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生态学报

(SHENGTAI XUEBAO)

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封面图说: 水杉农田防护林中的小麦熟了——水杉曾广泛分布于北半球,第四纪冰期以后,水杉属的其他种类全部灭绝,水杉却在中国川、鄂、湘边境地带得以幸存,成为旷世奇珍,野生的水杉是国家一级保护植物。由于水杉耐水,适应力强,生长极为迅速,其树干通直挺拔,高大秀颀,树冠呈圆锥形,姿态优美,自发现后被人们在中国南方广泛种植,不仅成为了湖边、道路两旁的绿化观赏植物,更成为了农田防护林的重要树种。此图中整齐划一的水杉防护林像忠实的哨兵一样,为苏北农村即将成熟的麦田站岗。

彩图提供: 陈建伟教授 北京林业大学 E-mail: cites.chenjw@163.com

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唐罗忠, 葛晓敏, 吴麟, 田野, 魏勇. 南方型杨树人工林土壤呼吸及其组分分析. 生态学报, 2012, 32(22): 7000-7008.

Tang L Z, Ge X M, Wu L, Tian Y, Wei Y. Partitioning of autotrophic and heterotrophic soil respiration in southern type poplar plantations. Acta Ecologica Sinica, 2012, 32(22): 7000-7008.

南方型杨树人工林土壤呼吸及其组分分析

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摘要: 采用开沟隔离法, 利用 LI-8100 型土壤呼吸测定系统, 对 15 年生的南方型杨树 (*Populus deltoides*) 人工林土壤呼吸进行了研究, 并试图区分根系呼吸和土壤微生物呼吸。结果表明, 开沟隔离处理后的 10 个月内, 由于土壤中被截断根系具有自养呼吸和分解作用, 土壤呼吸中的根系呼吸与微生物呼吸尚难以区分。尽管如此, 研究表明 15 年生杨树人工林的土壤总呼吸通量为 $9.74 \text{ tC} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$, 其中, 枯枝落叶等土壤表层凋落物分解所释放的碳通量是 $2.63 \text{ tC} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$, 占总量的 27.0%; 林木根系呼吸与土壤微生物呼吸通量的和为 $7.11 \text{ tC} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$, 占总量的 73.0%。土壤各组分呼吸速率与 10 cm 深处的土壤温度之间存在着显著的指数函数关系。不同直径的杨树根系被截断后的活力变化有所不同, 根系越粗, 存活时间越长。

关键词: 杨树; 人工林; 土壤呼吸; 根系呼吸

Partitioning of autotrophic and heterotrophic soil respiration in southern type poplar plantations

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Abstract: Soil respiration in forests is an important part of the carbon cycle in terrestrial ecosystems. It primarily includes respiration occurring in plant roots (autotrophic respiration) and in soil microbes (heterotrophic respiration). The carbon sources for autotrophic and heterotrophic respiration are different, and their contributions to total soil respiration may also be different. Understanding the mechanisms of soil respiration require separating its component. Many studies have focused on developing methods to separate the components of soil respiration, such as the root exclusion method, isotopic method, and *in situ* root techniques although each method has some defects. The trenching method is generally considered effective and can separate root and microbial contributions from total soil respiration in forested ecosystems. Poplar, one of the most important timber species, also provides important ecological services. Currently, China has about seven million hectares of poplar plantations, and it plays an important role in a supplying the country's timber demand. However, few published reports can be found related to the characteristics of soil respiration. The contributions of root and microbial respiration to the total soil respiration in poplar plantations remain unclear. In this paper, the components of soil respiration were partitioned in a poplar (*Populus deltoides* Bartr. cv. 'Lux') plantation using the trenching method with a LI-8100 automated CO₂ flux system (LI-COR, Inc., Lincoln, NE, USA). The study was conducted at a 15-year-old poplar plantation located at Siyang Farm, Siyang County, Jiangsu Province, China (33°42'N, 118°09'E). The trees averaged 30 cm diameter at breast height and 26 m tall.

In early January, 2009, experiments with three treatments and four repetitions were set up in this poplar plantation.

