植物生态学报 2015, **39** (7): 674–681 doi: 10.17521/cjpe.2015.0064
Chinese Journal of Plant Ecology http://www.plant-ecology.com

不同来源可溶性有机物对亚热带森林土壤CO_2排放的影响

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摘 要 采用室内培养法, 比较分析了亚热带地区杉木(*Cunninghamia lanceolata*)和米槠(*Castanopsis carlesii*)鲜叶及凋落叶浸提得到的可溶性有机物(dissolved organic matter, DOM)组成和化学性质差异对土壤CO_2排放的影响。结果表明: 添加不同来源的DOM后, 土壤CO_2瞬时排放速率在培养第1天内均显著高于对照(添加去离子水) ($p < 0.05$), 分别比对照增加了91.5% (添加杉木鲜叶DOM)、12.8% (添加米槠鲜叶DOM)、61.0% (添加杉木凋落叶DOM)和113.3% (添加米槠凋落叶DOM), 但培养5天后, 分别下降到对照的24.1%、8.3%、14.6%和13.2%, 随后逐渐趋于平稳。单次添加外源DOM到土壤中, 引起土壤CO_2排放速率增加的强度较大, 但持续时间短暂。培养31天时, 添加不同来源的DOM均对土壤CO_2累积排放量具有显著影响($p < 0.05$), 而在培养59天时, 添加杉木鲜叶和凋落叶DOM的土壤CO_2累积排放量均显著高于添加米槠鲜叶和凋落叶DOM的土壤CO_2累积排放量, 但添加相同树种鲜叶与凋落叶DOM的土壤CO_2累积排放量之间差异不显著。培养结束后, 添加杉木鲜叶DOM和杉木凋落叶DOM后增加的土壤碳排放量, 分别是外源添加可溶性有机碳量的1.76倍和2.56倍, 而添加米槠鲜叶DOM和米槠凋落叶DOM后增加的土壤碳排放量只占外源添加可溶性有机碳量的22.5%和50.0%, 表明单次添加不同来源的DOM对土壤总有机碳库的影响是不一致的。

关键词 碳矿化, 米槠, 杉木, 可溶性有机物, 鲜叶, 凋落叶

引用格式: 万菁娟, 郭剑芬, 纪淑蓉, 任卫岭, 司友涛, 杨玉盛 (2015). 不同来源可溶性有机物对亚热带森林土壤CO_2排放的影响. 植物生态学报, 39, 674–681. doi: 10.17521/cjpe.2015.0064

Effects of different sources of dissolved organic matter on soil CO_2 emission in subtropical forests

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Abstract

Aims Dissolved organic matter (DOM) is an important carbon and nutrient pool, but the effects of different sources of DOM on soil carbon cycling are less well understood. Our objective in this study was to investigate how differences in the quantity and quality of DOM from fresh leaves and leaf litter of *Cunninghamia lanceolata* and *Castanopsis carlesii* affected soil CO_2 fluxes in a laboratory incubation experiment.

Methods Mineral soils (0–10 cm) from an 11-year-old *Cunninghamia lanceolata* plantation in Sanming of Fujian Province, China, were incubated for 59 days after adding the DOM from fresh leaves and leaf litter of *Cunninghamia lanceolata* and *Castanopsis carlesii*. Carbon (C) mineralization during incubation was determined using CO_2 respiration method.

Important findings Compared to the controls, the rates of C mineralization significantly increased by 91.5%, 12.8%, 61.0% and 113.3% on day 1, following additions of DOM from fresh leaves and leaf litter of *Cunninghamia lanceolata* and *Castanopsis carlesii*, respectively; the magnitudes of the increases declined to 24.1%, 8.3%, 14.6% and 13.2% by day 5, indicating that addition of DOM had significant but short-term influences on soil CO_2 emission. DOM from different sources had significant effects on the cumulative CO_2 production following addition of DOM by day 31 ($p < 0.05$). After 59 days of incubation, the cumulative quantity of mineralized C following addition of DOM from fresh leaves and leaf litter of *Cunninghamia lanceolata* was significantly greater than

