长白山杨桦次生林和阔叶红松林主要树种的根系分布习性均尚未知,不过在本次采样中发现杨桦次生林在 10~20 cm 土层往往有较多的细根分布,而阔叶红松林细根则高度集中在 0~10 cm 土层.这可能主要是土壤生境差异所致;阔叶红松林下白浆层明显发育,严格限制林木根系集中分布在相对肥沃的 A 层(深度大致相当于 0~10 cm 土层,表 2);而杨桦次生林下地表有机层变薄(表 1),滞水性下降,白浆化过程在一定程度上被阻断,由于土壤动物活动及根系分布使 A 层与 E 层的界限变得模糊, A 层向深度发展(表 2),这又进一步促进了林木细根向深层(10~20 cm)的分布.上述土壤生境改变所致的根系分布深度和土壤动物活动变化,可以较好地解释两种林型为什么在 10~20 cm 土层达到有机碳、氮积累的最大差异(图 2).

土壤碳氮周转的主要环境控制因素是水热条件,树种组成的变化会因地表有机层的小气候变化影响土壤碳氮周转<sup>[68]</sup>.如上所述,土壤生境改变可引起成土作用、动物活动、根系分布等变化,此外,更可能影响土壤有机质形成、积累与分解的微生物过程和生物化学过程,这都有待进一步研究.

## 4 结 论

长白山典型杨桦次生林比原始阔叶红松林在土壤表层和亚表层积累了更多的有机碳、氮,且前者土

壤有机质中相对更加富氮.土壤有机碳和全氮是协同积累的,与阔叶红松林相比,杨桦次生林上部土层中有机碳的积累在更大程度上依赖含氮有机质的积累.次生演替导致的土壤有机碳、氮库的增加主要在于矿物质结合态稳定性土壤有机碳、氮积累增加.凋落物分解和稳定性土壤有机质形成中的碳氮耦合机制是次生演替过程中土壤有机碳、氮库变化的重要驱动机制.

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