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The three treatments were designed as litter removal with trenching (treatment A), litter removal without trenching (treatment B), and a control (treatment C). Based on the trenching method theory, soil microbial respiration equaled soil respiration from treatment A, while root respiration and litter respiration were obtained based on the difference in soil respiration between treatments B and A and between treatments C and B, respectively. Soil respiration field observations were conducted during the middle of January, March, May, June, July, August, September, October, and December, in 2009, using a LI-8100 automated CO₂ flux system. Soil temperature at 10 cm depth was recorded hourly at a site using a thermo recorder (TR-71U, T & D Corporation, Japan). Root activity of four different root diameter classes was also analyzed after cutting by TTC (2, 3, 5-triphenyltetrazolium chloride) reaction.

The results indicated soil respiration seasonally fluctuated, reaching a maximum in summer and a minimum in winter. Treatment C obviously had the highest soil respiration of the three treatments, while treatments A and B were not distinctly different during the first 9 months. Starting in the tenth month, treatment A had obviously lower soil respiration than treatment B. These results show root and microbial respiration are difficult to separate in the first ten months after trenching and the contribution of each could not be evaluated because the truncated roots still respired as they decomposed.

Also, the annual carbon dioxide efflux from the soil was 9.74 tC·hm⁻²·a⁻¹ in the 15-year-old poplar plantation, divided as follows: 27.0% for decomposition of the litter layer (2.63 tC·hm⁻²·a⁻¹) and 73.0% for root-microbial respiration (7.11 tC·hm⁻²·a⁻¹).

Soil respiration of each treatment was exponentially and significantly correlated to soil temperature at 10 cm deep. The correlation coefficients of the regression equation were in the order of treatment A > treatment B > treatment C. The Q_{10} values of each treatment were calculated using the regression equations, and showed a similar order: 2.94, 2.69, and 2.59 for treatments A, B, and C, respectively. The largest Q_{10} value of treatment A revealed microbial respiration might be more sensitive to temperature than root respiration.

The truncated roots had different survival times depending on root diameter. After cutting, the activity of fine roots ($D < 2$ mm) diminished to 0 during the first month. Small ($2 \text{ mm} \leq D < 5 \text{ mm}$), medium-sized ($5 \text{ mm} \leq D < 10 \text{ mm}$), and coarse roots ($D > 10 \text{ mm}$) showed the highest activity during the 2nd, 3rd, and 4th month after cutting. As the diameter increased, roots obviously survived for longer periods.

Key Words: poplar; plantation; soil respiration; root respiration

森林生态系统在全球碳循环中起着十分重要的作用^[1-5]。近年来,随着气候异常现象的日益增多,森林的碳汇等环境效应越来越受到重视^[6-14]。

土壤是一个巨大的碳库,碳贮量约为 1400 Pg^[15],而森林土壤碳贮量约占全球土壤碳库的 73%^[16],在全球碳循环中发挥着极其重要的作用^[17]。全球每年通过土壤呼吸向大气释放的碳约为 68 Pg,仅次于全球总初级生产力,超过全球陆地生态系统的净初级生产力^[18],是化石燃料燃烧释放的碳量的十多倍^[19]。所以,土壤呼吸即使发生微小的变化,对全球碳循环,特别是对大气 CO₂ 浓度的变化将产生重大影响。土壤呼吸是指未扰动的土壤中产生 CO₂ 的所有代谢过程^[20],包括 3 个生物学过程(植物根系呼吸、土壤微生物呼吸、土壤动物呼吸)和一个化学氧化过程^[21]。土壤动物呼吸和化学氧化过程所释放的 CO₂ 往往较少,在实际测定中常常被忽略。所以,土壤呼吸可简单地划分为根系呼吸和土壤微生物呼吸,各呼吸所利用的碳源不同,对土壤呼吸的贡献也有差异,对全球变化的作用和响应也不同。区分土壤各组分呼吸并深入研究各组分呼吸的机理,已经在世界范围内形成热点。

土壤呼吸组分的分离测定一直是个难点,国内外对此作了许多研究和总结^[22-27]。不同的方法具有各自的优缺点。国外开展相关研究比较早^[28-36],近年来,我国研究者也陆续对森林以及草地生态系统进行了相关研究,取得了一定成果^[37-43]。由于研究方法和研究对象不同,各研究结果不尽相同。Hanson 等^[22]对世界上

