

森林土壤呼吸及其对全球变化的响应

杨玉盛¹, 董 彬², 谢锦升², 陈光水¹, 高 人¹, 李 灵², 王小国², 郭剑芬²

(1. 福建师范大学地理科学学院, 福建福州 350007; 2. 福建农林大学林学院, 福建南平 353001)

摘要: 森林土壤呼吸是全球碳循环的重要流通途径之一, 其动态变化将直接影响全球 C 平衡。森林土壤呼吸由自养呼吸和异养呼吸组成, 不同森林类型、测定季节和测定方法等直接影响其所占比例。土壤温度和湿度是影响森林土壤呼吸的最主要因素, 共同解释了森林土壤呼吸变化的大部分。因树种组成、生产力和枯落物数量等不同而使不同森林类型土壤呼吸速率表现出明显差异。采伐对森林土壤呼吸的影响结果有增加、降低或无影响, 因采伐方式、森林类型、采伐迹地上植被恢复进程和气候条件等而异。火烧一般导致土壤呼吸速率降低。因肥料种类、施用剂量和立地条件不同, 施肥对森林土壤呼吸的影响出现增加、降低或无影响等不同结果。大气 CO₂ 浓度升高和升温均可促进森林土壤呼吸。N 沉降有可能刺激了土壤呼吸, 而酸沉降则可能降低了土壤呼吸。臭氧浓度和 UV-B 辐射强度亦会在一定程度上影响森林土壤呼吸。但目前全球变化对森林土壤呼吸的综合影响尚不清楚, 深入探讨森林土壤呼吸的调控因素及其对全球变化和营林措施的响应等仍是今后努力的主要方向。

关键词: 森林土壤呼吸; 全球变化; 碳循环; 影响因素

Soil respiration of forest ecosystems and its response to global change

YANG Yu-Sheng¹, DONG Bin², XIE Jin-Sheng², CHEN Guang-Shui¹, GAO Ren¹, LI Ling², WANG Xiao-Guo², GUO Jian-Fen² (1. College of Geography Science, Fujian Normal University, Fuzhou 350007, China; 2. College of Forestry, Fujian Agriculture and Forestry University, Nanping 353001, China). *Acta Ecologica Sinica*, 2004, 24(3): 583~591.

Abstract: Soil respiration in forest ecosystems is one of the major pathways of C flux in the global C cycle, second only to the gross primary productivity, and is markably affected by the global change. The review summarized the important role of forest soil respiration in global carbon cycle, its components, its controlling factors, and its response to the global change.

Forest soil respiration is the sum of heterotrophic (microbes, soil fauna) and autotrophic (root) respiration. The contribution of each group needs to be understood to evaluate the implications of environmental changes on soil carbon cycling and carbon sequestration. There is a large variation in the relative contributions of autotrophic and heterotrophic respiration to total soil CO₂ efflux, and the estimated contributions from root respiration range from 10% to as high as 90%. Some of this variation may come from differences in methodology and from differences in forest and soil types. The critical factors influencing forest soil respiration include soil temperature, soil moisture, forest types (substrate quality, net ecosystem productivity, the relative allocation of NPP above- and belowground) and forest management (land-use and/or disturbance regimes, fertilization). The temperature effect is always described as an exponential function. The effect of soil moisture, in contrast, has been described by numerous equations including linear, logarithmic, quadratic, and parabolic functions. Soil respiration is frequently maximized when soil is at an intermediate water content. Soil temperature and soil humidity together explain a large part of variations in soil respiration. Forest types may affect soil respiration by influencing the soil microclimate and structure, the quantity and quality of substrate, and the overall rate of root respiration. At the global scale, soil

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作者简介: 杨玉盛 (1964~), 男, 福建仙游人, 博士, 教授, 主要从事亚热带常绿阔叶林 C、N 等元素循环的研究。E-mail: ffcyys@public.npoptt.fj.cn

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Biography: YANG Yu-Sheng, Ph. D. Professor, principally engaged in study on C and N cycling in subtropical evergreen broad-leaved forests. E-mail: ffcyys@public.npoptt.fj.cn

respiration rates in forests are correlated positively with litterfall rates. Despite this complex array of factors that affect forest soil respiration, soil respiration is typically modeled either as a simple Q_{10} function or as a step relationship based on temperature response curves.