收稿日期Received: 2014-10-29 接受日期Accepted: 2015-03-31

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that from those of *Castanopsis carlesii*, while there was no significant difference in the cumulative CO_2 production between DOM from fresh leaves and leaf litter of the same tree species, suggesting that difference in tree species had a greater influence on C mineralization than difference in the degree of leaf decay. Addition of DOM originated from fresh leaves and leaf litter of *Castanopsis carlesii* resulted in increased C mineralization by 22.5% and 50.0% of C added over the course of 59 day incubation, whereas increases by additions of DOM from fresh leaves and leaf litter of *Cunninghamia lanceolata* were 1.76 times and 2.56 times, respectively. Thus, a single addition of different sources of DOM may lead to diverse effects on total soil carbon stocks.

Key words　C mineralization, *Castanopsis carlesii*, *Cunninghamia lanceolata*, dissolved organic matter, fresh leaves, leaf litter

Citation: Wan JJ, Guo JF, Ji SR, Ren WL, Si YT, Yang YS (2015). Effects of different sources of dissolved organic matter on soil CO_2 emission in subtropical forests. *Chinese Journal of Plant Ecology*, 39, 674–681. doi: 10.17521/cjpe. 2015.0064

土壤有机碳库是陆地生态系统最大碳储存库，储量高达1 500 Pg (Eswaran *et al*., 1993)，是大气碳库的2倍、植物碳库的3倍多，因此土壤碳库的动态变化对全球碳循环起着重要作用。土壤有机碳库变化受到凋落物输入与土壤有机碳(SOC)矿化的共同影响(Vesterdal *et al*., 2012)。而土壤有机碳矿化不仅受到温度、水等环境因素的调控，也受外源有机物(包括有机物的质量和数量)的影响(Kirschbaum, 2004; Fierer *et al*., 2005; Hartley & Ineson, 2008)。如输入活性碳到土壤中后，会增加土壤有机碳矿化(Kuzyakov *et al*., 2000; Blagodatskaya & Kuzyakov, 2008; Kuzyakov, 2010; Cheng *et al*., 2014)。在森林生态系统中，降雨淋溶、凋落物淋溶的可溶性有机物(DOM)是土壤有机物(SOM)中活性碳库的重要来源(Gauthier *et al*., 2010)，亦是土壤微生物分解作用的主要底物来源(Marschner & Kalbit, 2003; Li *et al*., 2010)，因此，研究不同来源的DOM对土壤碳库的影响具有重要意义。

已有研究发现不同来源的DOM化学组成和性质差异较大(Inamdar *et al*., 2012; Kothawala *et al*., 2012)。如阔叶树凋落叶可溶性有机碳(DOC)含量高于针叶树(Wieder *et al*., 2008)，相同树种的凋落叶DOC含量高于鲜叶(Cleveland *et al*., 2004)，鲜叶淋溶的DOM中含有更多低分子量、易分解的有机物，而凋落叶DOM中含有更多的芳香性化合物和腐殖化程度更高的有机物(Kalbitz *et al*., 2007; Inamdar *et al*., 2012)。因此，分析不同树种鲜叶与凋落叶DOM的差异对土壤CO_2排放的影响是生态系统碳循环的重要环节。已有的野外研究表明不同树种DOM对土壤CO_2累积排放量具有显著影响(Kiikkilä *et al*., 2012)。室内试验也证明添加不同树种凋落叶DOM后，会影响土壤CO_2排放而影响土壤碳库(Wieder *et al*., 2008)。

中亚热带常绿阔叶林是全球同纬度带上的“绿洲” (全球同纬度地带多为荒漠、稀树草原)，亦是全球重要的森林碳汇区，其中米槠(*Castanopsis carlesii*)是常绿阔叶林的重要群系之一(章浩白, 1993)。而杉木(*Cunninghamia lanceolata*)作为我国南方特有的经济树种，种植面积已经达到12 × 10^6 hm^2，占世界总人工林面积的6.5% (Chen *et al*., 2013)。本研究选择米槠和杉木的鲜叶及凋落叶DOM作为研究对象，探讨添加不同来源的DOM对土壤CO_2排放差异及其土壤碳库的影响，为该区森林土壤碳循环研究提供一个新思路。

