

# Sources of dissolved organic carbon in forest soils: evidences from the differences of organic carbon concentration and isotope composition studies

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**Abstract** There is considerable discussion and uncertainty in the literature regarding the importance of fresh litter versus older soil organic matter as sources of soil dissolved organic carbon (DOC) in forest floor. In this study, the differences of organic carbon concentration and stable isotope composition were analyzed under different background conditions to identify the origins of DOC in forest soil. The data show that there is no significant difference in SOC content between these collected soil samples ( $P > 0.05$ ), but the litter-rich surface soils have relatively higher DOC concentration than the litter-lacking ( $P < 0.01$ ) ones, and the  $\delta^{13}\text{C}$  values of DOC ( $\delta^{13}\text{C}_{\text{DOC}}$ ) are closer to  $\delta^{13}\text{C}$  of litter than  $\delta^{13}\text{C}$  values of SOC ( $\delta^{13}\text{C}_{\text{SOC}}$ ). In the litter-lacking surface soil samples, the range of  $\delta^{13}\text{C}_{\text{DOC}}$  is between  $\delta^{13}\text{C}_{\text{SOC}}$  and  $\delta^{13}\text{C}$  of dominant plant leaves. These results suggest that DOC mainly derive from litter in the litter-rich surface soil with, and the main path of DOC sources may change with surrounding conditions. In addition,  $\delta^{13}\text{C}_{\text{SOC}}$  and  $\delta^{13}\text{C}_{\text{DOC}}$  become more positive, and the absolute values of  $\Delta$  ( $\delta^{13}\text{C}_{\text{DOC}} - \delta^{13}\text{C}_{\text{SOC}}$ ) decrease with depth in the soil profiles, which indicate that the percentage of DOC below 5 cm, derived from degradation of humus, may increase with soil depth.

**Keywords** Sources · Dissolved organic carbon · Carbon isotope composition · Forest soil

## Introduction

Characterized with high mobility and bioavailability (Chantigny 2003; Wright et al. 2008), dissolved organic carbon (DOC) accounts for only a small proportion of soil organic carbon (SOC), but it has been an important player in various ecological roles—as the link of carbon cycle between the geosphere and the hydrosphere, as well as the link between the biosphere and the non-biosphere (Kalbitz et al. 2000; Ashworth and Alloway 2004). It is been proposed that the change of DOC would influence the process of carbon cycle between different spheres. Naturally, quantifying the proportion of DOC from various sources and pathways is fundamental to understand the long-term controls of DOC production and flux in soils and will be particularly important in realistic estimates of the effects of various environmental changes on soil C dynamics (Hagedorn and Machwitz 2007).

Recently, there are considerable discussions about the sources of DOC in soil (McDowell and Likens 1988; Kalbitz et al. 2000; McDowell 2003; Giesler et al. 2007). However, the relative importance of different inputs of DOC to forest soils remains uncertain. McDowell and Likens (1988) hypothesized that leaching and microbial decay of humus rather than of recent litter were largely responsible for the DOC production in the forest floor. Zsolnay and Alessandro (1996) also suggested that humified organic matter was the major source of DOC because of the relatively high proportion of humus in relation to litter in soils. The soil microbial biomass was also considered to be a potentially important source of DOC

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because it was highly labile (Williams and Edwards 1993). Guggenberger and Zech (1994) suggested that most of DOC was an end product of microbial metabolism, yet short-term experimental manipulations of organic matter sources showed that fresh litter also contributed significantly to the production of DOC (Park et al. 2002). Those reports indicated that the fresh litter and the humus were the two major sources of DOC in soil, but whether DOC originates primarily from recent litter or from relatively stable organic matter (equal to humus in this paper) in the lower part of organic horizons is still not clear. The contribution of litter and soil stable organic carbon to the DOC production in the forest floor and organic soil horizons is not fully understood (Kalbitz et al. 2000; Giesler et al. 2007).

In this study, the differences of DOC concentrations and carbon stable isotope composition were compared under different background conditions. The aim was to characterize the vertical patterns of DOC concentration and stable carbon isotope and to obtain better insights about the relative contribution of the litter and the old organic matter to the DOC production in organic soil horizons and forest profiles.

## Area descriptions, methods, and material studied

### Study sites

Sites were selected in Guiyang city (26°11'N–26°55'N, 106°27'E–107°03'E, Average altitude: 1,250 m), the capital city of Guizhou Province. It is located at the east side of Yunnan-Guizhou Plateau (Fig. 1), southwest of China. Mountains and deep valleys are wide spread over the 8,304 km<sup>2</sup> land. With a typical subtropical climate, the

annual average temperature is 15.3°C and the annual average precipitation is 1,197 mm. According to 2005 local governmental administrative statistics, the percentage of agricultural land and forest land were 65 and 35%, respectively. The soil in Guiyang area is developed on widely distributed bedrocks of dolomite, limestone, and quaternary red clay. The main forest soil types are yellow soil, limestone soil, etc. The main forest types are pure Masson pine forest, deciduous broad-leaved forest, conifer and broad-leaved mixed forest, and shrub.