Harvest cutting could stimulate, suppress, or show no effect on soil respiration, depending on harvest methods, forest types, speed of regeneration and climate conditions. Slash burning usually decrease soil respiration rate. Fertilization might enhance, reduce or show no effects on soil respiration, depending on fertilizer types, loading levels and site conditions.

The elevated atmospheric CO_2 could increase the efflux of CO_2 from soils, while simultaneously leaving a greater store capacity of carbon in the soil. Rising temperature increases the efflux of CO_2 from soils with a net release of soil carbon and, thus, will further global warming. Nitrogen deposition may promote the sequestration of carbon in vegetation and soils. The integrated effects of these global changes is unknown yet, but it seems unlikely to mitigate the rise of atmospheric CO_2 in this century through a large increase in the soil carbon pool. Ozone concentration and radiant intensity of UV-B could somehow influence soil respiration directly or indirectly.

Despite intensive researches in recent years, there still need some efforts before we can make an understanding of the interactions between global changes and forest soil respiration: (1) developing appropriate methods for separating various components of soil respiration; (2) implementing long-term in situ research on the effects of anthropic disturbance, particularly those of intensive disturbances (e.g. clearcutting, fire); (3) understanding mechanisms on responses of forest soil respiration to global changes in different climatic zone; (4) developing techniques for the data to scale up from a small chambers to a stand or ecosystem level, and even to a regional or global level; and (5) establishing a global research network on forest soil respiration and perfecting the global CO_2 FLUX web.

Key words: forest soil respiration; global change; carbon cycle; effect factors

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随着全球变化逐渐成为公众和科学界关注的热点, CO_2 作为一种重要的温室气体,其源、汇及通量的精确测定受到格外重视。土壤呼吸是大气 CO_2 的重要来源,主要由根呼吸和微生物分解有机物产生,另有极少部分来自于土壤动物呼吸与化学氧化。全球陆地生物群落的总净初级生产力约为 $62.6 Pg C a^{-1}$,而世界范围土壤呼吸高达 $80.4 Pg C a^{-1}$,仅次于海洋释放到大气的 CO_2 通量,是化石燃料燃烧释放 CO_2 的 13 倍^[1]。因而,土壤呼吸在生物圈和大气圈 C 交换中起着关键作用。之外,土壤呼吸亦是指示土壤和枯枝落叶层 C 代谢、林木地下 C 分配以及生态系统生产力、土壤肥力等信息的良好指标^[2~4]。

森林生态系统是陆地最大碳储存库,其地上部分含 $360\sim 480 Pg C$ (占地上部分的 80%左右),地下部分含 $790\sim 930 Pg C$ (占地下部分的 40%左右)^[5]。森林土壤呼吸亦是陆地生态系统土壤呼吸的重要组成部分,其动态变化将对全球 C 平衡产生深远的影响。全球森林过度采伐和其他土地利用变化导致土壤 CO_2 释放的增加量,占过去两个世纪来因人类活动释放的 CO_2 总量的一半^[5],是除化石燃烧释放 CO_2 导致大气 CO_2 浓度升高的另一重要因素(图 1)。森林土壤呼吸亦是目前已建立的长期监测 CO_2 通量网站的重要研究对象之一^[1,6]。因而,鉴于森林土壤呼吸对全球碳循环和碳预算重要性(图 1),森林土壤呼吸及研究其对全球变化的响应具有重要价值。本文通过对森林土壤呼吸的各个分室、影响因素及其对全球变化的响应进行系统综述,以期对制定合适的森林保护、森林培育的决策提供理论依据。

1 森林土壤呼吸的组成

森林土壤呼吸由自养呼吸(根呼吸)和异养呼吸(微生物呼吸)组成^[2, 7, 8]

