

Effect of fire intensity on active organic and total soil carbon in a *Larix gmelinii* forest in the Daxing'anling Mountains, Northeastern China

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Abstract Studying contents and seasonal dynamics of active organic carbon in the soil is an important method for revealing the turnover and regulation mechanism of soil carbon pool. Through 3 years of field sampling and lab analysis, we studied the seasonal variations, content differences, and interrelationships of total organic carbon (TOC), light fraction organic carbon (LFOC), and particulate organic carbon (POC) of the soil in the forest areas burned with different fire intensities in the Daxing'anling Mountains. The mean TOC content in the low-intensity burned area was greater than that in the unburned area, moderate-intensity, and high-intensity burned areas in June and November ($P < 0.05$). LFOC and POC in the low-

intensity burned area were greater than that in either moderate-intensity or high-intensity burned areas, with significant differences in LFOC in September and November ($P < 0.05$). A significant difference in LFOC between the unburned and burned areas was only found in July ($P < 0.05$). However, the differences in POC between the unburned and burned areas were not significant in all the whole seasons ($P > 0.05$). Soil LFOC and POC varied significantly with the seasons ($P < 0.05$) in the Daxing'anling Mountains. Significant linear relationships were observed between soil TOC, LFOC, and POC, which were positively correlated with soil nitrogen and negatively correlated with soil temperature in the Daxing'anling Mountains.

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Introduction

Soil organic carbon, including light fraction organic carbon (LFOC) and particulate organic carbon (POC), derives from animal and plant material, microorganisms, and degraded and synthesised organic matter. Although LFOC and POC account for only a very small proportion of total soil organic carbon (TOC), they do belong to the active organic carbon of soil, which has a specific solubility, moves through the soil quickly, is easily oxidised and mineralised, and has a higher level of biological activity in plants and soil microorganisms (Sundquist 1993). Therefore, LFOC and POC can reflect slight changes of active organic carbon before changes of TOC in soil. Previous studies have shown that variations in the soil organic

carbon pool usually occur in the active carbon pool (Biederbeck and Zentner 1994). Active organic carbon is the driving force behind soil nutrients; it is directly involved in the process of soil biochemical conversion, and is an energy source for microbiological activities in the soil (Wander et al. 1994).

Fire is an important factor that influences the carbon cycle of terrestrial ecosystems. Globally, more than 4×10^8 ha of forests, shrubs, and grasslands are affected by fire each year and approximately 1.74 Pg carbon is transferred into the atmosphere (Cui et al. 2012). Studies on how TOC and active carbon components in soils change under forest fire interference are less. Recent studies mainly focus on the effects of forest fires on microorganisms and organic carbon content (Cui et al. 2012; Jiang et al. 2012), the differences and factors affected active organic carbon components in the soil by different levels of fire interference (Cambardella and Elliot 1992, 1994; Conant et al. 2003), and the properties of the soil organic carbon and nitrogen (Cui et al. 2012). The physical and chemical properties and processes of soils have direct effects on biomass productivity and soil organic matter (SOM) dynamics. Thus, their alteration during fire can substantially affect SOM quality and quantity both in the short and the long term (Bird et al. 2000). The effect of fire on SOM depends on fire intensity, vegetation type, and fuel load as well as soil texture and slope. Intense fires can lead to the complete destruction of the organic layer and SOM in the topsoil (Kraemer and Hermann 1979).

Variations within ecosystems and fire intensities influence the soil organic and active carbon components, causing differences in the soil carbon pools, especially in the active and organic carbon components in Mexican volcanic soils (Knicker 2007). Hence, studying the effect of different fire intensities on the dynamic variations in the soil active organic carbon components and total carbon in a *Larix gmelinii* forest is of critical importance for the evaluation of forest soil fertility, carbon pool balance, and the carbon cycle. By measuring the three indices—TOC, LFOC, and POC—we examined the effects of different fire intensities on the variation, content difference, and related factors affecting soil active organic carbon, and provided basic data on the effect of different fire intensities on soil organic carbon activities in a *L. gmelinii* forest in the Daxing'anling Mountains, Northeastern China.