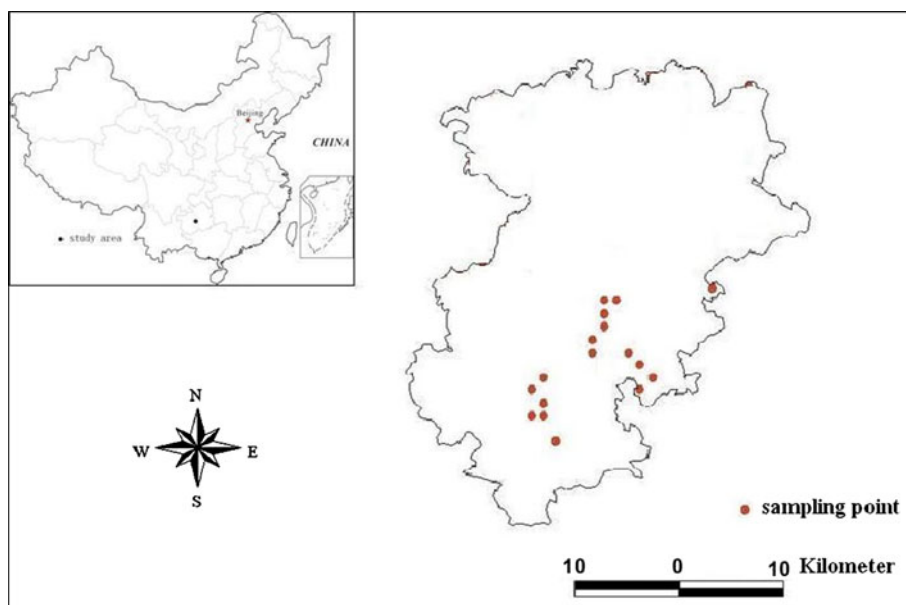
### Sample description

Samples were collected in the autumn of 2006. Surface soil samples were divided into four types according to soil type and the floor with litter (litter-rich) or without litter (litter-lacking). Furthermore, three forest soil profiles with perfect genetic layers were selected. Soil samples were collected by shovel at the depths of 0–5, 5–10, 10–20, 20–30, 30–40, 40–60, 60–80, and 80 cm. Visible plant residues and roots were removed. Soil samples were divided into two parts: one part was stored at 4°C prior to analysis (fresh soil), and the other was air dried and grounded to pass through a 0.154 mm (100 mesh) stainless-steel sieve. Relevant characteristics of the sites and soil samples were given in Tables 1, 2 and 3. At the same time, a few mixed litter and some dominant plant leaves were collected around these selected sites.

### Analytical methods

Soil pH value was measured with a pH electrode (Orion) in a ratio of 1:2.5 (m/v) soil to de-ion water. Soil particle size

**Fig. 1** Location of the study of area and distribution of sampling points



**Table 1** Characteristics of surface soil sampling site

| Soil type      | Dominant plant   | Litter | <i>n</i> | Moisture content (%) | pH      | <i>W</i> <sub>SOC</sub> (g kg <sup>-1</sup> ) | <i>W</i> <sub>DOC</sub> (mg L <sup>-1</sup> ) |
|----------------|--|--------|----------|----------------------|---------|---|---|
| Yellow soil    | <i>Pinus massoniana</i> ,<br><i>Camellia oleifera</i> , et al.                               | Rich   | 7        | 33.3–53.8            | 3.9–5.3 | 24.6–73.3                                     | 27.8–132.9                                    |
|                |  | Lack   | 4        | 28–40                | 4.9–5.8 | 42–48.2                                       | 8.3–17.2                                      |
| Limestone soil | <i>Lyeium chinense</i> , <i>Pyracantha fortuneana</i> ,<br><i>Lonicera japonica</i> , et al. | Rich   | 6        | 18.4–37.5            | 6–8.2   | 24.6–87.6                                     | 35.3–69.2                                     |
|                |  | Lack   | 8        | 8.3–29.3             | 5.9–7.6 | 34.3–93.3                                     | 10.2–26.7                                     |

**Table 2** Characteristics of soil profile sampling site

| Land-use type                         | Soil type      | Dominant plants   | Thickness of litter (cm) | $\delta^{13}\text{C}$ of dominant plant leaves (‰) | $\delta^{13}\text{C}$ of mixed litter (‰) |
|---------------------------------------|----------------|---|--------------------------|--|---|
| Camellia and Masson pine mixed forest | Yellow soil    | <i>Pinus massoniana</i> ,<br><i>Camellia oleifera</i> , et al.      | About 2                  | -26.6 ± 0.13                                       | -27.2                                     |
| Shrub                                 | Limestone soil | <i>Pyracantha fortuneana</i> ,<br><i>Lonicera japonica</i> , et al. | About 5                  | -27.5 ± 0.27                                       | -27.2                                     |
| Pure Masson pine forest               | Yellow soil    | <i>Pinus massoniana</i>   | 5–10                     | -27.4  | -27.3                                     |