1.1 自养呼吸

根呼吸(森林土壤自养呼吸)与林木地上光合作用所能提供的同化物密切相关^[8]。全球范围内林木根呼吸对土壤呼吸的贡献为 10%~90%(主要集中在 40%~60%),与森林类型、测定季节和测定方法等有关^[7,9~12]。寒冷的北方森林生态系统中根呼吸占土壤呼吸的比例较高(50%~93%)^[10,13],温带(33%~62%)和热带森林生态系统则稍低^[7,14]。目前测定根呼吸方法主要有排除根法(Root exclusion)、离体根法(Isolated/ in vitro methods)、PVC 管气室法(Cuvette methods)和同位素法(Isotopic methods)等^[7,15]。用排除根法测定的根呼吸包括根际微生物呼吸,而 PVC 管气室法、同位素法和离体根法则未含根际微生物呼吸^[10,14]。排除根法和离体根法因相对简单,成本低,常用于森林生态系统中;而同位素法因对土壤-植物系统的干扰小,可以原位确定根和土壤微生物呼吸,结果相对精确,但高成本和/或因缺少适当的专业技术使其应用受限^[7]。

1.2 异养呼吸

异养呼吸包括根际微生物呼吸、无根土壤呼吸和枯枝落叶层呼吸。异养呼吸占土壤呼吸的比例在热带和温带森林生态系统

中较高(30%~83%)^[2,16,17],在寒冷地带则较低(7%~50%)^[10,13]。植物的年根际呼吸估计为植物根系当年新增C储量的20%~80%^[8,18]。Susfalk等^[19]得出林木根际呼吸所占土壤呼吸的比例为35%~45%。Kelting等^[8]观察到成龄橡树林(*Quercus rubra*)无根土壤呼吸和根际微生物呼吸分别占土壤呼吸的48%和20%。Bowden等^[2]得出温带阔叶混交林地下凋落物呼吸占土壤呼吸的30%;Rey等^[20]观察到栎树矮林(coppice oak forest)土壤有机质和地下凋落物的分解约占土壤呼吸的55%。Chambers等^[21]认为亚马逊森林中部粗凋落物(直径>10 cm干和大枝)的呼吸释放到大气的CO₂占总碳损失的76%。Bowden等^[2]观察到温带阔叶混交林枯枝落叶层呼吸占土壤呼吸的37%。吴仲民等^[22]观察到尖峰岭热带山地雨林枯枝落叶层呼吸仅占土壤呼吸的9.9%;而骆士寿等^[23]却观察到枯枝落叶层呼吸仅占土壤呼吸的1.7%~2.8%。

2 影响森林土壤呼吸的因素

土壤温度和湿度是影响森林土壤呼吸的主要因素^[20,24~36],此外还有森林类型^[9]、土壤肥力及营林活动(人为干扰)等^[27]。由于受诸多因素共同影响,森林土壤呼吸不仅有明显的季节变化,在24h内的波动幅度也较大;空间上相距很近的也可能相差颇大,因此土壤呼吸具有极其强烈的时空变异性^[27,28]。

2.1 土壤温度与森林土壤呼吸

森林土壤呼吸与土壤温度具有良好的相关性^[29,30]。吴仲民等^[22]观察到热带森林土壤呼吸与地表温度之间具有极显著的指数函数关系;Keith等^[31]观察到桉树林土壤呼吸与土壤温度表现出高度显著的对数关系。Irvine等^[30]观察到老龄西黄松(*Pinus ponderosa*)林的土壤呼吸与64 cm深土壤温度呈较强的正相关。Maier和Kress对11a火炬松(*Pinus taeda*)林研究指出,虽然土壤呼吸与土壤温度相关性未达显著水平,但7cm深处土温解释了土壤呼吸变化的70%^[33]。Certini等^[34]观察到欧洲冷杉(*Abies alba*)和山毛榉纯林土壤呼吸与大气和土壤温度的相关性大于土壤湿度,且冷杉林的这种关系较山毛榉林的好。Kätterer等^[35]认为土壤呼吸作用的Q₁₀为2左右。刘绍辉等^[36]推算了全球森林生态系统的土壤呼吸量,观察到土壤呼吸量随着纬度的增加而逐渐降低;在不考虑湿度影响下,得出了全球森林植被的土壤呼吸速率的Q₁₀值为1.57。土壤呼吸各分室对温度的敏感性不同。根呼吸对温度有强烈的敏感性^[25,26,37],Boone等观察到85a生温带混交林的根呼吸对温度的敏感性比全土的大,其中根呼吸的Q₁₀值是4.6,无根土壤呼吸的是2.5,全土的为3.5^[37]。