The Nanweng River Nature Reserve in the Songling District of the Daxing'anling Mountains, Heilongjiang Province, was chosen, because there was a big fire a few years ago. *L. gmelinii* is the main plantation in this area. In April 2006, a lightning-caused forest fire burned $>5 \times 10^4$ ha of forest (geographic coordinates, $125^{\circ}07'55''$ – $125^{\circ}50'05''$ E, $51^{\circ}05'07''$ – $51^{\circ}39'24''$ N, Fig. 1). The nature reserve is located in the southeast forest of the

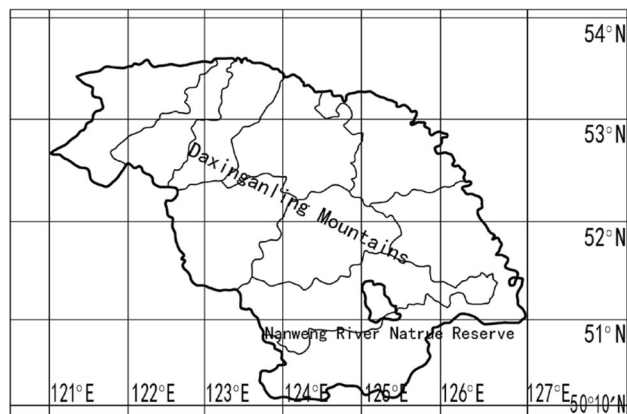


Fig. 1 Location of the study area

Daxing'anling Mountains in the Songling District with a total area of 229,523 ha.

The nature reserve covers an area of 229,523 ha at an altitude of 400–800 m. It is located in the cold temperature zone, with a low-temperature continental monsoon climate, characterized by long, cold winters and short, hot summers. The highest temperature is 35.5°C and the lowest is -43.8°C , with an annual average temperature of -3°C . There is an average of 2500 h of sunshine each year, with 90–100 frost-free days, 110 days in the growing season, and 415–500 mm annual rainfall.

The nature reserve has a low, hilly landscape, and a shadow slope that ranges from 25° to 50° . The soil is brown coniferous forest soil. The principal tree species in the area is *L. gmelinii*. The subdominant species include *Betula platyphylla* Suk., *B. davurica*, *Xylosma japonicum*, and *Populus davidiana* Dode. In this study, we utilized three indicators (TOC, POC, and LFOC) and discussed the influence on climate change, content, and soil active organic carbon to provide basic data about the influence of different fire intensities on soil active organic carbon in *L. gmelinii* forest.

Materials and methods

Sample plots

Three sample plots were selected in a *L. gmelinii* forest that was burned in April 2006; each had been exposed to different fire intensities (low, moderate, or high; Table 1). An adjacent un-burned area was selected as the control plot. Each sample plot included three smaller plots selected in some way from the much larger sample plots, for a total of 12 sub plots (each of these measured 20×20 m). The geographic coordinates of the plots are: unburned area ($125^{\circ}07'45''$ E, $51^{\circ}07'47''$ N); area of low fire intensity ($125^{\circ}09'02''$ E, $51^{\circ}09'20''$ N);

Table 1 Criteria for classifying forest fire intensity (Hu et al. 2007)

Fire intensity	Index level/ (kW m ⁻¹)	Classification criteria
High (H)	>3500	Trees >70 % burned or burned completely; the undergrowth shrubs all blackened height, burned to more than 5 m. Mineral soil colour and structure changed due to complete burning of soil organic matter
Moderate (M)	750–3500	Between high- and low-level fire. Upper part of forest litter burned
Low (L)	350–750	Trees <30 % burned, partial burning of undergrowth shrubs (<50 %), smoked height below 2 m

Table 2 Characteristics of *Larix gmelinii* forest exposed to different fire intensity (mean ± SE)

Fire intensity	Age (a)	Trees/shrubs burn rate (%)	Diameter at breast height (cm)	Height (m)	Dominant undergrowth
Unburned (UB)	Mid-maturation forest		10.01 ± 0.45	12.15 ± 0.34	<i>Rhododendron dauricum</i> , <i>Spiraea salicifolia</i> L., <i>Convallaria majalis</i>
Low (LI)	Mid-maturation forest	29.91/25.0	13.21 ± 0.56	11.97 ± 0.26	<i>Rhododendron dauricum</i> , <i>Spiraea salicifolia</i> L., <i>Pyrola calliantha</i> H. Andr., <i>Convallaria majalis</i>
Moderate (MI)	Mid-maturation forest	64.60/>50	15.52 ± 0.66	12.28 ± 0.31	<i>Rhododendron dauricum</i> , <i>Spiraea salicifolia</i> L., <i>Convallaria majalis</i> , <i>Thalictrum aquilegifolium</i> L. var. <i>sibiricum</i> Regel
High (HI)	Mid-maturation forest	88.04/100	11.20 ± 0.31	11.61 ± 0.11	<i>Rhododendron dauricum</i> , <i>Spiraea salicifolia</i> L., <i>Lespedeza bicolor</i> Turcz

moderate fire intensity (125°09′00″E, 51°09′21″N); high fire intensity 125°08′94″E, 51°09′18″N, Fig. 1). The forest type before the fire was *Rhododendron L. gmelinii* and the species composition was *L. gmelinii*: *Betula*: *Populus* = 10:1:1. The stand characteristics of the sampling areas are shown in Table 2.