**Table 3** Basic chemical-physical properties in the soil profiles

| Land-use type                         | Depth (cm) | pH (H <sub>2</sub> O) | Moisture content (%) | <i>W</i> <sub>SOC</sub> (g kg <sup>-1</sup> ) | <i>W</i> <sub>DOC</sub> (mg L <sup>-1</sup> ) | Sand (%) | Silt (%) | Clay (%) |
|---------------------------------------|------------|-----------------------|----------------------|---|---|----------|----------|----------|
| Camellia and Masson pine mixed forest | 0–5        | 4.2                   | 32.2                 | 30.7  | 47.4  | 33       | 41       | 26       |
|                                       | 5–10       | 4.1                   | 27.3                 | 5.6   | 26.4  | 33       | 37       | 29       |
|                                       | 10–20      | 4.1                   | 52.5                 | 4.5   | 37.1  | 20       | 41       | 39       |
|                                       | 20–40      | 4.1                   | 37.5                 | 6.1   | 31.1  | 27       | 40       | 33       |
|                                       | 40–60      | 4                     | 40.0                 | 6.4   | 39.2  | 35       | 33       | 31       |
|                                       | 60–        | 4.2                   | 42.1                 | 1.6   | 17.7  | 32       | 38       | 29       |
| Shrub                                 | 0–5        | 5.7                   | 40.0                 | 43.2  | 117.2   | 19       | 43       | 38       |
|                                       | 5–10       | 5.1                   | 36.4                 | 23.9  | 21.2  | 23       | 36       | 41       |
|                                       | 10–20      | 6.1                   | 21.0                 | 8.2   | 5.3   | 14       | 36       | 50       |
|                                       | 20–30      | 5.8                   | 22.2                 | 6.2   | 5.1   | 18       | 29       | 53       |
|                                       | 30–40      | 6.6                   | 20.8                 | 5.5   | 6.6   | 21       | 23       | 56       |
|                                       | 40–60      | 6.7                   | 21.4                 | 4.5   | 6.1   | 22       | 28       | 50       |
|                                       | 60–80      | 6.1                   | 20                   | 5.9   | 5.5   | 37       | 20       | 43       |
|                                       | 80         | 6.6                   | 40                   | 4.6   | 3.2   | 38       | 22       | 40       |
| Pure Masson pine forest               | 0–5        | 3.9                   | 33.3                 | 72  | 132.9   | 26       | 28       | 36       |
|                                       | 5–10       | 3.9                   | 14.3                 | 46.2  | 51.4  | 46       | 23       | 31       |
|                                       | 10–20      | 4.3                   | 30.0                 | 11.9  | 9.5   | 35       | 22       | 43       |
|                                       | 20–30      | 4.3                   | 27.3                 | 6.9   | 5.5   | 30       | 20       | 50       |
|                                       | 30–40      | 4.5                   | 25.0                 | 5.9   | 9.1   | 27       | 13       | 60       |
|                                       | 40–60      | 4.6                   | 20.0                 | 7.2   | 4.8   | 25       | 13       | 62       |
|                                       | 60–80      | 4.6                   | 33.3                 | 6.3   | 11.2  | 15       | 22       | 63       |
|                                       | 80         | 5.2                   | 42.9                 | 5.2   | 4.6   | 36       | 21       | 43       |

composition was calculated by sinking rates. Total soil organic carbon (SOC) was quantified by the catalytic combustion of grounded samples in elemental analyzer (PE2400 II, USA) with an analytical precision of 0.1%.

Carbonate was removed before analysis by HCl-fumigation of soil for 24 h (Harris et al. 2001). For analysis of DOC in soil, fresh subsoil was extracted with 0.5 M K<sub>2</sub>SO<sub>4</sub> at a 1:5 w/v ratio, shaken for 1 h, and filtered with 0.45 μm

membrane after centrifuging at  $3,000\times g$  for 10 min (Jones and Willett 2006). DOC concentration in filtrate was quantified with total organic carbon analyzer (O.I. 1030W, USA).