2.2 土壤湿度与森林土壤呼吸

土壤含水量对呼吸速率影响较为复杂。森林土壤呼吸一般随土壤湿度的增大而增加^[27],在接近田间持水量的一定范围内,土壤呼吸量最高;在饱和或永久萎蔫含水量时,呼吸作用停滞^[38]。Maier和Kress则认为当土壤含水量较低时,土壤呼吸与土壤含水量呈显著相关,土壤微生物呼吸对土壤湿度的响应一般较根敏感^[33]。

土壤湿度一般与土壤温度共同对土壤呼吸起作用,土壤呼吸的大部分变化可由土壤温度和湿度共同解释^[26,33]。Burton等观察到土壤有效水和土壤温度共同解释了赤松(*Pinus resinosa* Ait.)人工林和糖槭(*Acer saccharum* Marsh.)林根呼吸速率变化的76%和71%^[26];Rey等在栎树矮林中研究指出温度和湿度共同解释了土壤呼吸年变化的91%^[20]。Qi和Xu^[24]观察到温度和湿度共同解释了针叶林土壤呼吸变化的89%。Keith等^[31]观察到土壤温度、土壤和凋落物湿度解释了桉树林土壤呼吸变化的97%。

当土壤出现干湿交替时,土壤呼吸也会出现与土壤干湿交替类似的变化,这种现象在野外^[18,30,38]和室内模拟实验中^[39]均有观察到。产生这种现象可能与干旱时受抑制的土壤微生物和酶活性突遇增湿而迅速增强有关^[18,30,38,39]。

2.3 森林类型与土壤呼吸

不同森林类型的土壤呼吸速率差异明显(表1)。一般来说,裸子植物比被子植物有较低的根呼吸速率^[25];生长在相同土壤上针叶林的土壤呼吸速率比邻近的阔叶林的低10%左右^[40,41]。Weber^[40]观察到白杨(*Populus tremuloides*)林土壤呼吸速率比附近松树林的旁数据ns等^[41]也观察到阔叶林的土壤呼吸速率比附近松树人工林的高。但Raich和Potter观察到针叶林和阔叶林的土壤呼吸速率间没有差异^[42]。Raich等观察到热带和亚热带常绿阔叶林的土壤呼吸速率比任何其他植被类型的都

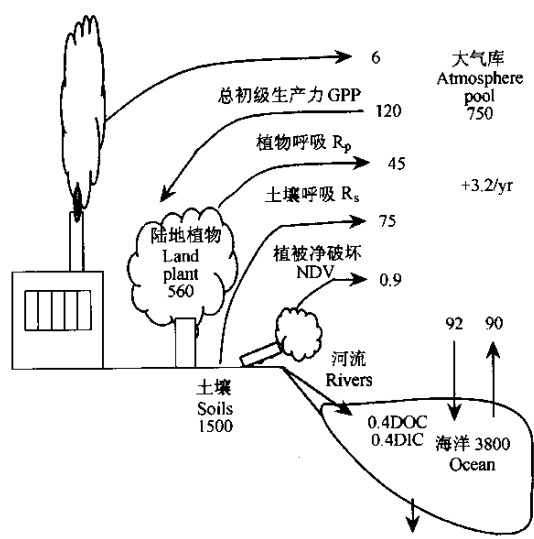


图1 全球碳循环。所有库和通量的单位分别为PgC和PgC a^[1]
Fig. 1 The global carbon cycle. All pools and all fluxes are expressed in units of PgC and PgC a, respectively^[1]
根据 Schlesiger 等(2000)略有改动 Modified from Schlesinger & Andrews(2000). (1Pg=10¹⁵)

大^[9]。草原的土壤呼吸速率一般比相应的森林的高 20%，比邻近农田的土壤呼吸速率高 25%^[9]。但 Larionova^[43]观察到土壤呼吸速率大小顺序则为农田<草地<森林。Davidson 等^[38]观察到在湿润季节原始林和高生产力牧场土壤 CO₂ 的释放量最大,在干燥季节原始林和次生林的 CO₂ 释放量比高生产力牧场和退化牧场的高。