Sample collection

Soil samples were collected from May to November in 2010, 2011, and 2014. Sampling began in early May when the soil started to thaw and was repeated in the last 10 days of each month. The five spots-mixed random sampling method was applied to each sampling area (Gregorich et al. 1994). Surface soil samples were taken from each of the five points using a soil auger; at each point, the litter layer and humus layer were removed and the soil auger rotated downward to a maximum depth of 15 cm (determined by auger head setting). It was set in 15 cm of soil auger head. The study area soil is very thin, about 15–20 cm, followed by stone.

Soil from the five sampling points was then combined into a single soil sample. Three repetitions were taken for each sampling area with different fire intensity levels in the same area, bringing the total number of combined samples to 12. The soil samples were taken back to the lab to remove debris.

Then, each sample was divided into four groups in preparation for soil analysis: group 1 (analysis of TOC) was dried naturally and passed through a 0.25-mm sieve; group 2 (analysis of POC and LFOC) was fresh, at 0–4 °C, and passed through a 2 mm sieve; group 3 (total nitrogen) was passed through a 0.149-mm sieve; and group 4 was air dried for physiochemical analysis (pH, temperature).

Sample analysis

Determination of soil LFOC

Twenty-five grams of dried soil was passed through a 2-mm sieve, placed into a centrifuge tube and 50 ml NaI (specific weight 1.70 g/ml) solution was added. This was shaken for 1 h (200 rpm), then centrifuged for another 20 min at 1000 rpm. The supernatant NaI solution was poured through a funnel containing 0.45-µm nylon filter paper for air evacuation filtration. Another 50 ml NaI solution was added and the process was repeated three times, until a total of 150 ml NaI solution was added. The resulting solution was eluted with 0.01 mol/L CaCl₂ solution, using 75 ml CaCl₂ each time, and then rinsed with distilled water repeatedly until no Cl⁻ response was seen, followed by testing with AgNO₃ solution. Then, the light

fragment organic matter on the filter papers was washed with distilled water into a 50-mL beaker, left to rest for 24 h, oven dried for 72 h at 60 °C, and finally weighed. The LFOC content of the entire sample was calculated based on the measured organic carbon content (Gregorich et al. 1994).

Determination of soil POC

Twenty grams of sieved soil was weighed and placed into 100 ml (NaPO₃)₆ (5 g/L) solution, shaken for 15 min by hand, and then placed into a shaker for 18 h at 90 rpm. The soil suspension was sieved through a 0.053-mm sieve and repeatedly washed with deionised water. The substance remaining on the sieve was oven dried for 12 h at 60 °C, weighed, ground, and sieved again using a 0.5-mm sieve. It was then tested using a Multi C/N 3000 analyser (Elementar Analysensysteme GmbH, Germany). The POC content of the entire sample was calculated based on the measured organic carbon content (Garten 2002; Barrios et al. 1997). This procedure was repeated with each soil sample.

Soil TOC was determined using the potassium dichromate oxidation–external heating method. Total nitrogen was measured using a Vario EL3 element analyser (Elementar Analysensysteme GmbH, Germany). Soil temperature was measured using a soil thermometer.

Data analysis

Data was analysed using Excel 2003 and SPSS 13.0, and the least significant difference (LSD) test was used for variance analysis. An alpha level of 0.05 was used for all statistical tests in this study. Multiple pair-wise comparisons were made between the experimental group and control group mean. The significance test level was 0.05 in this study.

Results

Total organic carbon and active organic carbon contents of soil in the forest areas of different fire intensities

TOC contents of soil in the unburned areas and the low-intensity, moderate-intensity, and high-intensity burning areas were 37.01–92.43, 40.13–91.45, 27.89–83.55, and 40.28–82.31 g/kg. Differences in TOC between soils in the unburned area and the burned areas varied from month to month. The significant differences were found only in June and September ($P < 0.05$). Soil TOC was highest in the low-intensity burning area. The difference in TOC of the

low- and moderate-intensity burning area were significant in July, September, and November ($P < 0.05$). TOC of soil in the control area was higher than that in the moderate-intensity and high-intensity burning area in May, June and November, but the differences were not significant ($P > 0.05$). The difference in TOC of the moderately and severely burned area was not significant ($P > 0.05$) (Fig. 2a–c).