相关的研究结果进行了总结,认为根系呼吸占土壤总呼吸的 10%—90%,平均而言,森林植物的根系呼吸占土壤总呼吸的 45.8%,非森林植物为 60.4%。Rochette 等^[44]认为根排除法是区分土壤各组分呼吸的有效方法,对于森林土壤系统尤为适宜。Kuzyakov^[23]从实用性和对土壤系统的扰动性两个方面对现有的方法进行了综合评价认为,同位素标记法虽然对系统的扰动比较小,但是其实用性并不是最好的,相反,根排除法虽然扰动大,实用性却很强。根排除法中的开沟隔离法被认为是研究森林生态系统土壤呼吸组分的有效方法,在实际研究中得到了广泛应用。

杨树是世界上重要的用材林树种和生态防护林树种,我国的杨树林面积达到了 700 万 hm^2 ,为解决我国的木材供需矛盾起到了巨大的作用,同时也为提高我国森林碳汇能力起到了积极的作用,但是有关杨树人工林的土壤呼吸研究还十分匮乏,尚不能全面和深入地了解杨树人工林的碳循环特征。本文采用开沟隔离法对我国南方地区杨树人工林土壤呼吸进行了研究,旨在掌握土壤呼吸通量及其组成比例,为进一步研究杨树人工林的碳循环规律及其对环境的响应提供依据。

1 研究地概况和研究方法

1.1 研究地概况

研究地设在江苏省中北部黄淮海平原区的宿迁市泗阳农场(东经 $118^{\circ}09'$,北纬 $33^{\circ}42'$),属于季风半湿润气候。年均气温 14.9°C ,极端高温 40.3°C ,极端低温 -22.19°C ;年均降水量 932.4 mm,年均蒸发量 1490.3 mm,无霜期 221.3 d,年均日照时数 2390.3 h,有效积温 4569.6°C 。土壤为黄河故道冲积沙壤土。该地区为南方型杨树的适宜分布区,也是我国南方型杨树最早的引种试验区和栽培示范区。

试验林选择 15 年生的南方型杨树 I-69 杨(*Populus deltoides* Bartr. cv. 'Lux')人工林,林木株行距为 $5\text{m}\times 7\text{m}$,造林成活率和保存率均在 95% 以上,平均胸径和平均树高分别为 30 cm 和 26 m,郁闭度达 0.9 以上。

1.2 研究方法

2009 年 1 月初,在杨树试验林中设定 A、B、C 3 种处理区。A 区:开沟切根且去除凋落物处理区,选择 4 块面积各为 $1.5\text{m}\times 1.5\text{m}$ 的正方形样方,在样方四周小心挖沟,沟宽 20 cm,深 80 cm,四周设置塑料板,以阻止外部根系的侵入,回填土壤,小心除去样方内的地表凋落物,并罩上直径约 1 m、高度约 30 cm 的尼龙网罩,以防止凋落物掉入;B 区:去凋落物处理区,面积为 $1.5\text{m}\times 1.5\text{m}$,重复 4 次,不作开沟切根处理,去除地表凋落物后罩上尼龙网罩;C 区:对照处理区,保持原样,不作开沟切根处理,保留地表凋落物层,面积 $1.5\text{m}\times 1.5\text{m}$,重复 4 次。

设置土壤温度自动记录仪(Thermo Recorder TR-71U, T & D Corporation, Japan),每隔 1 h 自动记录 1 次 10 cm 深处的土壤温度。在每个处理区地表各设置 1 个土壤圈,分别于当年的 1、3、5、6、7、8、9、10、12 月中旬的某 1 天,采用 LI-8100 开路式土壤碳通量测量系统(LI-COR Inc., Lincoln, NE, USA)对不同处理下的土壤呼吸速率进行测定。分析土壤呼吸速率与土壤温度的关系,通过土壤呼吸速率与土壤温度的指数回归方程计算各处理区的土壤年呼吸通量。

为了明确杨树根系被切断后的生理活性,4 月中旬挖掘试验林中的杨树根系,采用氯化三苯基四氮唑(TTC)法分别测定根径为 0—2 mm 的细根、2—5 mm 的小根、5—10 mm 的中根和 10 mm 以上的粗根的活力,其中细根活力包含木质部,其他根径的根系活力不包含木质部(即测定根皮和韧皮部的活力);同时采用网袋法(孔径为 0.1 mm 左右的尼龙网)将已知重量、不同直径的新鲜根系分别与 50 倍于鲜根重量的土壤混合后分别埋在重新设置的开沟断根样方 10 cm 深的土壤中,每隔 1 个月每种根径样品各收取 3 份,拣出根系后洗净,称重并测定其活力。

