Dissolved Organic Carbon Dynamics and Controls of Planted Slash Pine Forest Soil in Subtropical Region in Southern China

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Abstract: Soil dissolved organic carbon (DOC) is an active fraction of the soil organic carbon (SOC) pool and links terrestrial and aquatic systems. The degradation of DOC can affect carbon cycling, nutrient dynamics and energy supply to microorganism, and consequently change biogeochemical processes. This study investigated the vertical and seasonal variability of soil DOC concentrations and its controls in a 23-year-old planted slash pine (Pinus elliottii) forest at Qianyanzhou Forest Experimental Station (QFES) in Southern China. Soil solutions were collected at bimonthly intervals at depths of 10, 20 and 30 cm by a mechanical–vacuum extractor from November 2007 to March 2009, and at monthly intervals at depths of 10, 30 and 50 cm from April 2009 to October 2010. The DOC concentrations were determined with a total organic carbon (TOC) analyzer. Mean (±standard deviation) DOC concentrations at depths of 10 cm, 20 cm, 30 cm and 50 cm were 12.4 ± 4.4, 10.6 ± 6.3, 8.7 ± 2.6, and 8.0 ± 5.9 mg L−1, respectively. Both seasonal and spring means of DOC concentration showed a decreasing trend with increasing depth, while there was no clear trend for the summer, autumn, or winter seasons. DOC concentrations during spring, summer, autumn and winter ranged from 4.8 to 21.5, 4.9 to 26.2, 5.4 to 17.1, 4.9 to 14.6 mg L−1, respectively, their mean DOC concentrations were 10.2, 10.5, 10.8 and 8.3 mg L−1, respectively. No consistent pattern of seasonal variability of DOC concentrations at different depths was observed. No obvious relationship between organic carbon content of forest litter and DOC concentration was found. There was a positive linear relationship between SOC and DOC concentration (R2=0.19, p<0.01), which showed that SOC was one of the main controls of DOC. A positive exponential relationship existed between soil temperature at 5 cm and DOC concentrations at 10 cm depth in slash pine, masson pine (Pinus massoniana) and Chinese fir (Cunninghamia lanceolata) planted forests (R2=0.12, p<0.01). DOC concentrations showed a negative linear relationship with soil moisture at all depths in slash pine forest (R2=0.15, p<0.001), and DOC concentrations at depth of 10 cm demonstrated a negative exponential relationship with soil moisture at 5 cm depth in three planted forests (R2=0.13, p<0.001). Precipitation in sampling months and mean seasonal DOC concentration were not correlated. However, a more detailed analysis of precipitation events at different times before sampling and seasonal DOC concentration showed that the timing of precipitation events prior to sampling had different effects on seasonal DOC concentrations at different depths. Our study highlights the importance of DOC dynamics for the carbon cycle in planted slash pine forest and it provides evidence for evaluating the effects of ecological restoration in subtropical red soil region.

Key words: dissolved organic carbon; DOC concentration; profile and seasonal variability; characteristics analysis; controlling factors
1 Introduction

Dissolved organic carbon (DOC) is often defined as organic molecules that can pass through a filter of 0.45μm (Kalbitz et al. 2000). As a linkage of terrestrial ecosystems and aquatic environments, DOC plays a significant role in biogeochemical cycle of carbon (C) and nutrients including nitrogen (N) and phosphorus (P) as well as soil formation and transport of pollutants (Kalbitz et al. 2000; Michalzik et al. 2001; Neff and Asner 2001; Fröberg et al. 2006; Peichl et al. 2007). Generally observed DOC concentrations and fluxes result from release processes such as leaching and desorption, and removing processes such as biodegradation and adsorption (Kalbitz et al. 2000; Yang et al. 2003). Due to the contradictory results from lab study and field investigation, there is still much uncertainty about the controls on DOC concentrations and fluxes (Kalbitz et al. 2000). The physical and biogeochemical factors controlling DOC change with environmental conditions, resulting in difficulties in determining DOC controls and predicting DOC production and consumption (Kalbitz et al. 2000; Neff and Asner 2001). Some important factors on DOC include solar radiation and temperature, soil temperature and moisture, availability of N, iron (Fe) and aluminium (Al), soil pH, C/N ratio, amount and quality of organic matter, and land use and management effects (Kalbitz et al. 2000; Michalzik et al. 2001; Neff and Asner 2001; Harrison et al. 2008).