The POC contents of soil in all areas ranged from 11.10 to 61.19 g/kg, accounting for 12–66.20 % of TOC. POC contents of soil in unburned areas and the low-, moderate-, and high-intensity burning area were 13.88–47.95, 14.9–61.19, 11.10–45.23 and 14.21–42.55 g/kg, respectively. POC contents varied among the different burning areas from

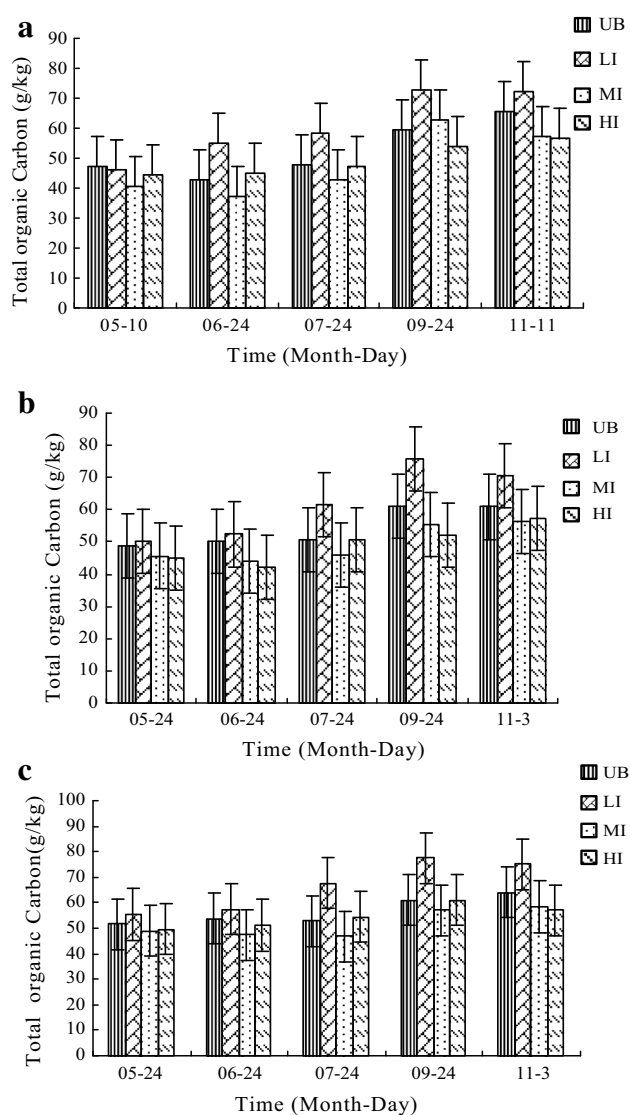


Fig. 2 Mean \pm SE, total organic carbon [60 samples; in the year of 2010 (a), 2011 (b), 2014 (c)] change with time in different intensities (unburnt, low, moderate and high) of the burned area

month to month. POC of soil in the low-intensity burned area was higher than that in the moderate- and high-intensity burning areas only in September ($P < 0.05$), while other month differences were not significant ($P > 0.05$). In July, September, and November, POC of soil in the low-intensity burning area was significantly higher than that in the unburned area ($P < 0.05$). In June, POC of soil in the unburned area was higher than that in the low-, moderate-, and high-intensity burning areas, but the difference was not significant ($P > 0.05$) (Fig. 3a–c).

The LFOC contents in soil in the unburned area and the low-, moderate-, and high-intensity burning areas were 1.42–22.57, 3.06–33.98, 2.31–19.77, and 2.08–15.52 g/kg. The ratio of LFOC to soil TOC was 1.54–36.76 %. The LFOC contents varied amongst the different burning areas from month to month. Soil LFOC in the low-intensity burning area was significantly higher than that in the moderate- and high-intensity burning areas in September and November ($P < 0.05$). The differences in LFOC of soil in the unburned area and the burned areas were significant only in July ($P < 0.05$). LFOC in the low-intensity burned area was significantly higher than that in the unburned area

in July, September and November ($P < 0.05$). The differences of soil LFOC were not significant in the moderate- and high-intensity burning area ($P > 0.05$) (Fig. 4a–c).

Seasonal variation of active organic carbon content of soils in the burning areas

Significant seasonal variations in the active organic carbon content were observed in all the areas and these showed a V-shaped trend, initially decreasing then increasing ($P < 0.05$) (Figs. 2, 3, 4). POC of soil in all areas also showed a similar trend that first decreased and then increased with time, with the lowest POC values occurring in June and the highest in November, except for the low-intensity burning area, where the lowest POC levels occurred in July (2010). Soil TOC showed no significant seasonal variations ($P > 0.05$) (Fig. 2a–c).