1.3 数据处理方法

应用 Microsoft Excel 2003 和 SPSS 13.0 软件对数据进行处理,采用单因素方差分析法检验不同处理之间数据的差异性。

2 结果与分析

2.1 不同处理条件下杨树人工林土壤呼吸速率的动态变化

由图 1 可以看出,A 处理(开沟断根且去凋落物)、B 处理(去凋落物)和 C 处理(对照)3 种处理的土壤 CO_2 释放速率具有明显的季节变化规律,其中,夏季最高,春季和秋季次之,冬季最低。C 处理的土壤 CO_2 释放速率明显高于 A 处理和 B 处理,而 A 处理和 B 处理之间在试验开始后的 1—9 月份没有明显差异,10 月之后,A 处理的土壤 CO_2 释放速率明显小于 B 处理。表明 A 处理根系在试验早期可能处于存活状态,仍然进行自养呼吸,这与南方型杨树 I-69 杨具有明显的无性繁殖特性有关。一定时期后,A 处理的根系虽然死亡,但是死根作为土壤有机物被微生物分解,土壤的异养呼吸增强,因而在 12 个月的试验中,A、B 两种处理的土壤 CO_2 释放速率的差异总体上不显著。所以,采用开沟隔离法分别测定南方型杨树人工林土壤呼吸中的根系呼吸和土壤微生物呼吸时,应该在断根处理之后经过较长时间的分解平衡才可能减少断根的影响。

2.2 地温动态变化

由图 2 可知,虽然有一定的波动性,但是 10 cm 深处的土壤温度具有明显的季节变化规律,6—9 月的地温主要在 20—30 °C 之间,4、5 月和 10 月的地温主要在 10—20 °C 之间,11—2 月的地温基本上在 10 °C 以下。地温的年变化规律与图 1 的各处理土壤 CO_2 释放速率的年变化规律相似,表明土壤呼吸速率受温度的影响。