The natural abundance of heavy isotopes was expressed as parts per thousand relative to the international standard PDB (Peedee belemnite) using delta units ( $\delta$ ). The  $\delta^{13}\text{C}$  was calculated according to Eq. 1:

$$\delta^{13}\text{C}(\text{‰}) = [(\delta_{\text{sample}}/\delta_{\text{standard}}) - 1] \times 10^3 \quad (1)$$

where  $\delta_{\text{sample}}$  is  $^{13}\text{C}/^{12}\text{C}$  ratio of sample, and  $\delta_{\text{standard}}$  is  $^{13}\text{C}/^{12}\text{C}$  ratio of the reference standard (PDB). For stable isotopic analyses of soil organic carbon, a sample mass yielding 0.5 mg carbon was placed in a quartz tube with CuO. The sample tube was then evacuated and flame-sealed. Organic carbon in the sample was oxidized to  $\text{CO}_2$  at  $850^\circ\text{C}$  for 5 h.  $\text{CO}_2$  was purified with liquid nitrogen, then measured with a Finnigan MAT252 isotope ratio mass spectrometer for carbon isotopic relative content. Three to five replicated measurements per sample were carried out, and the  $\delta$  value was presented as the average of these measurements. IAEA- $\text{C}_3$  ( $\delta^{13}\text{C} = 24.91\text{‰}$ , cellulose) was used a correction standard for  $\delta^{13}\text{C}$  and analytical precision ( $n = 5$ ) was  $\pm 0.1\text{‰}$ .

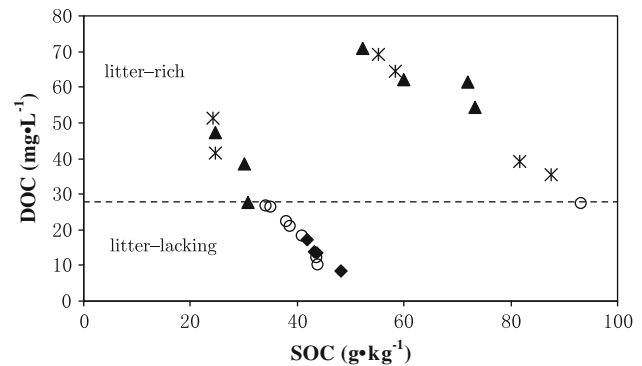
Before determination of  $\delta^{13}\text{C}_{\text{DOC}}$ , the inorganic C in filtrate was removed by adjusting the pH to 2 using  $\text{H}_3\text{PO}_4$ . No flocculation of organic matter was observed on acidification of the filtrate. Then, the acidified filtrate was dried down to a salt crust in glass bowls below  $60^\circ\text{C}$ . Dried salts were scraped from bowls and loaded into quartz tube, sealed under vacuum, and combusted for 5 h at  $850^\circ\text{C}$ . Other steps are same as the analyzing process of  $\delta^{13}\text{C}_{\text{SOC}}$ .

## Results

### SOC and DOC contents in soil

The concentrations of SOC in surface soil samples range from 24.6 to  $93.3 \text{ g kg}^{-1}$  (Table 1). On average, the SOC concentration in litter-rich limestone soils has the highest value ( $55.2 \text{ g kg}^{-1}$ ), than in the litter-rich ( $50 \text{ g kg}^{-1}$ ) yellow soils and in the litter-lacking ( $46 \text{ g kg}^{-1}$ ) limestone soils. The SOC concentration in the litter-lacking yellow soils has the lowest mean value ( $44.2 \text{ g kg}^{-1}$ ). But ANOVA analysis showed that the SOC concentration between different types of soil samples was not significantly different at the  $P < 0.05$  level.

The DOC concentrations in litter-rich surface soils range from 27.8 to  $132.9 \text{ mg kg}^{-1}$ , and that with litter-lacking ones range from 8.3 to  $26.7 \text{ mg kg}^{-1}$ , respectively (Table 1; Fig. 2). Obviously, no matter which soil type, yellow soil or limestone soil, and no matter the amount of



**Fig. 2** SOC and DOC content in surface soil. Filled triangle yellow soil with litter-lacking; filled diamond yellow soil with litter-lacking; open circle limestone soil with litter-lacking; asterisk limestone soil with litter-rich

SOC, the DOC in litter-rich surface soils is relatively higher than that in litter-lacking one. One-way  $t$  test analysis showed that there was significant difference between them at the  $P < 0.01$  level. In addition, there are no significant relationships between SOC and DOC in any type of surface soils ( $P > 0.05$ ).

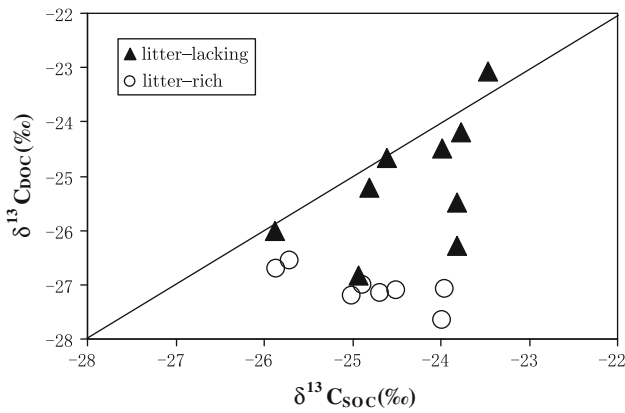
In three soil profiles, the maximal values of SOC content are at surface layer (0–5 cm), which are 30.7, 43.2, and  $72 \text{ g kg}^{-1}$ , and decrease abruptly with soil depth (Table 3). The DOC contents below 5 cm are less than that at surface layer greatly in all selected soil profiles, but it does not show possibility of reduction or increase with depth. DOC contents below 10 cm are very close, especially in Pure Masson pine forest and shrub soil profiles. Beside, there are also no significant relationships between SOC and DOC in any type of soil profiles ( $P > 0.05$ ).