Soil LFOC content in burned areas showed significant seasonal variations, showing the pattern of first a decrease, then an increase, and then a decrease again. Soil LFOC reached the lowest levels in June and the highest in September and November, with a slight decrease again in

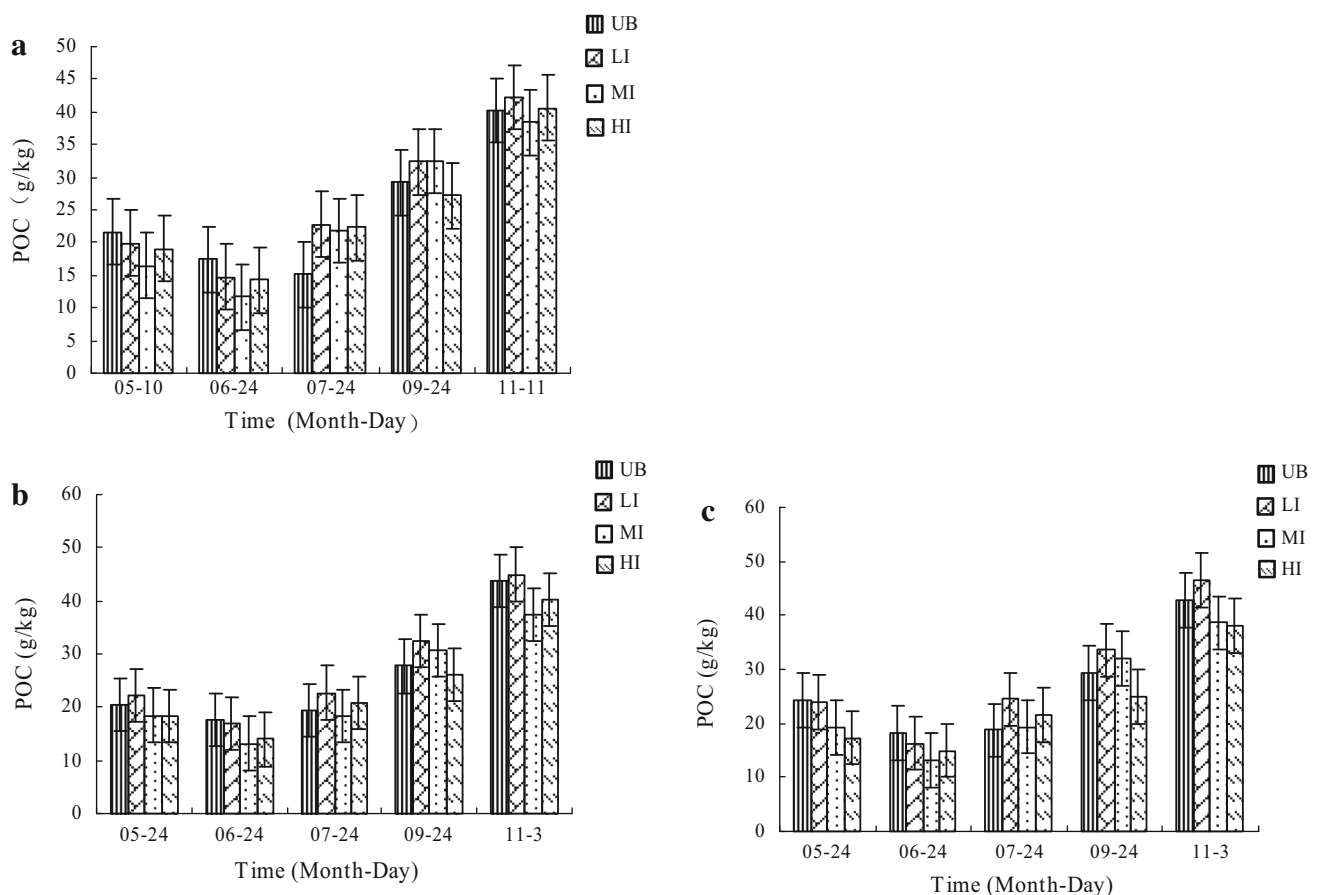


Fig. 3 Mean \pm SE particulate organic carbon (POC) [60 samples, in the year of 2010 (a), 2011 (b), 2014 (c)] change with time in different intensities (unburnt, low, moderate and high) of the burned area