1　材料和方法

1.1　试验地概况

试验地在福建省三明市格氏栲自然保护区(26.17º N, 117.47º E)。该保护区气候属于中亚热带季风气候，试验地附近的三明市年平均气温20.1 ℃，年降水量1 670 mm，降水多集中于3–8月份(吴君君等, 2014)。杉木人工林为2003年米槠次生林皆伐后营造人工纯林形成，树龄11年。

1.2　样品采集

2014年3月，于杉木人工林的上、中、下坡，随机布设3块20 m × 20 m的标准样地，在每个标准样地内按照S型布设5个点，分别用土钻取表层土壤(0–10 cm)，混合，迅速冷藏并带回实验室。一部分用于风干测定其理化性质(表1)，另一部分在4 ℃冷藏保存，用于后续的培养实验。同时在杉木人工林和临近的米槠天然林试验样地内，布设上、中、下坡3条平行于等高线的样线，每条样线上随机设10

表1 试验地表层土壤(0–10 cm)性质(平均值±标准误差)
Table 1 Surface soil (0–10 cm) properties of the study sites (mean ± *SE*)

试验地 Study site	有机碳 Organic carbon ($g\cdot kg^{-1}$)	全氮 Total N ($g\cdot kg^{-1}$)	C:N	可溶性有机碳 Dissolved organic carbon ($mg\cdot kg^{-1}$)	可溶性有机氮 Dissolved organic nitrogen ($mg\cdot kg^{-1}$)	微生物生物量碳 Microbial biomass carbon ($mg\cdot kg^{-1}$)
杉木人工林 *Cunninghamia lanceolata* plantation	17.55 ± 1.70	1.31 ± 0.133	13.37 ± 0.55	73.27 ± 8.15	8.79 ± 0.79	423.52 ± 5.93

表2 不同来源可溶性有机物的性质(平均值±标准误差)
Table 2 Properties of different sources of dissolved organic matter (mean ± *SE*)

	可溶性有机碳 Dissolved organic carbon ($g\cdot kg^{-1}$)	可溶性有机氮 Dissolved organic nitrogen ($g\cdot kg^{-1}$)	紫外吸收值 Special ultraviolet visible absorption (*UV*)	腐殖化指标 Humification index (*HIX*)	分子量大小 Molecular size	pH
杉木鲜叶 Fresh leaves of *Cunninghamia lanceolata*	2.60 ± 0.51^{a}	0.005 ± 0.001^{a}	0.24 ± 0.01^{a}	0.26 ± 0.01^{a}	5.24 ± 0.98^{a}	5.98 ± 0.12^{a}
米槠鲜叶 Fresh leaves of *Castanopsis carlesii*	0.80 ± 0.11^{b}	0.024 ± 0.002^{b}	0.76 ± 0.08^{b}	1.75 ± 0.11^{b}	3.75 ± 0.10^{b}	5.91 ± 0.05^{b}
杉木凋落叶 Leaf litter of *Cunninghamia lanceolata*	0.99 ± 0.03^{c}	0.014 ± 0.001^{c}	1.61 ± 0.02^{c}	1.91 ± 0.03^{c}	6.90 ± 0.07^{c}	5.76 ± 0.05^{c}
米槠凋落叶 Leaf litter of *Castanopsis carlesii*	1.59 ± 0.02^{d}	0.020 ± 0.001^{d}	1.64 ± 0.04^{c}	1.90 ± 0.02^{c}	4.80 ± 0.30^{d}	4.28 ± 0.01^{d}

不同小写字母表示不同来源可溶性有机物之间有显著差异。
Different lowercase letters indicate significant differences among different sources of dissolved organic matter.