### $\delta^{13}\text{C}$ of plant leaves, litter, SOC, and DOC in surface soil and soil profile

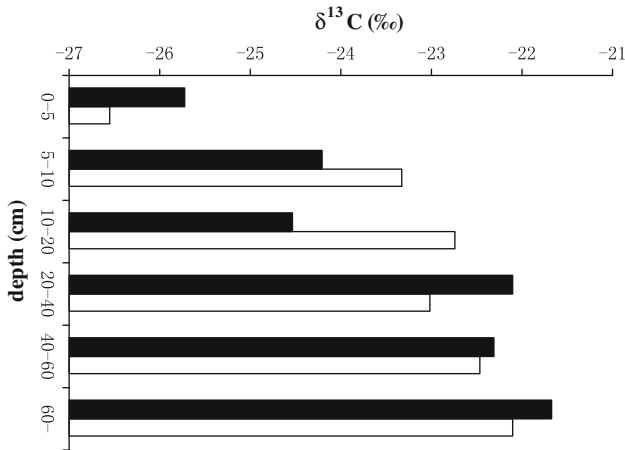
The plants in experimental fields all are the plants with C3 photosynthesis (Calvin cycle), whose leaves have  $\delta^{13}\text{C}$  values in the range from  $-29.09$  to  $-25.9\text{‰}$  (Further details about the plant leaves stable carbon isotope composition can be found in Table 4). The differences of  $\delta^{13}\text{C}$  values between mixed litters and dominant plant leaves are very small (Table 2). The values of  $\delta^{13}\text{C}_{\text{SOC}}$  in the surface soil range from  $-25.88$  to  $-23.77\text{‰}$ , and there is no difference between litter-rich and litter-lacking soil. Compared with the  $\delta^{13}\text{C}$  of the dominant plant leaves and mixed litter, the  $\delta^{13}\text{C}_{\text{SOC}}$  of surface soil increase by 2.1–4.7 and 1.5–2.6‰, respectively. The  $\delta^{13}\text{C}_{\text{DOC}}$  of samples under litter-rich range from  $-27.65$  to  $-26.55\text{‰}$  and are closer to the  $\delta^{13}\text{C}$  of the mixed litter or dominant plant leaves than  $\delta^{13}\text{C}_{\text{SOC}}$ . Although some values of  $\delta^{13}\text{C}_{\text{DOC}}$  under litter-lacking are similar to that under litter-rich, there is

**Table 4**  $\delta^{13}\text{C}$  of dominant plant leaves (‰)

| Plant                          | $\delta^{13}\text{C}$ (‰) | Plant                             | $\delta^{13}\text{C}$ (‰) | Plant                     | $\delta^{13}\text{C}$ (‰) |
|--------------------------------|---------------------------|-----------------------------------|---------------------------|---------------------------|---------------------------|
| <i>Pinus massoniana</i>        | -27.4                     | <i>Cladrastis wilsonii</i> Takeda | -27.2                     | <i>Castaea esquinii</i>   | -27.4                     |
| <i>Camellia oleifera</i>       | -27.72                    | <i>Betula lunilifera</i>          | -28                       | <i>Paulownia fortunei</i> | -28.42                    |
| <i>Pyracantha foruneana</i>    | -29.09                    | <i>Rhus chinensis</i>             | -28.17                    | <i>Artemisia</i> sp.      | -25.9                     |
| <i>Dicranopteris dichotoma</i> | -28.8                     | <i>Lyeium chinense</i>            | -29.2                     |                           |                           |



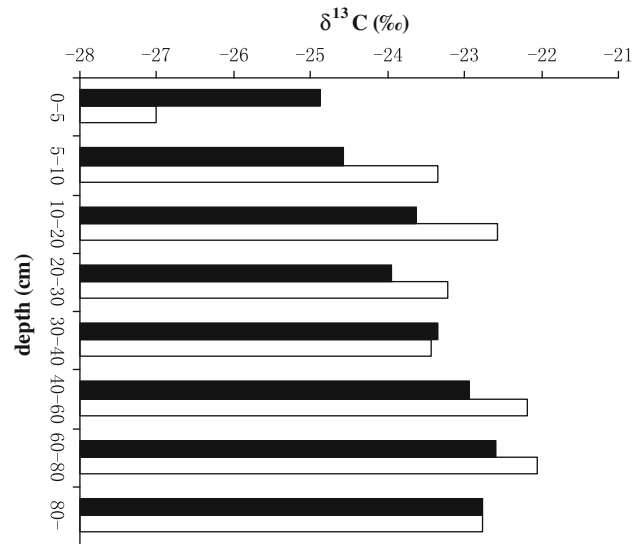
**Fig. 3** Correlation of carbon isotope composition between SOC and DOC. Filled triangle litter-lacking; open circle litter-rich