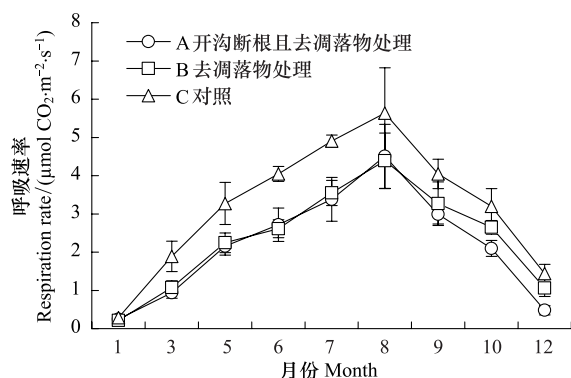


图 1 不同处理下的土壤呼吸速率

Fig. 1 Rates of soil respirations in different treatments

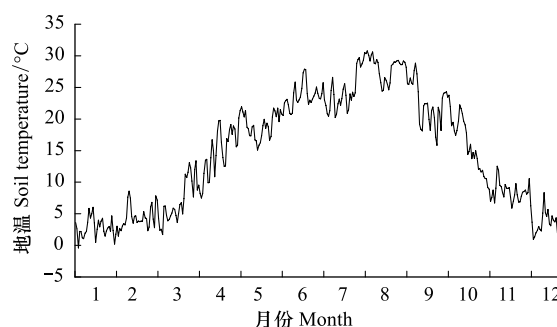


图 2 10 cm 深处的土壤温度动态变化

Fig. 2 Dynamics of soil temperature at 10 cm depth

2.3 不同处理区土壤呼吸速率与地温的关系

结果表明(图 3),A(开沟断根且去凋落物处理)、B(去凋落物处理)和 C(对照处理)3 种处理的土壤呼吸速率与 10 cm 深处的土壤温度之间存在着极显著($P < 0.01$)的指数函数关系,其中,A 处理的土壤呼吸速率与土壤温度之间的指数函数方程拟合效果最佳($P < 0.001$),其次为 B 处理($P < 0.01$),C 处理的拟合效果虽然较差,但也达到了极显著水平($P < 0.01$)。凋落物层的呼吸速率(C 处理与 B 处理的土壤呼吸之差)与土壤温度的相关关系比较弱($P < 0.05$)。其原因主要是:A 处理的土壤呼吸主要来源于矿质土壤中的微生物呼吸,其呼吸强度与土温关系密切;B 处理的土壤呼吸一方面来自于矿质土壤中的微生物呼吸,另一方面来源于活的树根呼吸,树根呼吸强度不仅与土温有关,它也受控于树体地上部分的生理活性,因而影响因素较多;C 处理区由于地表存在大量的凋落物,凋落物分解时释放 CO_2 的速度虽然受到土壤温度的影响,但是与气温的变动也有密切关系,同时,凋落物的含水量变化比较剧烈,所以,采用 10 cm 深处的土壤温度拟合对照区土壤呼吸速率和凋落物呼吸速率,其效果相对较差。

2.4 不同处理条件下土壤的年呼吸通量

根据拟合方程(图 3)以及地温的年变化数据(图 2)可以计算不同组分的土壤年呼吸通量,结果(表 1)表明,A 处理的土壤年呼吸通量为 $6.83 \text{ tC} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$,B 处理的土壤年呼吸通量为 $7.11 \text{ tC} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$,两者相差无几。正如前文所述,这是由于开沟断根处理后所经历的时间较短,被截断的根系存在自养呼吸和异养呼吸

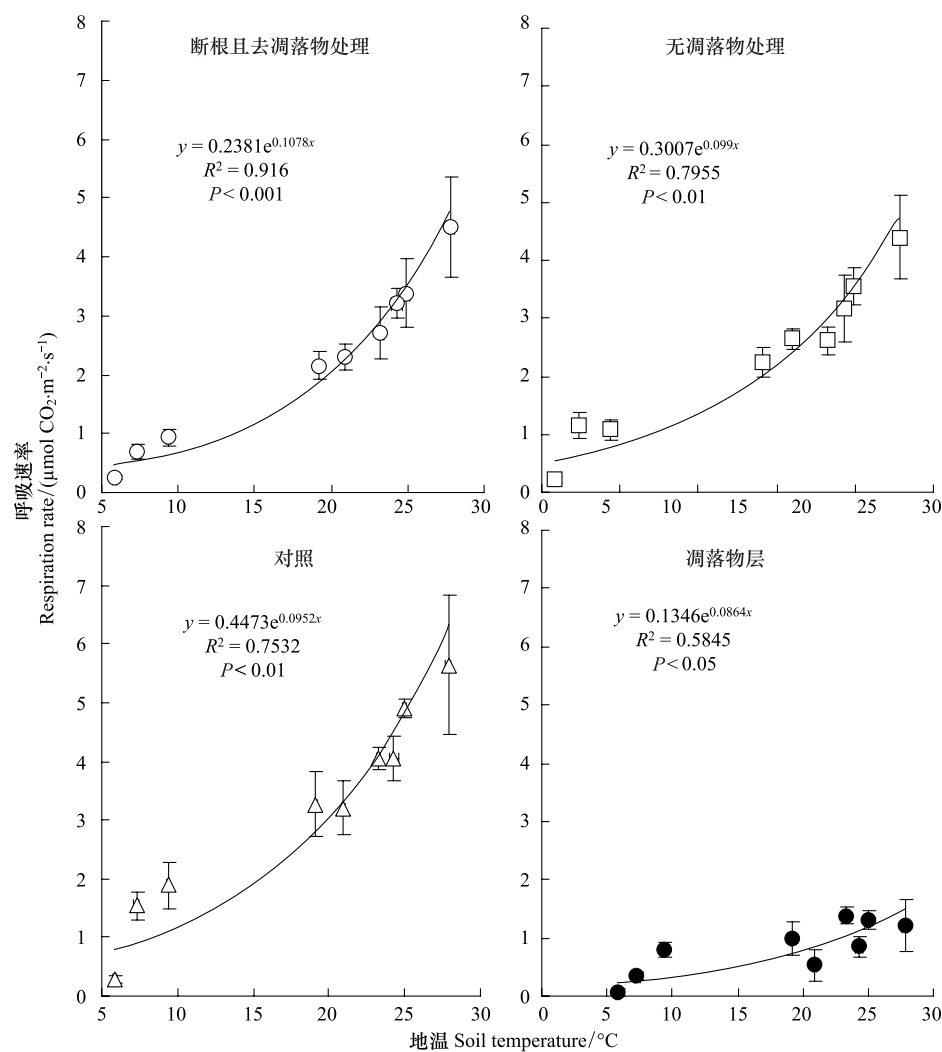


图3 不同处理下的土壤呼吸速率与土壤温度的相关关系

Fig.3 Relationships between soil respiration rates and soil temperature in different treatments