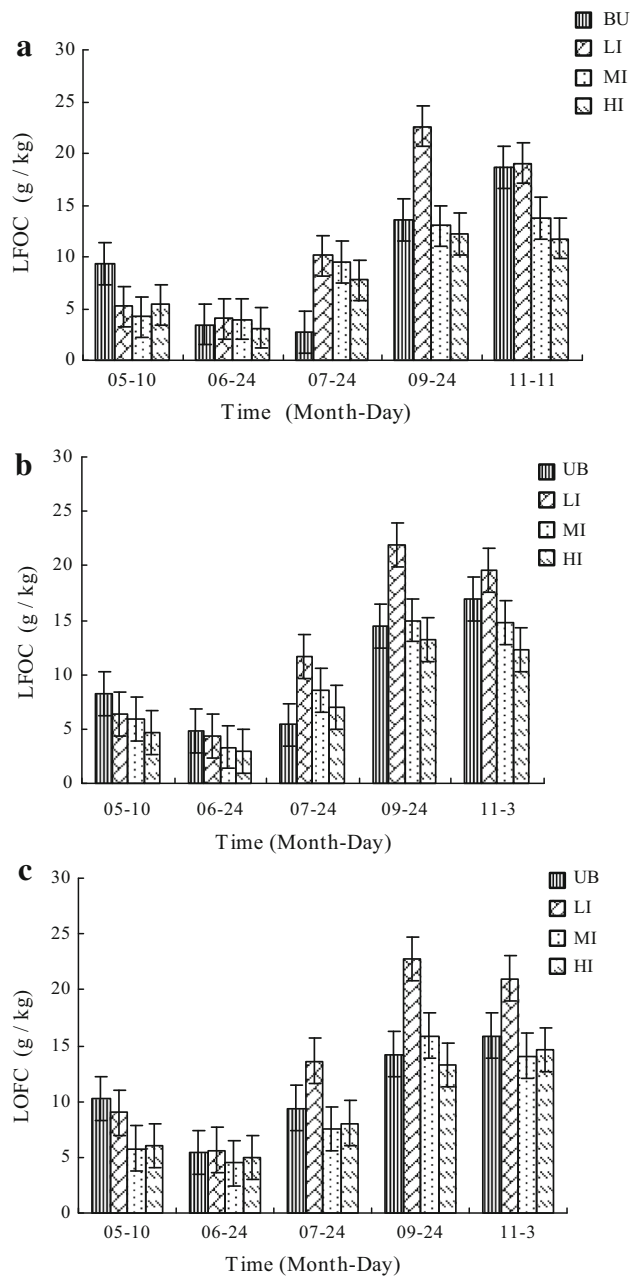


Fig. 4 Mean \pm SE light fraction organic carbon (LFOC) [60 samples; in the year of 2010 (a), 2011 (b), 2014 (c)] change with time in different intensities (unburnt, low, moderate and high) of the burned area

November. LFOC content of soil in the unburned area also showed significant seasonal variations; however, the variation pattern was slightly different from that in the burned areas. LFOC of soil in the unburned area reached the lowest level in July and the highest in November.

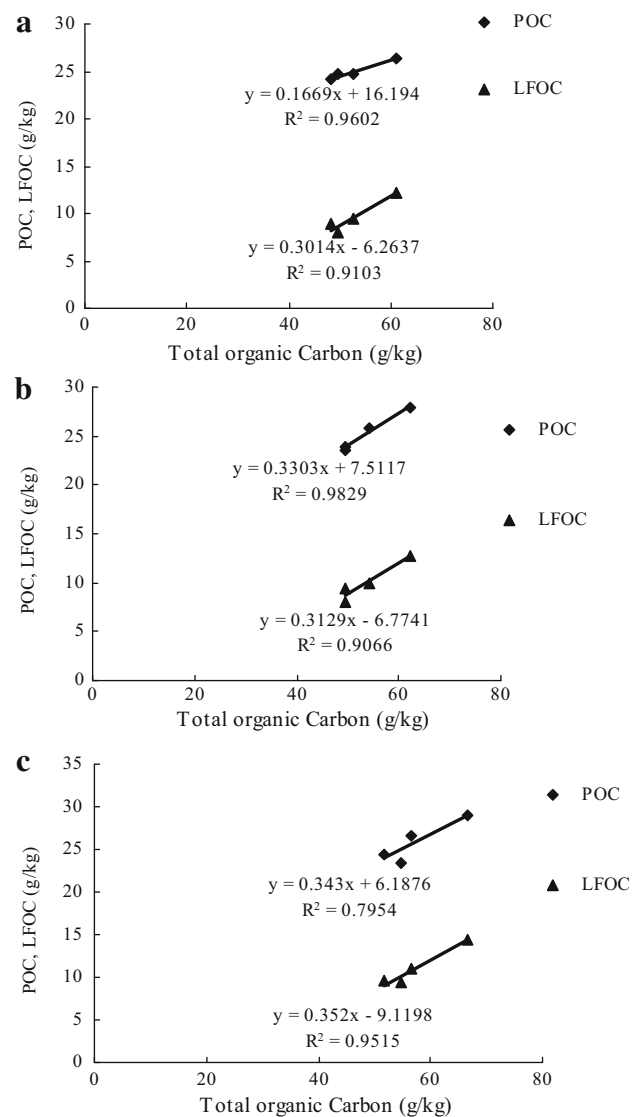


Fig. 5 The correlation of total organic carbon, POC and LFOC in the year of 2010 (a), 2011 (b), and 2014 (c)

The relationship between soil active organic carbon and TOC

As shown in Figs. 5a–c and 6a–c, there was significantly positive correlation between soil LFOC or POC and TOC ($P < 0.05$) and between LFOC and POC ($P < 0.05$). Soil POC, LFOC, and TOC were positively correlated with soil total nitrogen ($P < 0.05$) but negatively correlated with soil temperature ($P > 0.05$) (Table 3).