个25 cm × 25 cm的小样方，收集未分解的凋落叶样品，并用高枝剪从东、西、南、北四个方向采摘树冠中上部的鲜叶，带回实验室。一部分烘干测定含水量，另一部分保存在低温环境中，用于后续的浸提实验。

1.3 试验设计

DOM浸提采用样品与水的比例为1:2，即各取100 g杉木鲜叶(相当于66.56 g干质量)、米槠鲜叶(相当于76.51 g干质量)、杉木凋落叶(相当于89.67 g干质量)和米槠凋落叶(相当于87.98 g干质量)，加入200 mL去离子水，浸泡24 h后，上清液用0.45 μm玻璃纤维过滤器减压过滤，滤液在4 ℃保存，并及时测定DOM的性质(表2)。

取相当于50 g风干土重的鲜土样品到500 mL的特质瓶中，调节土壤含水量为饱和含水量(43.7%)的40%，放置在25 ℃生化培养箱中进行15天预培养，使土壤内部环境趋于稳定。预培养结束后，分别加入按照上面方法浸提得到的杉木鲜叶DOM (DOC:MBC是1:9, MBC是微生物生物量碳)、米槠鲜叶DOM (DOC:MBC是1:26)、杉木凋落叶DOM (DOC:MBC是1:12)和米槠凋落叶DOM (DOC:MBC是1:8)各4 mL，等量去离子水作为对照，调节土壤含水量达到饱和含水量的60%，每个处理3个重复。在添加不同来源DOM后的第1、2、3、5、7、10、17、24、31、38、45、52、59天抽气取样，取样前2 h将瓶盖拧紧，取样结束后调节土壤含水量，然后将气体注入气相色谱仪(GC-2010, Shimadzu, Kyoto, Japan)进行分析，计算土壤CO_2排放速率和CO_2累积排放量。

浸提得到的DOC及用氯仿-熏蒸浸提法得到的MBC，用总有机碳分析仪(TOC-VCPH, Shimadzu, Kyoto, Japan)测定；DON用流动注射分析仪(San^{++}, Skalar, Breda, Netherlands)测定；土壤C、N元素含量采用碳氮元素分析仪(vario MAX, Elementar Analysensysteme GmbH, Hanau, Germany)测定。

为了测定结果的可比性，用于紫外和荧光光谱测定样品的DOC浓度用去离子水稀释至10 $mg\cdot L^{-1}$，pH值用稀HCl调为2。用紫外可见分光光度计(UV-2450, Shimadzu, Kyoto, Japan)测定紫外可见吸光值，待测液在254 nm处的紫外吸光值(*UV*)可用于计算芳香性指数(*AI*)；用250 nm和365 nm的紫外吸光度比值计算分子量大小E_2:E_3；荧光发射光谱通过日立F7000仪器(Hitachi, Tokyo, Japan)获得，激发波长λ_{ex} = 254 nm，狭缝宽10 nm，发射波长λ_{em}是300–480 nm，狭缝宽10 nm，扫描速度2 400 $nm\cdot min^{-1}$，腐殖化指标HIX通过计算发射光谱中Σ435–480 nm区域与Σ300–345 nm区域峰面积比值获得(熊丽等，2014)。

1.4 计算方法及数据处理

CO_2产生速率计算方法:

$$F = k \times v/m \times \Delta c/\Delta t \times 273/(273 + T)$$

式中, F表示气体排放的速率($mg \cdot kg^{-1} \cdot h^{-1}$); k是常数, 取值为1.964 $kg \cdot m^{-3}$; $\Delta c/\Delta t$表示在观测时间内气体浓度随时间变化的直线斜率($mg \cdot h^{-1}$); v为培养容器的体积(m^{-3}); m为土壤质量(kg); T为培养温度(℃)。CO_2累积排放量采用相邻两次产生CO_2速率的平均值乘以间隔的时间而获得。

E_2:E_3可以反映DOC的平均分子量大小(Peuravuori & Pihlaja, 1997), E_2:E_3值越高, 说明DOC的平均分子量越小, 其计算公式如下:

$$E_2:E_3 = UV_{250}:UV_{365}$$

式中UV_{250}为250 nm的紫外吸光度值, UV_{365}为365 nm的紫外吸光度值。

所有数据的处理主要在Excel和SPSS 17.0的软件下完成, 相关图表在Origin 8.0 软件下完成。采用单因素方差分析(one-way ANOVA)检验添加不同来源的DOM对土壤CO_2排放的影响和多因素方差分析(multiple comparisons ANOVA)检验杉木和米槠的鲜叶及凋落叶DOM组成和化学性质差异的显著性。