The forest ecosystem of red soil hilly region in Southern China suffered serious damage at the end of 1970s and at the beginning of 1980s of last century. Restoration efforts on the red soil ecosystem have started since the mid of 1980s. A series of studies on carbon cycle including carbon storage, carbon flux, soil respiration, carbon turnover, and aboveground biomass have been conducted at QFES of Chinese Ecosystem Research Network (CERN) (Wang et al. 2004; Yu et al. 2005; Wen et al. 2006; Wang et al. 2009). However, soil DOC concentration and its controlling factors are still unknown. Considering the large afforested area, about 61.68 million hectares, mostly located in southern China, it is of vital significance to monitor the DOC dynamics, and study its controls.

The objectives of this study are: (i) to determine the soil DOC concentrations and storage on the profile 0–50 cm of planted slash pine forest; (ii) to generalize the characteristics of seasonal variability and profile distribution of DOC concentration and storage; and (iii) to analyze the controlling factors for seasonal variability and vertical distribution of DOC concentration.

2 Material and methods

2.1 Study site

The study site is located in QFES (26°44′48″N, 115°04′13″E), CERN, in Jiangxi Province of Southern China. The site is a typical red soil subtropical hilly region, with an elevation of 102 m and Central-Asia subtropical monsoon climate. The mean annual air temperature, precipitation, solar radiation and frost-free period from 1985–2004 in the QFES are 17.9℃, 1485 mm, 4349 MJ m⁻² and 323 days, respectively. During the sampling period from Nov. 2007 to Oct. 2010, the monthly mean precipitation of spring, summer, autumn and winter was 83.1, 141.3, 67.3 and 53.5 mm, respectively. The planted tree species are slash pine (Pinus elliottii), masson pine (Pinus massoniana) and Chinese fir (Cunninghamia lanceolata). Before 1983, the original natural forest was destroyed, and soil erosion by water was severe. After plantation the accumulation of carbon has increased largely in this region during more than 20 years and the forest coverage reached 78.81% (Ma et al. 2007). The soil parent materials include sand stone and mud stone in this region and the soil is mainly red land with low water holding capacity. A detailed description of soil properties and stand characteristics of the study site are summarized in Table 1.

2.2 Sample collection and chemical analysis

Three experimental plots (6 m×6 m, with direction of True North and 8° of slope inclination; Fig.1) were selected for soil solution, litter and soil sampling. Total 56 samples of soil solutions in slash pine forest were collected by a mechanical-vacuum extractor with a plastic tube into plastic sampling bottles, at bimonthly intervals at depths of 10, 20 and 30 cm from Nov. 2007 to March 2009, and at monthly interval at depths of 10, 30, and 50 cm from April 2009 to Oct. 2010. The number of sampling replicates was 3 in the period from April 2009 to October 2010. At months with little or no precipitation, no samples could be acquired. Sometimes the damage of sampling device by animals resulted in the lack of samples as well. Soil solutions were filtered through a glass fiber paper (< 0.45 pore diameter) and stored at 4℃. DOC concentrations were determined by TOC Analyzer (Elementar Analysensysteme GmbH, Germany).

Table 1 Forest characteristics and soil properties of the study site.