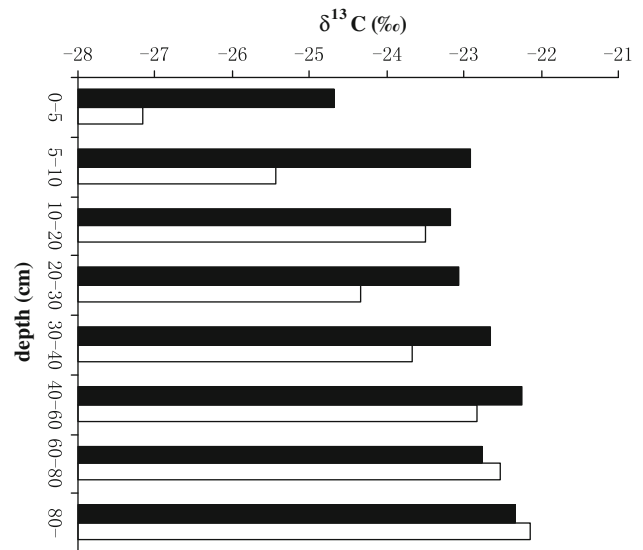
**Fig. 4** Carbon isotope composition in the soil profile of Camellia and Masson pine mixed forest. Filled square  $\delta^{13}\text{C}_{\text{SOC}}$ ; open square  $\delta^{13}\text{C}_{\text{DOC}}$

significant difference between litter-rich and litter-lacking samples ( $P > 0.05$ ) (Fig. 3, some soil samples were not available). In addition, there are no significant relationships between  $\delta^{13}\text{C}_{\text{DOC}}$  and  $\delta^{13}\text{C}_{\text{SOC}}$  in any type of soil samples ( $P > 0.05$ ).

The  $\delta^{13}\text{C}_{\text{SOC}}$  in three soil profiles increase by 4.1, 2.1, and 2.3‰ from surface to the lowest layers respectively, and become more positive with soil depth (Figs. 4, 5, 6). The ranges of  $\delta^{13}\text{C}_{\text{DOC}}$  are bigger than  $\delta^{13}\text{C}_{\text{SOC}}$ , but the variance trend of  $\delta^{13}\text{C}_{\text{DOC}}$  is similar to  $\delta^{13}\text{C}_{\text{SOC}}$  in these

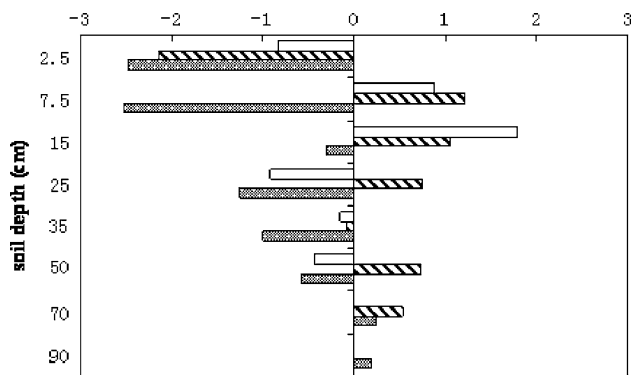





**Fig. 5** Carbon isotope composition in the soil profile of shrub. Filled square  $\delta^{13}\text{C}_{\text{SOC}}$ ; open square  $\delta^{13}\text{C}_{\text{DOC}}$



**Fig. 6** Carbon isotope composition in the soil profile of the pure Masson pine forest. Filled square  $\delta^{13}\text{C}_{\text{SOC}}$ ; open square  $\delta^{13}\text{C}_{\text{DOC}}$

soil profiles. The absolute values of  $\Delta$  ( $\delta^{13}\text{C}_{\text{DOC}} - \delta^{13}\text{C}_{\text{SOC}}$ ) decrease with soil depth (Fig. 7). There are no significant relationships between  $\delta^{13}\text{C}_{\text{DOC}}$  and  $\delta^{13}\text{C}_{\text{SOC}}$ .