2　结果和分析

2.1　DOM含量和光谱特征

通过多因素方差分析发现, 不同树种、相同树种鲜叶和凋落叶、不同树种的鲜叶和凋落叶的交互作用均对DOC浓度具有极显著影响($p < 0.01$)。如米槠凋落叶DOC浓度最大(698.8 $mg \cdot L^{-1}$), 而米槠鲜叶DOC浓度最小(203.7 $mg \cdot L^{-1}$), 其相互之间差异多于3倍(表2)。相同树种鲜叶的可溶性有机氮(DON)浓度显著低于凋落叶DON浓度($p < 0.05$), 说明鲜叶中N元素更难释放, 即凋落叶DOM中含有更多的含氮营养物质。腐殖化指标(*HIX*)、紫外吸收值(*UV*)和分子量大小(E_2:E_3)是用来表示DOM化学性质的指标, 本研究发现杉木鲜叶DOM的*HIX*、*UV*均显著低于米槠鲜叶DOM的($p < 0.05$), E_2:E_3则相反, 表明阔叶树种鲜叶DOM比针叶树种鲜叶DOM中含有更多高分子量的、腐殖化程度较高的有机物。这与相对荧光光谱图的趋势一致(图1), 由针叶树种到阔叶树种最大荧光强度所对应波长向更长的波长转移, 表明DOM中共轭体系在增大, 分子复杂结构更多。另外, 相同树种鲜叶DOM的*HIX*、*UV*显著低于凋落叶DOM的($p < 0.05$), E_2:E_3值则相反, 表明鲜叶浸提得到的DOM中含有更多低分子量、易分解的有机物, 而凋落叶DOM中以高分子量的腐殖质为主。

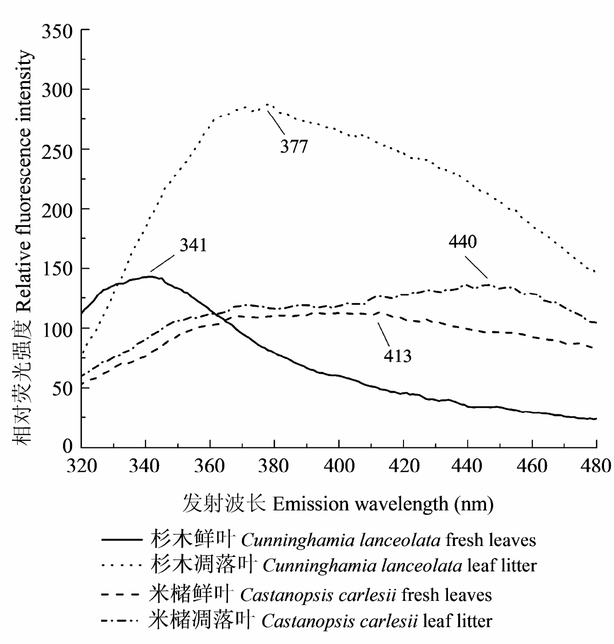

图1　不同来源可溶性有机物的荧光发射光谱。

Fig. 1　Fluorescence emission spectra of different sources of dissolved organic matter.

2.2　添加不同来源DOM后土壤CO_2排放速率特征

本研究发现添加杉木鲜叶DOM、米槠鲜叶DOM、杉木凋落叶DOM和米槠凋落叶DOM到土壤中后, 培养第1天土壤CO_2瞬时排放速率均显著高于对照($p < 0.05$), 分别比对照增加了91.5%、12.8%、61.0%和113.3%, 但培养5天后, 分别下降到对照的24.1%、8.3%、14.6%和13.2%, 随后逐渐趋于平稳(图2), 表明单次添加外源DOM到土壤中后, 引起土壤CO_2排放速率增加的强度较大, 但持续时间短暂。添加不同来源DOM后土壤CO_2瞬时排放速率均在培养第1天达到最大值, 其中添加杉木鲜叶DOM后土壤CO_2瞬时排放速率显著高于添加杉木凋落叶DOM的18.9%, 添加米槠凋落叶DOM后土壤CO_2瞬时排放速率显著高于添加米槠鲜叶DOM的89%, 但随着培养时间延长, 添加不同来源的DOM对土壤CO_2排放速率影响不显著。