表 1 森林类型与土壤呼吸
Table 1 Forest type and soil respiration

地点 Location	森林类型 Forest type	土壤呼吸 Soil respiration (g C m ⁻² d ⁻¹)	参考文献 Reference
巴西 Brazil	常绿森林 Evergreen forest	2.96~3.53	[44]
巴西 Brazil	森林 Forest	3.66~3.72	[45]
加拿大 Canada	落叶林 Deciduous forest	2.33	[46]
加拿大 Canada	黑云杉 Black spruce forest	14.53(最大值 Max/)	[28]
意大利 Italy	栎树林 Oak forest	3.01	[20]
德国 Germany	桤木林 Alder forest	4.81	[12]
印度 India	栎树林,松树林 Oak forest,pine forest	1.82,1.42	[47]
印度 India	阔叶混交林 Broad-leaved mixed forest;	4.67	[47]
印度 India	栎树林,柳杉林 Oak forest,cedar fores	1.28, 1.05	[48]
日本 Japan	柳杉林 Cedar fores	1.37~1.62	[49]
日本 Japan	栎树林 Oak forest	0.96~4.80	[50]
阿拉斯加 Alaska	杨树林 Poplar forest	0.93	[51]
阿拉斯加 Alaska	白云杉林 White spruce forest	0.89	[51]
阿拉斯加 Alaska	桦树-杨树林 Birch-aspen forest	1.08	[51]
阿拉斯加 Alaska	白杨林 Aspen forest	5.66±3.67	[27]
阿拉斯加 Alaska	白云杉林 White spruce forest	6.15±2.75	[27]
阿拉斯加 Alaska	黑云杉林 Black spruce forest	3.67±1.64	[27]
夏威夷 Hawaii	老龄雨林 Old rain forest	1.78~2.44	[52]
美国密歇根州	北方阔叶林 Boreal Broad-leaved forest	1.29~1.31	[29]
美国缅因州 Maine	落叶林 Deciduous forest	2.10	[53]
美国纽约 New York	赤松 Red pine	0.41	[41]
北京 Beijing	栎树林 Oak forest	1.30~1.53	[54]
北京 Beijing	白桦林,辽东栎林,油松林,Birch,Oak,Chinese pine forest	0.85,1.07,0.68	[32]
浙江 Zhejiang	青冈林,毛竹林 Cyclobalanopsis,Moso bamboo	1.80,2.30	[55]
福建 Fujian	杉木林 Chinese fir	0.22 (Jan.), 1.81(Aug.)	
福建 Fujian	栲氏栲林 Castanopsis kawakamii	0.87 (Jan.), 2.43(Aug.)	
海南 Hainan	热带雨林 Tropical rain forest	11.08,15.30(最大值 Max.)	[23]

在全球尺度上,森林土壤呼吸速率与森林 NPP 及森林凋落物量(地上和地下)呈正相关^[3,9,47]。Raich 等观察到在成龄森林生态系统中土壤呼吸速率随凋落物和林地生产力的增加而增加^[3]。热带森林土壤的呼吸速率最大与热带林的生长量和凋落量大且环境条件也较适于分解者活动有关^[1]。Irvine 等^[30]对比了幼龄和老龄西黄松(*Pinus ponderosa*)林的土壤呼吸,观察到老龄林之所以有较高的土壤呼吸,是因为老龄林立地上有较大的生产力和易分解的碎屑。但 Weber^[40]观察到白杨林的土壤呼吸速率只略大于相似林龄的较低生产力的北美短叶松(*Pinus banksiana*)。Raich 观察到高生产力的夏威夷森林比较低生产力的 NPP 高 86%,但土壤呼吸速率只高 36%^[52]。在 Michigan 低地^[56]和 Alaska^[51]等地亦观察到地上生产力显著不同的森林有相似的土壤呼吸速率。