(分解),导致 A 处理土壤呼吸通量与 B 处理之间没有明显差异(表 1)。C 处理的土壤年呼吸通量为 9.74 tC·hm⁻²·a⁻¹,将 C 处理与 B 处理相减即可得到凋落物层的呼吸通量为 2.63 tC·hm⁻²·a⁻¹。

根据图 3 中的拟合方程也可以计算不同处理区土壤呼吸速率的 Q₁₀ 值(温度提高 10℃后土壤 CO₂ 释放速率与温度未提高时的土壤 CO₂ 释放速率的比值,见表 1),其中,A 处理为 2.94,B 处理为 2.69,C 处理为 2.59,凋落物层为 2.37。

表 1 不同处理下的土壤年呼吸通量(平均值±标准差)及其组成比例和 Q₁₀ 值

Table 1 Annual flux of soil respiration(mean±SD), percent of components and its Q₁₀ values

	A 处理 A treatment	B 处理 B treatment	凋落物层 Litter floor	C 处理 C treatment
年呼吸通量 Annual flux/(tC·hm ⁻² ·a ⁻¹)	6.83±0.99 b	7.11±0.92 b	2.63±0.42 c	9.74±1.26 a
比例 Percent/%	70.1	73.0	27.0	100.0
Q ₁₀	2.94	2.69	2.37	2.59

A 处理:开沟断根且去凋落物;B 处理:去凋落物;C 处理:对照;同一行数据后不同字母表示差异达到 0.05 显著水平

2.5 杨树根系活力的动态变化

为了明确杨树根系被切断后的生理活性及其对土壤呼吸的影响,从 4 月份开始对杨树不同径阶根系进行

了6个月的活力动态测定试验,结果(图4)表明,细根(根径<2 mm)的活力呈下降趋势,埋入土壤2个月,其活力近似于0;其他径阶的根系活力均有上升阶段,其中,小根(根径2—5 mm)被埋入土壤2个月时的活力最高,之后迅速下降;中根(根径5—10 mm)被埋入土壤3个月时的活力最高;粗根(根径>10 mm)活力在4个月时最高。由此可见,土壤中的杨树根系被切断之后,能够存活一段时间,尤其是直径较粗的根系能够维持较长时间的活力;较粗的根系被切断之后,其活力有一个上升的过程,这可能与其在死亡之前,新陈代谢加剧,呼吸作用增强有关。

研究结果还表明,经过6个月的埋根处理,直径小于2 mm的杨树细根重量减少了30%左右;直径在2—5 mm的根系重量减少了20%左右;直径大于5 mm的根系重量减少了5%以下。

3 结论与讨论

15年生的南方型杨树人工林(I-69 杨)土壤的 CO_2 释放通量为 $9.74 \text{ tC} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$,这一结果高于相似纬度的其他森林的平均值^[2,45],也高于低湿地条件下的10年生相同树种I-69 杨人工林^[46],但是与江苏沿海地区20年生的毛白杨(*Populus tomentosa*)成熟林相当^[47]。所以,不同树种、不同立地、不同年龄阶段的人工林土壤呼吸通量存在一定差异。南方型杨树属于速生丰产性树种,林木生长快,根系发达,凋落物多,这些因子都有利于土壤呼吸速率的增加和呼吸通量的增大。当然,在特殊的立地条件下^[46],如地下水位偏高、土壤粘重而板结等,易导致林木生长减缓,且不利于土壤呼吸。

开沟隔离法是通过挖壕沟并用隔离板阻止样地外部根系侵入,将对照区与处理区的土壤呼吸之差作为根系呼吸^[24-25,27]。这一方法可以应用在不同的生态系统中。河原辉彦^[28]利用该法测得15年生的日本赤松(*Pinus densiflora*)和5年生的日本柳杉(*Cryptomeria japonica*)的根系呼吸分别占土壤总呼吸的20%和40%;Bowden 等人^[32]利用该法对温带阔叶混交林进行测定知,根系呼吸占土壤总呼吸的33%—49%。Lavigne 等人^[48]通过此法研究胶冷杉(*Abies balsamea*)林时发现土壤呼吸对温度的依赖性主要受根呼吸的影响,这与Boone 等人^[49]通过相同方法对根系呼吸的研究结果相似。近年来,国内也有一些学者采用开沟隔离法对我国东北和南方地区的林木根系呼吸进行了研究^[38-40,42-43,50],其结果存在一定的差别。