2.3　添加不同来源DOM后土壤CO_2累积排放量的差异

在培养31天时, 添加杉木和米槠DOM、鲜叶和凋落叶DOM均对土壤CO_2累积排放量具有显著影响($p < 0.05$), 而在培养59天时, 添加相同树种鲜叶与凋落叶DOM的土壤CO_2累积排放量之间差异不

doi: 10.17521/cjpe.2015.0064

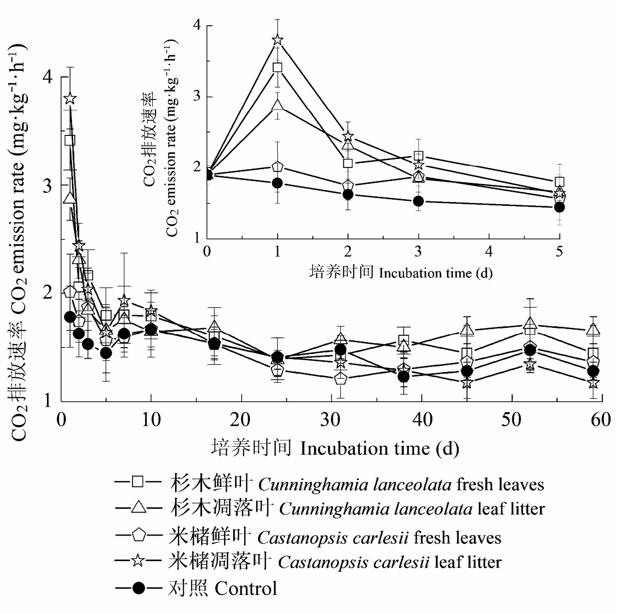

图2 添加不同来源可溶性有机物后土壤CO_2排放速率的变化(平均值 ± 标准误差)。

Fig. 2 Changes in the rate of CO_2 emission following addition of different sources of dissolved organic matter (mean ± *SE*).

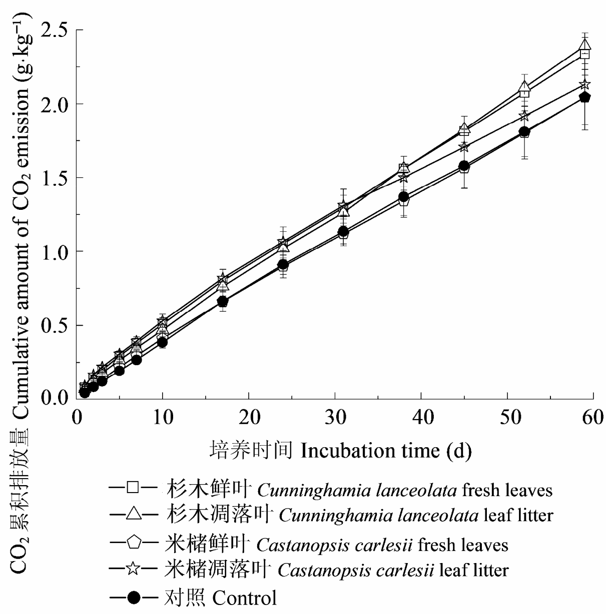

图3 添加不同来源可溶性有机物后土壤CO_2累积排放量(平均值 ± 标准误差)。

Fig. 3 Cumulative emission CO_2 following addition of different sources of dissolved organic matter (mean ± *SE*).