**Fig. 7** Organic carbon isotope composition difference between SOC and DOC.  Pure Masson pine forest;  shrub;  Camellia and Masson pine mixed forest

## Discussion

### The vertical distribution of SOC and DOC

In experiment field, because local residents collect some plant debris for fuel once in a while, some soil samples were picked out on the floor without plant debris. There is almost no significant difference on SOC contents between different types of soil samples ( $P > 0.05$ ) (Fig. 2). So, human activity does not influence the SOC accumulation obviously in the forest floor of this region. Besides, under the subtropical monsoonal humid climate, the high temperature and abundant rainfall environment are propitious to vegetation's fast growth. There is considerable plant debris input annually into the soil, which usually makes the surface SOC contents maintain high level ( $>20 \text{ g kg}^{-1}$ ). In addition, the distribution of SOC with depth is closely related to the evolution of soil profiles. The source of SOC decreases gradually from surface to deep soil, but the losses due to decomposition increase continuously. As a result, SOC content reduces with the increase of profile depth (Chen et al. 2005).

Similarly, the highest contents of DOC are at surface layer. The DOC contents below 5 cm are less than that at surface layer greatly, but it does not show possibility of reduction or increase with depth. DOC contents below 10 cm are very close, especially in Pure Masson pine forest and shrub soil profiles. It is different from others' reports (Michalzik et al. 2001; Cory et al. 2004). Some researchers considered the drastic DOC decrease in deep soil was caused by microbial utilization of DOC, but Qualls and Haines (1992) concluded that biological decomposition of soil water DOC was too slow to account for the decrease in concentration with depth. In addition, many studies suggested that sorption of DOC to mineral surfaces was more important than decomposition in mineral soil for decreasing DOC concentration with soil (Currie et al. 1996;

Kalbitz et al. 2000; Solinger et al. 2001). The soil sorption capacity of DOC was positively correlated with the soil clay content as well as the soil water solution ionic strength and pH (Shen 1999; Kalbitz et al. 2000). Similarly, this study also found that the variance trends of DOC contents below surface soil were similar to that of clay contents (Table 3), but there were no significant relationship between DOC content and clay content ( $P > 0.05$ ). Besides, there are also no significant relationships between SOC and DOC in any type of soil profiles ( $P > 0.05$ ).

### The difference of DOC concentrations for indicating its source in surface soil

Generally, the DOC in forest surface soil derives from primary soil organic matter, new plant debris (litter), microbial biomass (Zsolnay and Alessandro 1996; Michalzik and Matzner 1999; Kalbitz et al. 2004; Weintraub et al. 2007). Throughfall is also an important source for DOC (Liu and Sheu 2003). Of course, recent litter and humus are thought to be the two most important sources of DOC in soils because of their abundance in the soil (Kalbitz et al. 2000). However, the contribution of these sources to the DOC production in the forest floor is not fully understood. In our study, plant debris influenced the DOC concentration significantly in the surface soil samples. The DOC concentrations in litter-rich soil were relatively higher than that in litter-lacking one. Therefore, this study considers DOC mainly derives from litter in the litter-rich surface soil. It is similar to Magill and Aber (2000) and Moore and Dalva (2001) laboratory studies.

### The difference of $\delta^{13}\text{C}$ for indicating DOC source in soil

Because this study did not sort the mixed litter according to their species, the  $\delta^{13}\text{C}$  difference of every plant leaves from their litter could not be identified. But the  $\delta^{13}\text{C}$  of pine needle only increase by 0.09‰ contrasting with fresh litter in pure Masson pine forest, and the  $\delta^{13}\text{C}$  of Camellia leaves only increase by 0.51‰ contrasting with fresh mixed litter in Camellia and Masson pine mixed forest. Consequently, the C isotope fractionation of leaves is very small in a period of time after it dropped down from branches.

The  $\delta^{13}\text{C}_{\text{DOC}}$  is closer to  $\delta^{13}\text{C}_{\text{leaves}}$  and  $\delta^{13}\text{C}_{\text{mixed litter}}$  than  $\delta^{13}\text{C}_{\text{SOC}}$  in the litter-rich surface soil samples. According to the theory of isotope trace and the principle of mass balance, the DOC in surface soil should mainly derive from mixed litter or the throughfall which is the rain passing through the tree canopies and barks. However, the DOC amount in throughfall is very low than that from litter based on previous observation (data is not shown) and other documents (Liu and Sheu 2003; Moller et al. 2005),

and it is easy to be decomposed by microbes (Michalzik et al. 2001). In addition, as mentioned earlier, the DOC content in the litter-rich surface soil is higher than that with litter-lacking one. In results, those evidences indicate that the DOC deriving from mixed litter is main source of DOC in litter-rich surface soil. In the litter-lacking surface soil samples, the range of  $\delta^{13}\text{C}_{\text{DOC}}$  is between  $\delta^{13}\text{C}_{\text{SOC}}$  and  $\delta^{13}\text{C}$  of dominant plant leaves, which indicate that, without plant debris on the soil floor, the main sources of DOC may change with surrounding conditions.