开沟隔离法与根移出法相比,对土壤的扰动较小,但残留在样地中的根系会死亡分解,从而使根呼吸的估计值偏低^[24]。再则,与根系移出法一样,开沟隔离法也容易导致土壤湿度上升而使结果的准确性降低,因为切根以后,根系与地上部分隔断,土壤水分不能被树木吸收和蒸腾^[23]。Ewel 等人^[51]认为,根切断几个月后再测 CO_2 释放量,并定期检查样方中的根生物量可以减少因根系分解产生的误差,并得到湿地松(*Pinus elliottii*)根呼吸占土壤总呼吸的比例是:9年生为51%,29年生为62%。Lee 等^[36]采用此法,并根据根系的分解速率修正处理区土壤呼吸,从而估计出日本中部山区栎树林根系呼吸占土壤总呼吸的27%—71%。

本研究结果表明,南方型杨树(I-69 杨)人工林断根处理后10个月,其土壤呼吸速率与未断根处理区的土壤呼吸速率相比没有明显差异,其原因可以被认为是,开沟断根处理区根系在断根处理早期处于存活状态(由图4可以表明),能进行自养呼吸,因为I-69 杨具有明显的无性繁殖特性,被截断的根能在较长时间内保持存活状态;之后,开沟断根处理区的根系虽然死亡,但是死根作为土壤有机物被微生物分解,土壤的异养呼吸增强,因而导致断根处理与未断根处理之间在近1年内,土壤呼吸通量差异并不显著。所以,采用开沟隔离法测定南方型杨树人工林土壤呼吸中的根系呼吸和土壤微生物呼吸时,建议在开沟断根处理后需要经过较长时间(近1年)的分解和平衡,这样才能减少断根的自养呼吸和异养呼吸所造成的影响。所以就本研究而言,

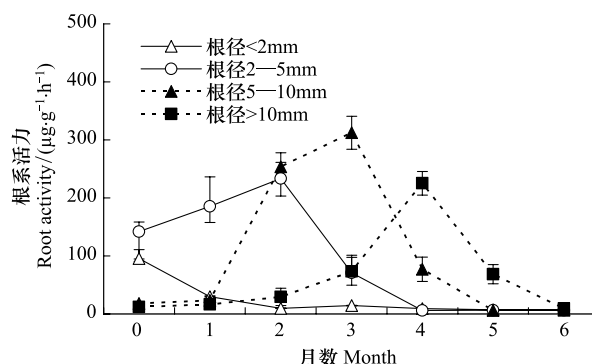


图4 不同直径的杨树根系活力动态变化

Fig. 4 Dynamics of poplar roots activities in different diameter

要精确区分林木根系呼吸和土壤微生物呼吸,还需要更长时间的试验观测。

土壤呼吸速率(CO_2 释放速度)的大小受多种因素的影响,其中土壤温度被认为是重要的影响因素^[6,8,18,49,52-53]。正如图 3 所示, CO_2 释放速率与土壤温度之间呈明显的指数函数关系。本研究地土壤呼吸速率的 Q_{10} 值在 2.5 至 3.0 之间,这一结果处于其他研究($Q_{10}=2-4$)^[18,49,52]的中间值状态。当然,在本研究中,不同处理之间的 Q_{10} 值存在一定差异,其中 A 处理(开沟断根且去凋落物处理)的 Q_{10} 值最大,表明其呼吸速率受温度的影响较大,所以,与杨树根系呼吸相比,土壤微生物呼吸对温度的敏感性可能更强。当然,关于根系的自养呼吸和土壤微生物的异养呼吸的温度敏感性问题十分复杂,至今尚没有定论^[54]。由于土壤呼吸速率与温度之间存在指数相关关系,因此不难想象,当地球温暖化时期真正到来的时候,土壤中的有机物可能会被加速分解,从而进一步提高大气 CO_2 浓度,加剧地球温暖化^[53]。

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