显著，表明随着培养时间的延长，添加不同树种DOM后土壤CO_2排放之间的差异比添加相同树种鲜叶与凋落叶DOM后土壤CO_2排放之间的差异更大。培养前31天，添加杉木鲜叶DOM的土壤CO_2累积排放量显著高于添加米槠鲜叶DOM的($p < 0.05$)，而添加杉木凋落叶DOM与添加米槠凋落叶DOM的土壤CO_2累积排放量之间没有显著差异。培养59天时，添加杉木鲜叶和凋落叶DOM的土壤CO_2累积排放量均显著高于添加米槠鲜叶和凋落叶DOM的($p < 0.05$) (图3)。

在培养59天时，添加不同来源的DOM增加的土壤碳排放量分别是外源添加DOC的176% (添加杉木鲜叶DOC量是46.9 mg·kg^{-1})、22.5% (添加米槠鲜叶DOC量是16.3 mg·kg^{-1})、256% (添加杉木凋落叶DOC量是35.7mg·kg^{-1})和50.0% (添加米槠凋落叶DOC量是55.9 mg·kg^{-1})，即外源添加米槠鲜叶和凋落叶DOM后，增加了土壤总有机碳库，而添加杉木鲜叶和凋落叶DOM后降低了土壤总有机碳库。

3 讨论

3.1 不同来源的DOM的差异

本研究发现杉木鲜叶DOC浓度(586.1 mg·L^{-1})显著高于米槠鲜叶DOC浓度(203.7 mg·L^{-1})，而米槠凋落叶DOC浓度(698.8 mg·L^{-1})显著高于杉木凋落叶DOC浓度(446.1 mg·L^{-1})，这与不同树种的叶片质量和结构差异有关。杉木鲜叶和凋落叶DOM的pH值均显著高于米槠鲜叶和凋落叶DOM的，这与Kiikkilä等(2011)的研究结果不一致，可能是由亚热带地区和温带地区的立地条件差异引起。*HIX*、*UV*和E_2:E_3均是衡量DOM化学性质差异性的指标，其中*HIX*能反映芳香类化合物的含量，且比*UV*更加灵敏，区分度更高(康根丽等, 2014)。本研究中相同树种鲜叶DOM的*HIX*和*UV*均显著低于凋落叶DOM的，相对荧光强度值也验证了这个结果，凋落叶到鲜叶所对应的波长由长波向短波转移表明DOM中共轭体系在减少(Haken & Wolf, 1995; Bu *et al*., 2011)，凋落叶淋溶的DOM化学性质更复杂(Inamdar *et al*., 2012)。同时，本研究结果显示杉木和米槠凋落叶DOM的*HIX*和*UV*差异不显著，这与前期研究的结果不一致，其原因可能在于浸提比例不一样。

3.2 添加不同来源的DOM后土壤CO_2排放的差异

已有研究表明，添加外源DOM后会显著影响土壤CO_2排放(Wieder *et al*., 2008; Leff *et al*., 2012)，本研究也发现，添加不同来源的DOM后土壤CO_2累积排放量均高于对照。在培养31天时，添加米槠凋落叶DOM的土壤CO_2累积排放量高于添加杉木凋

落叶DOM的(p = 0.351), 但培养结束时, 添加米槠凋落叶DOM的土壤CO_2累积排放量比添加杉木凋落叶DOM的低11%, 这除了与培养时间有关, 可能也与不同树种DOM的差异有关(Kiikkilä *et al*., 2014)。培养31天时, 添加米槠鲜叶DOM的土壤CO_2累积排放量显著低于添加米槠凋落叶DOM的, 这可能是因为外源添加DOC:DON大于25, 使外源N成了土壤微生物生长和繁殖的限制性因素, 因而, 含氮量高的DOM进入土壤后微生物迅速繁殖促进了土壤CO_2排放(Nourbakhsh & Dick, 2005; Sun *et al*., 2009)。而在培养59天时, 添加米槠鲜叶DOM的土壤CO_2累积排放量与添加米槠凋落叶DOM的差异不显著, 表明随着培养时间延长, 添加米槠鲜叶DOM与米槠凋落叶DOM的土壤CO_2累积排放量之间的差异在逐渐减小。同时, 添加杉木鲜叶和凋落叶DOM的土壤CO_2累积量均显著高于添加米槠鲜叶和凋落叶DOM的, 表明单次添加外源可溶性有机物到土壤中, 添加杉木树种DOM对土壤CO_2排放的影响更大。