2.4 营林活动与土壤呼吸

2.4.1 森林采伐与土壤呼吸 森林采伐对土壤呼吸的影响结果差异较大。在阿巴拉契亚山脉南部的阔叶林^[57]、日本的松树林^[58]、华盛顿 Pack Forest 的花旗松(*Pseudotsuga menziesii*)林^[59]、俄勒冈州铁杉林(*Tsuga heterophylla*)^[60]和萨斯喀彻温省东北北美短叶松-苔藓林地^[14]皆伐后均有土壤呼吸减少的现象。Striegl 等观察到皆伐使北美短叶松土壤呼吸下降了 50%(第 1 个生长季);在皆伐后的数年中,更新林木和地面植物的重新定居以及皆伐后的数年里采伐剩余物的分解使土壤呼吸增加了 40%^[61]。Weber^[40]观察到白杨林皆伐后前两个生长季节土壤呼吸下降,第 3 个生长季节恢复到原来水平。Laporte 等^[62]研究了皆伐、择伐、渐伐对阔叶林生态系统中土壤呼吸的影响,结果指出择伐和渐伐对土壤呼吸的影响最大(与对照相比,9 月和 10 月的土壤呼吸减小了)。有些研究则观察到采伐后土壤呼吸速率增加现象。Ohashi^[49]等观察到日本柳杉疏伐后第 1、2 年,

土壤呼吸速率明显比对照的更高,但第年这种现象消失。Lytle 等观察到北部云杉林皆伐比对照土壤呼吸高 16%,这与皆伐后由细根分解产生的 CO_2 明显增加有关^[63]。Gordon 观察到云杉林皆伐后土壤呼吸明显增加,夏季尤为如此^[64]。Ewel 等观察到湿地松人工林皆伐地土壤 CO_2 释放量最高,这与较高的地温和采伐剩余物分解有关。皆伐后土壤呼吸速率和变化数量不仅依赖于土壤有机质含碳量及其分解速率,还依赖于皆伐后采伐剩余物的数量及处理方式^[65]。在华盛顿的北美黄杉林^[66]、俄勒冈州的北美黄杉林^[60]和密歇根州的北方阔叶林^[29]中均没观察到皆伐对土壤呼吸速率的明显影响,可能是皆伐后微生物呼吸速率的增加由同等的根系呼吸作用的减弱抵消有关。

2.4.2 火烧与土壤呼吸 火烧一般导致土壤呼吸速率降低,这与火烧强度和随后林地地被物的发育程度有关^[27,40]。Sawamoto 等^[67]观察到火烧后森林土壤呼吸速率显著比未火烧的低。Reinke 等观察到有控制的火烧、除去 L 层和除去枯枝落叶层(O_1 和 O_2 层)3 种措施分别使长叶松(*Pinus palustris*)林土壤呼吸降低了 6%、5%、22%^[68]。O'Neill 等通过对阿拉斯加内黑云杉、云杉和白杨林火烧后环境因素对土壤 CO_2 通量的调控的研究,观察到火烧后,土壤温度明显升高,地表平均湿度降低,土壤呼吸速率降低^[27]。

2.4.3 施肥与土壤呼吸 施肥对森林土壤呼吸的影响结果不一,有增加、降低或无影响等^[4,33]。Borken 等观察到施用有机肥明显提高了 90a 生挪威云杉林土壤呼吸速率^[69]。Gallardo 等也观察到当施 N 肥时,土壤的呼吸作用有所提高^[70]。Oren 等通过施肥对 1 年生至 17 年生火炬松人工林土壤呼吸的影响的研究,观察到施肥对土壤呼吸的影响不明显,5 个立地中有 2 个没变化,两个下降,一个增加了 18%,但其生物量却增加了 250%之多^[4]。而 Keith 等观察到增加桉树(*Eucalyptus pauciflora*)林土壤有效性 P 使地上干物质增加,但土壤呼吸降低 8%。这种降低可能是由于由分配到地下的同化产物的减少造成的根活性的降低^[31]。Maier 等研究了 4a 施肥期间 11 年生火炬松人工林土壤呼吸,也观察到未施肥林分的土壤呼吸($3.22\mu\text{mol}/(\text{m}^2 \cdot \text{s})$)比施肥林分的($2.80\mu\text{mol}/(\text{m}^2 \cdot \text{s})$)高 13%^[33]。Persson 等观察到以 $74\text{ kg N}/(\text{hm}^2 \cdot \text{a})$ 比率长期(17a)施入 NH_4NO_3 ,导致欧洲赤松林土壤呼吸速率降低 30%~40%。这种高剂量的 N 施肥可能影响微生物群落,从而产生了抑制物质或抑制酶系统,导致土壤呼吸速率下降^[71]。