<table>
<thead>
<tr>
<th>Items</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest characteristics for slash pine (in 2007)</td>
<td></td>
</tr>
<tr>
<td>Mean tree height (m)</td>
<td>12</td>
</tr>
<tr>
<td>Mean tree diameter at DBH (cm)</td>
<td>15.8</td>
</tr>
<tr>
<td>Stem density (tree ha⁻¹)</td>
<td>809</td>
</tr>
<tr>
<td>Max. LAI (m² m⁻²)</td>
<td>5.6</td>
</tr>
<tr>
<td>Mean litterfall organic carbon content (mg g⁻¹)</td>
<td>526.8</td>
</tr>
<tr>
<td>Mean SOC content (mg g⁻¹)</td>
<td></td>
</tr>
<tr>
<td>10cm</td>
<td>7.53</td>
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<tr>
<td>20cm</td>
<td>4.60</td>
</tr>
<tr>
<td>30cm</td>
<td>4.07</td>
</tr>
<tr>
<td>50cm</td>
<td>3.01</td>
</tr>
<tr>
<td>Soil bulk density (0–20cm) (g cm⁻³)</td>
<td>1.51</td>
</tr>
<tr>
<td>pH (0–20cm)</td>
<td>4.90</td>
</tr>
<tr>
<td>Total nitrogen (0–20 cm) (%)</td>
<td>0.07</td>
</tr>
</tbody>
</table>
Soil samples were collected at bimonthly intervals by method of soil sampling probe at layers of 0–10 cm, 10–30 cm, and 30–50 cm with sampling replicates of 3 from Nov. 2007 to Oct. 2010 to determine pH and SOC content. SOC concentration was determined by method of potassium bichromate-outer heating. The SOC concentrations at 10, 30 and 50 cm were calculated via interpolation.

Samples of forest floor litter were collected by a partitioning layer method of collecting decomposed and half decomposed litter separately from Nov. 2007 to Oct. 2010, to determine their organic carbon content. The number of sampling replicates was 5. The samples of decomposed and half decomposed litter fall were mixed respectively.

Air temperature was monitored with air temperature and relative humidity sensors (Model HMP45C, Vaisala Inc.) and precipitation recorded with a rain gauge (Model 52203, RM Young, Inc.). Soil temperatures at five depths of 2, 5, 20, 50 and 100 cm were measured with thermocouples (105 T and 107-L, Campbell Scientific Inc.) near the study plot in QFES. Volumetric soil moisture data at depths of 10, 20, 30, 50 cm were collected from QFES, measured by neutron moisture meter CNC503 (DR). Soil temperature and soil moisture at those depths with no observed values were calculated via interpolation from the original data. Soil temperature at 5 cm depth was measured near sampling plots using portable thermocouples (JM 624) and soil moisture at 5 cm depth was measured using a portable TDR (Wang et al. 2009).

The software package Origin 8 was used for all statistics and regression analysis.

3 Results and discussion

3.1 Seasonal and profile variability of soil DOC concentration

From Nov. 2007 to Oct. 2010 DOC concentrations in soil solutions in slash pine plantation ranged between 4.8 and 26.2 mg L$^{-1}$ with high values occurring at 10, 20 and 50 cm depths during spring and summer (Fig. 2). DOC concentrations ranged between 4.8 and 21.5 mg L$^{-1}$ during spring, 4.9 to 26.2 mg L$^{-1}$ during summer, 5.4 to 17.1 mg L$^{-1}$ during autumn, and 4.9 to 14.6 mg L$^{-1}$ during winter. The DOC concentrations at shallow horizons are higher than at deeper horizons in any sampling month. The highest value
of DOC concentrations (26.2 mg L\(^{-1}\)) occurred at 50 cm depth at the end of August 2008, however due to the limited number of high-valued samples in the same month and at this depth, the highest value occurred could not be taken as seasonal or profile trend.

Mean DOC concentrations decreased with the increase of the depth on the soil profile (0–50 cm), from 12.3 mg L\(^{-1}\) at depth of 10 cm, 10.6 mg L\(^{-1}\) at 20 cm, 8.7 mg L\(^{-1}\) at 30 cm, to 7.9 mg L\(^{-1}\) at 50 cm (Fig. 3a). This indicated that DOC concentrations of soil leachates had a significant decreasing tendency with increasing depth.

The results of several field studies demonstrated that concentrations and fluxes of DOM in soil solutions decreased significantly with soil depth (Moore et al. 1992; Kalbitz et al. 2000; Prokushikin et al. 2010), adsorption of DOM to mineral surfaces was assumed to be a major and important factor for DOM concentrations reducing in mineral soil (Kaiser and Guggenberger 2000; Prokushikin et al. 2010). In addition, some studies showed that dead tree roots were a significant source of DOC (Kalbitz et al. 2000; Uselman et al. 2007; Hansson et al. 2010). In deeper layers, the root growth is reduced due to lack of nutrients, which resulted in the decrease of DOC.