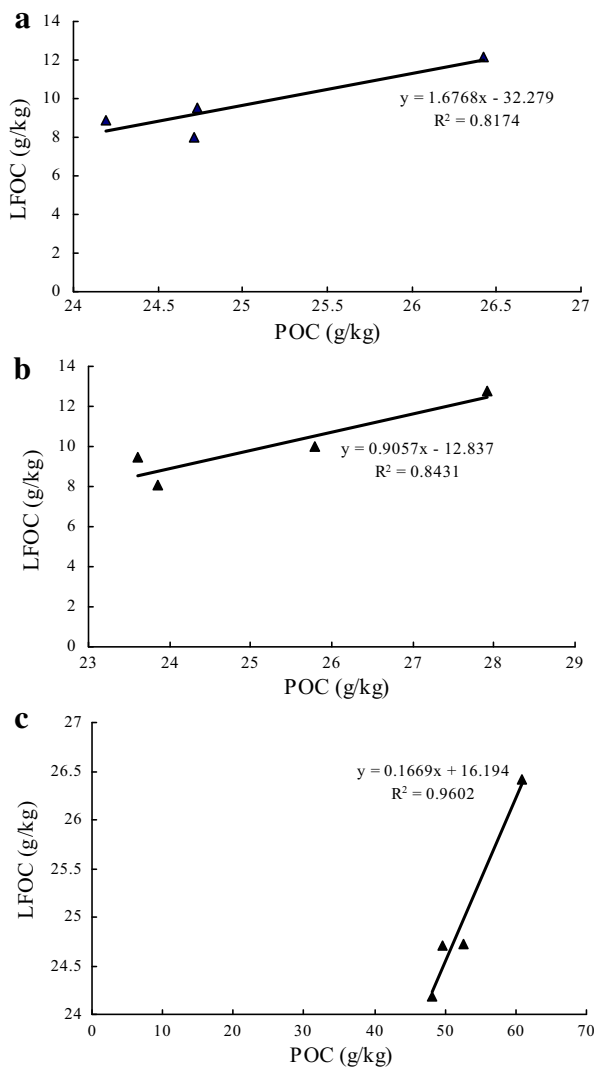


Fig. 6 The correlation of POC and LFOC in the year of 2010 (a), 2011 (b), and 2014 (c)

Table 3 Correlation of soil temperature and N with TOC, POC and LFOC

Time	Factors	TOC	POC	LFOC
Year 1	Soil temperature	-.592	-.733	-.692
Year 2		-.460	-.727	-.562
Year 3		-.512	-.780	-.646
Year 1	N	.982**	.946*	.995**
Year 2		.973**	.827	.926*
Year 3		.989**	.893*	.978**

** $P < 0.01$, * $P < 0.05$

Discussion

The range of soil TOC content in the unburned area and the low-, moderate-, and high-intensity burned areas identified in this study were similar to the results shown by Wang et al. (2011). He studied burned (46.5–80.1 g/kg) and unburned areas (49.0–92.1 g/kg) of the *L. gmelinii* forest in Ta River; both the results of Wang et al. and the present study were lower than the findings from a study by Zhang (2011) (soil TOC of 81.25–115.81 g/kg in the low-intensity burning area and 70.22–147.42 g/kg in moderate-intensity burn). The lower results might be caused by differences in vegetation type, measurement methods, and site conditions. Zhang (2011) used formula estimation, but the present study used the potassium dichromate oxidation–external heating method. Different conclusions were made about the impact of fire on soil TOC (Johnson and Curtis 2001; Antonio and Lorena 2011; Gonzalez et al. 2004).