3 森林土壤呼吸对全球变化的响应

3.1 森林土壤呼吸对全球大气 CO_2 浓度升高的响应

多数研究表明,大气中 CO_2 浓度升高将使土壤呼吸增加^[72,74]。大气 CO_2 浓度升高,促使植物光合产物更多地流向根系,导致植被中地下碳分配增加^[75]。同时伴随着根系分泌物增加、地上和地下部分凋落物增加,土壤微生物活性增强,从而导致土壤呼吸增加,其变化范围在 -10%至 +162%之间,一般为 45%^[73]。 CO_2 浓度升高亦可促进根系呼吸。升高的 CO_2 使地下生物量增加 14%,单位质量细根呼吸增加 13%^[76]。在 15 年生的火炬松林中进行的 FACE 实验中,观察到高 CO_2 浓度条件下土壤呼吸增加的约 30%~50%来自于根系呼吸的增加^[2]。

3.2 森林土壤呼吸对全球气温升高的响应

全球气温升高将使森林土壤呼吸增加,释放的更多的 CO_2 进一步使变暖加剧^[77~80]。对全球升温反应最强烈的是土壤表面的碎屑物质以及寒冷气候条件下的土壤^[78]。Melillo 等对 Harvard Forest 进行为期 10a(1991~2000)的增温研究,结果显示增温后前 6a 土壤 CO_2 释放量平均增加 28%,而后 4a 增加量显著下降(仅增加 5%),但 10a 间增温处理和对照间土壤 CO_2 释放量差异未达显著水平。增温后林木根呼吸仅占土壤呼吸的 20%,而土壤微生物高达 80%。从增温对土壤呼吸及根所占比例估计,10a 期间增温导致 C 损失为 $944\text{ g}/\text{m}^2$,相当于 60cm 表土有机 C 的 11.3%^[79]。Rustad 等用 meta-分析综合了代表 4 个生物区系(高纬度或高海拔苔原、低苔原、草地和森林)的 32 个研究点的土壤呼吸、净 N 矿化作用和植物地上生产力对实验性生态系统变暖的响应的数据,结果表明,在所有立地和年份,2~9a 的实验性温度增加($0.3\sim 6.0\text{ }^\circ\text{C}$)使土壤呼吸提高了 20%(相应增加值为 $26\text{ mg CO}_2\text{-C}/(\text{m}^2 \cdot \text{h})$);处理初始的 3a 中土壤呼吸对变暖的响应比后来的年份的大,森林生态系统中土壤呼吸对变暖的响应通常比低苔原和草地生态系统的大^[80]。

几乎所有全球气温改变的模型都预测全球气温的升高会导致土壤中碳的损失^[1,77]。全球温度升高可能降低土壤碳汇的能力,甚至使土壤转变为净碳源。Oechel 等观察到了北方森林和苔原地区土壤有机碳较大的损失是由于这些地区易分解有机质的储存量最大以及最近气候变暖的缘故^[81];Goulden 等^[82]观察到在几个温暖的年份土壤中碳也有较大损失。全球气候变暖、平均降水量增加等将使土壤微生物和土壤动物活动加剧,这将导致全球土壤碳库释放 CO_2 速度加快,但仍有待于深入的研究。

3.3 森林土壤呼吸对全球 CO_2 浓度和温度共同升高的响应

McGuire 等^[77]用基于过程的 TEM 模型得出在全球温度升高 $1\text{ }^\circ\text{C}$ 和大气中 CO_2 浓度提高到 $650\text{ mg}/\text{kg}$ 的条件下土壤将增加 28 PgC 。Pajari^[83]在大气高 CO_2 和温度下研究了 20~30a 生欧洲赤松林的土壤呼吸,观察到土壤呼吸随温度有显著的时空变化,且高温和高 CO_2 处理的土壤呼吸速率最大。Lin 等在美国环保局陆地生态生理研究区(TERA)项目中用稳定同位素法研究了 CO_2 和温度升高对北美黄杉林(*Pseudotsuga menziesii*)土壤呼吸的不同部分的影响,结果表明大气高 CO_2 浓度和高温都