The mean concentration of DOC on the profile in spring had an obvious and evenly decreasing trend with the increase of soil depth, from 13.7 mg L\(^{-1}\) at 10 cm, 10.9 mg L\(^{-1}\) at 20 cm, 8.5 mg L\(^{-1}\) at 30 cm, to 6.3 mg L\(^{-1}\) at 50 cm (Fig. 3b).

In winter, mean DOC concentration from 20 cm to 50 cm on the profile decreased with increasing depth as well. In summer and autumn, no profile pattern was observed.

Seasonal variability of mean DOC concentration showed little difference among spring, summer and autumn, ranging from 10.0 mg L\(^{-1}\) during spring, 10.5 mg L\(^{-1}\) during summer, to 10.8 mg L\(^{-1}\) during autumn. Lower value of 8.3 mg L\(^{-1}\) was observed during the winter (Fig. 4a). The decrease of DOC concentration in winter may result from the fact that decomposition of litter and microbial activity becomes weaker in winter due to lower temperature and substrate supply, which may explain the decrease of DOC production during this season. No common seasonal pattern of DOC concentration was observed at different soil depths (Fig. 4b).

### 3.2 The relationship between DOC and SOC concentrations

Profile variability of SOC suggested a decreasing tendency with the increase of depth in all seasons (Fig. 5). As for mean SOC at depth of 10 cm, it increased slightly from 6.79 mg g\(^{-1}\) during spring, 6.99 mg g\(^{-1}\) during summer, to 7.59 mg g\(^{-1}\) during autumn, and increased largely to 9.64 mg g\(^{-1}\) during winter. The differences between 10 cm depth and other three depths were large in all seasons, while the...
The DOC storage of each layer of the profile was calculated by the following equation:

$$DOC_D = 10 \times DOC_i \times M_i \times H_i$$

where $DOC_D$ is DOC storage (mg m$^{-2}$), $DOC_i$, $M_i$, and $H_i$ are DOC concentration (mg L$^{-1}$), soil moisture in volumetric percentage (m$^3$ m$^{-3}$), height of soil layer $i$ (cm), respectively.

The seasonal variability of DOC storage on 0–30 cm profile of slash pine forest was shown in Fig. 7. DOC storage ranged from 104.1 mg m$^{-2}$, which occurred at depth of 0–10 cm in Nov. 2009, to 582.9 mg m$^{-2}$ at depth of 0–10 cm in March 2009. Of 17 sampling months, DOC storage demonstrated an increasing tendency with increasing depth in 9 months, while there were no obvious characteristics in other sampling months.

The mean DOC storage values of soil layers on the profile were 282.6 (0–10 cm), 269.2 (10–20 cm), and 251.3 mg m$^{-2}$ (20–30 cm) with small differences among the three layers (Fig. 8 a).

As shown in Fig. 8b, profile variability of DOC storage in spring and summer had the same characteristics of decreasing from 0–10 cm to 10–20 cm, then to 20–30 cm depth. In autumn, DOC storage showed the contrary pattern of increasing from 0–10 cm to 10–20 cm and to 20–30 cm depth. In winter, DOC storage increased from 0–10 cm to 10–20 cm, no large differences existed between the values of 10–20 cm and 20–30 cm layers.

Fig. 8c showed seasonal variability of DOC storage. Seasonal variabilities of DOC concentration on the profile 0–30 cm were in order of summer > spring > autumn > winter. The lowest values of DOC storage for both 10–20 cm and 20–30 cm horizons occurred in winter, and the second lowest value of DOC storage for 0–10 cm horizon occurred in winter too. Except in the 20–30 cm horizon, where the highest value of seasonal DOC storage occurred in autumn, the highest values occurred during summer in the two upper layers of 0–10 cm and 10–20 cm (Fig. 8d).
3.4 Relationship between DOC concentration and soil temperature

DOC production is likely controlled by those factors controlling biological activity (Gödde et al. 1996). Laboratory experiments and field manipulations indicated that biology activity is affected by soil temperature and soil moisture (Kalbitz et al. 2000; Harrison et al. 2008). Seasonal and vertical variabilities of DOC concentrations in soil solution in slash pine forest and soil temperature were shown in Fig. 9. The relationships between soil temperature and DOC concentrations at all depths (Fig. 10a), and DOC concentrations at depth of 10 cm (Fig. 10b), 20 cm (Fig. 10c) and 50 cm (Fig. 10d) were demonstrated. No obvious relationship existed between DOC concentration and soil temperature in slash pine forest. DOC concentrations at 10 cm depth in planted slash pine, masson pine and Chinese fir forests (Fig. 11), however, showed a positive exponential relationship with soil temperature at 5 cm depth. No obvious relationships between DOC concentration and soil temperature were found in deeper horizons in these forests.