The values of  $\delta^{13}\text{C}_{\text{SOC}}$  and  $\delta^{13}\text{C}_{\text{DOC}}$  in the selected soil profiles become more positive with soil depth (Figs. 4, 5, 6), which is consistent with others' results (Balesdent et al. 1988; Powers 2006; Wynn et al. 2006). Many authors have discussed the possible factors leading to the observed enrichment of  $^{13}\text{C}$  with depth (Ehleringer et al. 2000; Powers 2006; Wynn et al. 2006; Zhu and Liu 2006): (1) influence of atmospheric change (Suess effect)—since the beginning of the Industrial Revolution,  $\delta^{13}\text{C}$  of atmospheric  $\text{CO}_2$  has decreased due to the addition of  $\text{CO}_2$  from fossil fuel emissions and biomass burning, which have a more negative  $\delta^{13}\text{C}$  signature (Friedli et al. 1986). Compared with the newly formed SOC of topsoil, SOC in these deeper soil layers that have originated at a time when the  $\delta^{13}\text{C}$  value of atmospheric  $\text{CO}_2$  were more positive has higher  $\delta^{13}\text{C}$  value. (2) Microbial fractionation during litter decomposition—in the process of metabolic reactions associated with litter decomposition and SOC oxidation, microorganisms preferentially use the carbon sources of depleted  $^{13}\text{C}$ , and then the residual SOC should become progressively more positive in its  $\delta^{13}\text{C}$  value (Benner et al. 1987). (3) Microbial and fungal residues become SOC and the  $\delta^{13}\text{C}$  values of microbes as a result of carboxylation reactions. This is because whenever a carboxylation reaction is involved in catabolism, that  $\text{CO}_2$  molecule is likely to have originated from the soil atmosphere, which is  $^{13}\text{C}$  heavier than the  $^{13}\text{C}$  content of the organic materials being decomposed. (4) Belowground biomass (roots) is enriched in  $^{13}\text{C}$  compared with that aboveground (leaves).

The variance trend of  $\delta^{13}\text{C}_{\text{DOC}}$  is similar to  $\delta^{13}\text{C}_{\text{SOC}}$  in the soil profiles, and the absolute values of  $\Delta(\delta^{13}\text{C}_{\text{DOC}} - \delta^{13}\text{C}_{\text{SOC}})$  decrease with soil depth (Fig. 7). It may indicate that the percentage of DOC derived from soil humus substance may increase with soil depth. On the other hand, Solinger et al. (2001) estimated that about 115–500 kg C/ha DOC in subsoil is from surface soil, but the DOC moved out of subsoil is very little in forest ecosystem, and some component of DOC is hard to biodegrade (Nelson et al. 1995; Marschner and Kalbitz 2003), and  $^{13}\text{C}$  can be enriched during litter decomposition. So, the DOC in subsoil layer may also derive from litter primitively, which were biodegraded and accumulated. In addition, Gregorich et al. (2003) found that the values of  $\delta^{13}\text{C}_{\text{DOC}}$  are more

similar to  $\delta^{13}\text{C}_{\text{SOC}}$  than  $\delta^{13}\text{C}$  of new plant debris and microorganism after C3 plant was replaced by C4 plant, and with increasing soil depth more carbon derived from decades old SOM and less recent carbon derived from plants is used as carbon source by all microorganisms. Consequently, the percentage of DOC derived from soil humus substance may increase with soil depth.

## Conclusions

In this study, two types of soils were selected and sampled according to the floor with litter-rich or without litter (litter-lacking). The amounts of DOC and SOC were compared, and the differences and relationships of carbon stable isotope composition between DOC and possible sources were analyzed. Some principal conclusions were presented as follows.

- (1) No matter which soil type and the amount of SOC, the DOC content in litter-rich surface soils are relatively higher than that with litter-lacking ( $P < 0.01$ ) one. Between SOC and DOC in any type of soil samples, the relationships are not significant ( $P > 0.05$ ). The  $\delta^{13}\text{C}_{\text{DOC}}$  in litter-rich surface soil is more similar to  $\delta^{13}\text{C}$  of litter-rich soil than that with litter-lacking soil. In the litter-lacking surface soil samples, the range of  $\delta^{13}\text{C}_{\text{DOC}}$  is between  $\delta^{13}\text{C}_{\text{SOC}}$  and  $\delta^{13}\text{C}$  of dominant plant leaves. These results suggest that DOC contents are mainly derived from litter in the litter-rich surface soil and the main sources of DOC may change with surrounding conditions.
- (2) In soil profiles,  $\delta^{13}\text{C}_{\text{SOC}}$  and  $\delta^{13}\text{C}_{\text{DOC}}$  become more positive with soil depth and have the similar trends. The absolute values of  $\Delta(\delta^{13}\text{C}_{\text{DOC}} - \delta^{13}\text{C}_{\text{SOC}})$  decrease with depth. This result indicates that the percentage of DOC below 5 cm, which is derived from degradation of humus, may increase with soil depth.

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