培养59天时, 添加米槠鲜叶和凋落叶DOM后增加了土壤总有机碳库, 这与许多外源添加有机物对土壤碳库的影响是一致的(Qiao *et al*., 2014; Xiao *et al*., 2014)。但添加杉木鲜叶和凋落叶DOM后降低了土壤总有机碳库, Fontaine等(2004)、Hoosbeek和Scarascia-Mugnozza (2009)也得到类似的研究结果, 这与外源添加DOM的差异有关。如Wieder等(2008)的研究表明, 添加不同树种凋落叶DOM到土壤中后, 对土壤总有机碳库的影响是不一致的, 这主要是由外源添加的DOM的化学性质差异引起。在培养前31天时, 添加米槠凋落叶DOM的土壤CO_2累积排放量比对照高15.4%, 但培养59天时下降到4.3%, 说明在培养后期添加米槠凋落叶DOM的土壤CO_2累积排放量与对照逐渐趋于一致, 这与其他3种处理的结果相反, 其原因除了与培养时间有关外, 还可能由于添加外源DOM的质量对土壤微生物活动的影响(Gauthier *et al*., 2010), 如本研究发现外源添加的米槠凋落叶DOM中含有更多大分子量、难分解的化合物。

3.3　外源DOM对土壤CO_2排放的影响机制

研究表明, 外源添加有机物的数量与质量均会影响土壤CO_2排放。如Cleveland等(2010)的研究表明土壤CO_2排放量随外源添加DOC的增加而增加。Wang等(2013, 2014)认为外源添加有机物的化学性质差异也会影响土壤CO_2排放。因异养微生物能快速利用土壤中活性的(低分子量)、易分解的有机物从而促进土壤CO_2排放(Abera *et al*., 2012; He & Ruan, 2014; Yang & Zhu, 2015)。本研究结果发现, 土壤CO_2排放受到外源添加DOM数量与质量的共同影响。如在培养第1天时, 添加不同来源的DOM的土壤CO_2瞬时排放速率随外源添加DOC的增加而增加。而在培养59天时, 添加杉木凋落叶DOM的土壤CO_2累积排放量显著高于添加米槠凋落叶DOM的土壤CO_2累积排放量, 但外源添加杉木凋落叶DOC (35.7 mg·kg^{-1})显著低于外源添加米槠凋落叶DOC (55.9 mg·kg^{-1}), 这可能与外源添加DOM的化学性质有关, 因为杉木凋落叶DOM的E_2:E_3值显著高于米槠凋落叶DOM的, 即外源添加的杉木凋落叶DOM中含有更多的小分子有机物, 而周转快的小分子物质能增加土壤CO_2的排放(van Hees *et al*., 2005; Fujii *et al*., 2010; Rousk *et al*., 2011)。因此, 为了更好地区分外源添加DOM的数量与质量对土壤CO_2排放的影响, 后期研究需要通过控制外源DOM的数量或者质量, 从而更加深入地分析添加不同来源的DOM对土壤CO_2排放的影响机制。

4　结论

单次添加外源DOM对培养初期土壤CO_2排放的影响较大。在培养59天时, 添加相同树种鲜叶DOM与凋落叶DOM的土壤CO_2累积排放量之间差异不显著, 但添加杉木鲜叶和凋落叶DOM的土壤CO_2累积排放量均显著高于添加米槠鲜叶和凋落叶DOM的。在培养结束时, 添加米槠鲜叶和凋落叶DOM后增加的土壤碳排放量是外源添加DOC量的22.5%和50.0%, 而添加杉木鲜叶和凋落叶DOM的超过了100%, 说明添加不同来源的DOM对土壤总有机碳库的影响是不一样的。因本研究没有采用同位素标记的技术, 因而不能区分土壤CO_2排放来源。今后可结合^{13}C-DOM标记技术, 并从微生物群落结构及酶活性等方面更加深入地研究不同来源的DOM添加对土壤CO_2排放的影响机制。

基金项目　国家自然科学基金(31370615、31130013和31470501)、国家重大科学研究计划课题(2014CB954003)和福建省教育厅重点项目(JA13065)。

doi: 10.17521/cjpe.2015.0064

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doi: 10.17521/cjpe.2015.0064