3.5 Relationship between DOC concentration and soil moisture

Seasonal and vertical variabilities of DOC concentration and soil moisture were shown in Fig. 12. Relationships between soil moisture and DOC concentration at all depths, and DOC concentrations at depth of 10 cm, 30 cm and 50 cm were demonstrated in Fig. 13 (a), (b), (c) and (d) respectively.

Fig. 9 Relationship between DOC concentration and soil temperature on 0-50 cm profile in slash pine plantation (from Nov. 2007 to Oct. 2010) (soil temperature data from QFES). Error bars indicate standard deviation.

Fig. 11 Relationship between soil temperature at 5 cm depth and DOC concentrations at 10 cm depth in three planted forests (from Nov. 2007 to Oct. 2010)
A negative linear relationship existed between soil moisture and DOC concentrations on the profile in Slash Pine forest (Fig. 14 a), and DOC concentrations at 10 cm depth showed a negative exponential relationship with soil moisture at 5 cm depth in three planted forests.

3.6 The relationship between DOC concentration and precipitation

The distribution of precipitation in sampling month, within one month before sampling and within two months before
sampling in slash pine plantation, and seasonal and profile variability of DOC concentrations were shown in Fig. 15a. Neither precipitation within sampling month, precipitation within one month before sampling, or precipitation within two months before sampling had an obvious effect on DOC concentration. Correlation of seasonal distribution of precipitation in sampling months and mean DOC concentrations in four seasons (Fig. 15b) suggested that from spring, summer to autumn precipitation decreased largely as mean DOC concentration varied little. However this pattern was not found in winter. As the value of DOC concentration in winter was much lower than in autumn, the precipitation did not decrease by much. In this study precipitation in sampling month did not affect the DOC concentration.

The correlations between precipitation within 10 days, 30 days and 60–30 days before sampling, and mean DOC concentrations at 10 cm, 30 cm and mean DOC concentration, respectively were made as shown in Fig. 16. The precipitation within a certain period before sampling had different effects on seasonal DOC concentration at different depths. For example, as for precipitation within 10 days, the least precipitation and the least DOC concentration at depth of 10 cm concurrently occurred in autumn, however, at depth of 30 cm the highest DOC concentration occurred in autumn. The precipitation within different time before sampling had different effects on mean seasonal DOC concentration at a certain depth.

Analyses of controls on DOC dynamics above demonstrated that SOC was one of the main sources of DOC. There was a difference between the effect of soil temperature on DOC concentrations at 10 cm depth and at other deeper depths. Differences in temperature effects between upper and lower soil horizons corresponded to the hypothesis that DOC concentration in the topsoil, with higher microbial activity than subsoil, is controlled mainly by microbial processes (Guggenberger et al. 1998) which are, in turn, partly controlled by temperature. Both the negative linear relationship between soil moisture and DOC concentrations on the soil profile of slash pine forest and negative exponential relationship between soil moisture at 5 cm and DOC concentration at 10 cm showed that soil moisture was one of main environmental controls of DOC concentration. The effects of soil temperature and soil moisture in this study were contrary to the conclusion Chow et al. (2006) made that under non-flooded condition the DOC production was independent of temperature and soil water content.

4 Conclusions

In this study, detailed analyses were conducted on seasonal and vertical profile characteristics of DOC concentration and SOC concentration (0–50 cm), and DOC storage (0–30 cm) in slash pine plantation in QFES from Nov. 2007 to Oct. 2010. Based on the findings in our study, the following conclusions were made:

No relationship between organic carbon content of forest litter and DOC concentration was found in slash pine forest. Both DOC and SOC concentrations decreased with increasing depth and the positively linear relationship between SOC and DOC concentration demonstrated that SOC was a major source of DOC. Adsorption of mineral soil and reduction of DOC in deeper soil in source of tree root may be responsible for the decreasing tendency of DOC concentration on the profile.