In this study, the TOC content of soil in the low-intensity burned area was higher than that in the moderate- and high-intensity burned areas. This is likely because higher-intensity fires removed most of the organic matter, and combined with volatilisation at high temperature, acted to greatly reduce the source of soil TOC and decrease the soil TOC contents. This finding was consistent with those of previous studies (Certini 2005; Kennard and Gholz 2001). TOC in the low-intensity burned area was higher than that in the unburned area, which was consistent with the results shown by Cui et al. (2012). The reason that low-intensity fire increases the soil TOC could be that plant material, litter, semi-carbonised particles, and decaying dead cells are involved (Cui et al. 2012). The variation pattern of soil TOC in the unburned area was different from that in the low- and high-intensity burned areas. In most months, soil TOC in the unburned area was higher than that in the moderate- and high-intensity burned areas, which might be related to the uneven distribution and dynamic change of TOC in the soil. Future experiments will be necessary to further prove this hypothesis.

Soil LFOC in the unburned and low-intensity burn areas was higher than that of the larch plantation (0.54–14.17 g/kg) and the secondary forest in the warm temperature zone (0.86–15.21 g/kg) (Wu et al. 2002). The results were similar for soil TOC in moderate- and high-intensity burned areas. The LFOC proportion of TOC was higher than that in the dark coniferous forest of west Sichuan 4.03–13.37 % (Xiang et al. 2010), and lower than the results of Spycher et al. (1983). Such differences might be related to disturbed organic soil matter layers, affected by fire intensity and might also be related to plant type and climate.

In the present study, POC in all areas ranged from 11.10 to 61.19 g/kg, accounting for 12–66.20 % of TOC. Xiang et al. (2010) reported a similar result of TOC (12.5–68.01 %) conducted in the dark coniferous forest of West Sichuan. POC in our study was higher than that reported by Wu et al. (2002) (POC content of 0.89–10.64 g/kg and proportion of 30.5–31.8 % for a larch forest in the warm temperature zone). In our study, the POC content of soil in the low-intensity burned area was higher than that in the moderate- and high-intensity burned areas, which was consistent with the results of Jaymie and Matthias (2010). This might be because some organic matter was converted to charcoal instead of carbon particles after high-intensity fire interference (Jaymie and Matthias 2010).

LFOC and POC contents of soil in the unburned area and the low-, moderate-, and high-intensity burned areas had different variation patterns in different months, which was inconsistent with the results of Jaymie et al., who found that LFOC and POC in an unburned area was higher than in a burned area (Jaymie and Matthias 2010). On one hand, this might be caused by the TOC variation patterns, because LFOC and POC contents were greatly dependent on TOC (Alvarez and Alvarez 2001). On the other, this might be because of the disuniform distribution and dynamic changes in organic matter after fire interference. In this study, LFOC content and its proportion of TOC were significantly lower than those of POC, which was consistent with the results of Xiang et al. (2010). This might be a function of heavy liquid density (Yang et al. 2004) or differences in the origin of particles and light-fragment organic matter (Xiang et al. 2010).

In this study, soil LFOC content showed significant seasonal variations, this result agrees with that of Spycher et al. (1983) and Jose et al. (2003), who found that soil LFOC content reached peak levels in September in 10–15 cm deep soil in a Douglas fire forest. Cambardella and Elliott 1992 arrived at similar conclusions in their study of LFOC dynamic change in soils in a pine forest. Because LFOC mainly consists of fresh plant debris newly added to soil and plant residuals at different stages of decomposition, the seasonal dynamics of plant litter and the decomposition rates of plant litter during different seasons affected seasonal variations in LFOC (Xie et al. 2008). POC contents were mainly from the decomposed products of plant residues with a moderate decomposition rate (Cambardella and Elliott 1993). High-temperature and high-humidity climate conditions in the summer rapidly decompose organic matter in the soil, this is why soil POC content drops to the lowest levels in June and July. Together with continuous input and accumulation of organic matter, and the gradual dropping of temperature and

humidity, soil POC content gradually increases, reaching the highest levels in November.

This study showed significant positive correlations of soil LFOC and POC contents with TOC, which was consistent with the results of Xiang et al. (2010) and Alvarez and Alvarez (2001). It also indicates that soil LFOC and POC contents were greatly dependent on TOC content. Significant positive correlations between soil LFOC and POC indicate a close interaction (Yang et al. 2004).

Soil LFOC and POC were positively correlated with soil total nitrogen, which was consistent with the results of Gamberdella et al. (1993), because nitrogen content in soil organic matter affects the microbiological decomposition rate (Cambardella and Elliott 1993; Xu et al. 2008a, b). Organic matter with high nitrogen content was easily degraded by microorganisms and had greater utilisation and conversion rate; therefore, it had certain effects on the soil TOC content (Xiang et al. 2010). Soil TOC, LFOC, and POC were negatively correlated with soil temperature, indicating that soil temperature was an important factor that affected the decomposition of soil organic matter. On the contrary, higher soil temperature leads to more intense microbiological decomposition and less TOC and active organic carbon accumulation, which is consistent with the results of Xu et al. (2008a, b).

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