刺激了根际呼吸和凋落物分解,而土壤有机质的氧化作用只受到温度升高的刺激。根呼吸对 CO₂ 浓度升高反应最敏感,而土壤有机质的氧化作用对温度升高的反应最为敏感。平均来说,高 CO₂ 处理使根际呼吸增加到 9%,凋落物分解增加 18%,但 SOM 的氧化作用降低 14%;正常 CO₂ 浓度下升高温度,根际呼吸、凋落物分解和 SOM 的氧化作用 3 个成分分别增加 60%、44%和 189%;与对照相比,高 CO₂ 高温处理,根际呼吸、凋落物分解和 SOM 的氧化作用分别增加 143%、69%和 93%^[72]。Oechel 等^[81]观察到暴露于高 CO₂ 和变暖的温度条件下的苔原土壤中 C 汇非常小。目前世界上许多研究团体正致力于研究 CO₂ 浓度和温度共同升高对陆地生态系统的影响^[72,77,83]。

3.4 森林土壤呼吸对 N 和酸沉降及 UV-B(紫外线)辐射增加等的响应

大气氮沉降可提高土壤矿化速率而影响土壤 CO₂ 的释放^[84,85]。在森林土壤中,一般的 N 沉降可能刺激 CO₂ 的释放,从而导致全球森林中巨大的碳汇的降低^[84]。Gallardo 等在 Carolina 中部和德国的温带森林观察到模拟 N 沉降使森林土壤的呼吸作用有所提高^[70]。Craine 等^[74]也得到了同样的结果。随着氮沉降增加的发生,植物生长过程中不同营养器官的 C/N 比会作出一定的响应,其归还到土壤的碎屑的 C/N 亦会相应发生改变,这又是影响土壤呼吸的另一因子^[85]。

许多研究都表明低 pH 值的人工酸雨使凋落叶和土壤的 pH 值降低,从而抑制了土壤呼吸。Persson 等报道了土壤酸度从 pH3.8 到 3.4 和从 4.8 到 4 分别使森林土壤呼吸速率降低 83%和 78%^[86]。但 Sitaula 等^[84]指出“雨”的酸度只有在 pH 为 2.5~3 时对土壤 CO₂ 释放的影响才显著。一般的酸雨(pH4.2~4.9)只对气体释放有较小的影响。Sursun 等观察到 SO₄²⁻ 对凋落物中 CO₂ 释放的抑制随 SO₄²⁻ 浓度的升高和 pH 值的降低而增强^[87]。

Edwards 观察到臭氧浓度的增加使火炬松幼苗根和土壤呼吸降低,在臭氧浓度增加环境中植物光合作用降低;对根部碳水化合物化合物的供给降低,同时根的分泌速率降低,使根际微生物的数量下降而影响土壤的呼吸速率,当环境中臭氧的浓度增加两倍时,根系的年呼吸速率降低 12%^[88]。Ollinger 等观察到 CO₂ 和 N 沉降的增加刺激了森林生长和碳吸收,但由于大尺度的臭氧空间特征与氮氧化物释放的特征相耦合,臭氧浓度增加使 N 诱导的 C 汇减小^[89]。Niemi 等^[90]观察到 UV-B 辐射增强使泥炭地 CO₂ 和甲烷(CH₄) 通量显著降低。Reich 等观察到在两个生长季节施 N 肥使土壤呼吸增加了 8% (0.37 μmol/(m²·s))^[88]。

4 研究展望

由于森林土壤呼吸在全球 C 循环中具有重要作用,因而,深入探讨森林土壤呼吸的调控因素及其对全球变化和营林措施的响应等仍是今后努力的主要方向。以下几方面应是我国今后深入研究重点方向:①分离森林土壤呼吸各分室特别是根呼吸及根际微生物呼吸的合适测定方法。②营林活动特别是干扰强度较大的皆伐、火烧等对森林生态系统土壤呼吸动态的影响,需要进行长期定位观测。③不同气候带森林特别是亚热带森林土壤呼吸对全球变化的响应特征及机制。④研究尺度应从较小的气室扩大至生态系统、区域甚至全球水平。⑤应尽快建设我国特别是亚热带地区的 CO₂ 通量网,为全球 C 循环研究做出贡献。

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