Seasonal variability of mean DOC concentration showed little difference among spring, summer and autumn seasons, but a large decrease during winter. Seasonal variability of DOC storage on the profile 0–30 cm were in order of summer > spring > autumn > winter. DOC storage dynamics were consistent with the variability of DOC concentrations in winter.

A positive exponential relationship existed between soil temperature at 5 cm and DOC concentrations at 10 cm in soil solutions in three planted forests, however no same effect of soil temperature was found at other deep depths. Soil moisture showed a negative linear relationship with DOC concentration in slash pine forest, and a negative
exponential relationship with DOC concentrations at 10 cm depth in three planted forests. A detailed analyses of precipitation at different times before sampling and seasonal DOC concentration showed that the different length and timing of precipitation events before sampling had different effects on seasonal DOC concentrations at different depths. SOC, environmental variables including soil temperature, soil moisture and rainfall were revealed as controlling factors of DOC in this study. Due to the complexity of DOC source and production, other controls such as seasonal dynamics of litter fall and fine root growth and turnover may also control DOC dynamics in subtropical slash pine plantations.

**References**


Fig. 16 The relationship between precipitation within 10 days (a), (b), (c) ; 30 days (d), (e), (f) ; and 60–30 days (g), (h), (i) before sampling and mean DOC concentrations at 10 cm, 30 cm and mean DOC concentration in slash pine plantation (from Nov. 2007 to Oct. 2010).


亚热带人工湿地松林土壤溶解性有机碳动态变化及控制因素

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摘 要: 土壤可溶性有机碳（DOC）是土壤有机碳库的活性组分，联接陆地和水生生态系统。DOC的降解影响碳循环、营养动力学机制和微生物的能源供给，因此改变生物地球化学过程。本研究对千烟洲森林试验站（QFES）土壤溶解性有机碳浓度垂直剖面和季节的变化及其控制因子，包括土壤性质和环境因素进行分析。2007年11月至2009年3月每两个月、2009年4月至2010年10月每月，分别在土壤10、20、30 cm深度和10、30、50 cm深度，采用机械式真空取样装置共收集了土壤溶液样品。用总碳分析仪（TOC）测定DOC浓度，DOC浓度平均值范围为3.0-26.2 mg L^{-1}。在土壤剖面10、20、30 cm深度DOC浓度平均值（±标准差）分别为12.4±4.4、10.6±6.3、8.7±2.6及8.0±5.9 mg L^{-1}。DOC季节平均浓度和春季DOC浓度平均值具有明显的随深度增加而降低的特征。而在夏季、秋季和冬季，DOC浓度在土壤剖面上的变化不具有明显的特征。春季、夏季、秋季和冬季DOC浓度平均值分别为10.2、10.5、10.8和8.3 mg L^{-1}，不同深度DOC浓度的季节变化没有一致的特征。分析表明，凋落物有机碳含量与DOC浓度之间无明显相关关系，SOC与DOC含量具有相同的土壤剖面变化特征，SOC与DOC之间具线性正相关关系（R^2=0.19, p<0.01），表明SOC是DOC的主要来源之一。在湿地松、马尾松和杉木林，土壤溶液10 cm深度和5 cm土壤温度间具有指数正相关关系（R^2=0.12, p<0.01）。在湿地松土壤剖面，DOC浓度与土壤湿度呈负线性相关关系（R^2=0.15, p<0.001），在湿湿地松、马尾松和杉木林，土壤溶液10 cm深度DOC浓度和5 cm土壤温度之间具有负指数相关关系（R^2=0.13, p<0.001）。取样月降雨量与DOC季节平均浓度不相关。然而，对取样前不同时间降雨量与DOC季节平均浓度的分析表明，取样前降雨事件的时间对不同深度的DOC季节平均浓度有不同的影响。通过分析揭示了SOC和环境变量土壤温度、土壤湿度和降雨是DOC的控制因子。本研究以人工湿地松林碳循环中DOC动力机制为重点，为评价亚热带红壤区生态恢复的效果提供依据。

关键词: 溶解态有机碳；DOC浓度；垂直及季节变化；特征分析；控制因子