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Dynamics of dissolved organic carbon in the mires in the Sanjiang Plain, Northeast China

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Abstract

Mires in boreal area had proved to be an important dissolved organic carbon (DOC) reserve for the sensitivity to climate change and human interfering. The study was focused on the temporal and spatial dynamics and controlling factors of DOC in a seasonally-waterlogged mire (SLM) and perennially-waterlogged mire (PLM) in the Sanjiang Plain, Northest China. In the two mires, DOC concentrations in both surface water and upper soil strata experienced pronounced seasonal variation. DOC concentrations in the surface waters were the greatest and averagely was 47.82 in SLM and 34.84 mg/L and PLM, whereas that in soil water at 0.3-m depth had little difference (20.25 mg/L in SLM and 26.51 mg/L in PLM). Results revealed that DOC concentrations declined 5–8 times vertically from the surface down to groundwater. DOC in the groundwater only was in a very small part with the average concentration of 5.18 mg/L. In relation to the surface water, DOC concentrations varied positively with temperature just before 8 August, and only in early spring and later autumn DOC concentrations exhibited identifiable spatial trends along with standing water depths in PLM. It was supposed that the influences from standing water depth took effect only in conditions of low temperature, and temperature should be the most powerful factor controlling DOC dynamics in the mires. Redox potential (Red) showed negative relationship with DOC values while total nitrogen (TN) and the majority of free ions in the soil solution exhibited no relationship. High soil TOC/TN ratio and low redox potentials also led to DOC accumulation in the mires in the Sanjiang Plain.

Key words: dissovled organic carbon; seasonal dynamics; mires; the Sanjiang Plain

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Introduction

Dissolved organic carbon (DOC) in natural wetlands is a complex mixture of compounds and comprises of a continuum of organic substances ranging from defined small molecules to highly polymeric humic substances (Thurman, 1985; Thackera et al., 2005). It is operationally defined as organic molecules that pass through a 0.45-μm filter. DOC fluxes are small compared to other carbon fluxes in the wetlands, but it has a number of important ecological and geochemical functions, especially in the processes of carbon balances (Kullberg et al., 1993; Arnostia and Holmer, 2003). The transportation of DOC in wetlands and rivers to marine regions constitutes a significant link in the global carbon cycle (Roulet and Moore, 2006).

It is increasingly recognized that persistently increased DOC concentration in catchment surface waters may lead to wide-ranging impacts on aquatic systems as reported in the UK upland and other sub-boreal settings (Bishop and Pettersson, 1996; Worrall et al., 2004; Evans et al., 2005). Wetlands in boreal area has been proved to be the most important but sensitive DOC reserve, and climate change and landscape drainage have been recognized the two decisive drivings controlling the dynamics of DOC both in and out of wetlands (Sommer 2006; Briggs et al., 2007). Uncompletely decomposed organic soils and vegetation litters of wetlands are main sources of allochthonous DOC to surface waters. Numbers of studies have demonstrated the biochemical processes of DOC production and transformation in wetlands (Gö and Niklas, 2004; Dawson et al., 2008). It indicated that DOC production was influenced by the quantity and quality of organic carbon, hydrological regimes as well as seasonal dymamics, and microbial activity was the key factor to the production rate and chemical composition (Ju et al., 2006; Catherine et al., 2008). Wetlands with different hydro-topographical features have disparate performances in DOC production and export, which resulting in difficulty to draw a universal conclusion. The dynamics of DOC in boreal wetlands are intricate and have not been well understood by far.

These conclusions mainly come from the research works on the peatlands or fens in Europe countries and North

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America, and limited studies have been reported in North China where is a large area of mire-wetlands, especially in the Sanjiang Plain. The objective of this study was to determine the temporal and spatial dynamics of DOC in different pools of mire-wetlands in the Sanjiang Plain. Two types of mires with different hydrological and soil features were surveyed and compared in detail to ensure valuable results. Climate parameters and hydrological regimes were also analyzed to investigate the controlling factors of the DOC dynamics, and the relationships with key nutrients and other biogeochemical parameters were also illustrated simultaneously.

1 Materials and methods

1.1 Site description

The Sanjiang Plain is located in the winter-cold zone in Northeast China and was formed by three major rivers of Heilong, Wusuli, and Songhua. Boreal climate conditions and low slope grade have led to the largest area of mire wetlands in North China. In the past 50 years, wetlands in the Sanjiang Plain have experienced a large scale of cultivation, and at present there are still 83.5×10^4 hm^2 wetlands. The study sites were located at the Sanjiang Mire-Wetland Experimental Station, Chinese Academy of Sciences (47°35′N, 133°31′E), in the floodplain between Bielahong River and Nongjiang River. This station experiences a mean annual temperature of 1.9°C and a mean annual precipitation of 600 mm. The coldest month was January with temperature –21.6°C and the warmest was July with 21.5°C (average temperature during 1981–2004).

There are two types of mires in the station, one is the seasonally-waterlogged mire (SLM) with *Salix brachypoda* as the predominant vegetation, another is the perennially-waterlogged mire (PLM) with *Carex lasiocarpa*. The distance between the two borders is less than 50 m. The standing water depth in the center of SLM ranged approximately from 0 to 0.5 m, while from 0.3 to 1.0 m in PLM. Droughts usually happen in mid-spring or late autumn, and water in SLM will be exhausted. Soils in both mires contain high proportion of organic carbon and covered by a layer of litters. More stable anaerobic environment make peat layer formed in PLM, and hence the bigger porosity and lower volume weight of top soils than in SLM. More information about the two mires is listed in Table 1. The water and soil are completely frozen from late October to the next April, and begin to melt in late April. Plants in the mire burgeon during the end of April and wilt in mid-October.

1.2 Samples collection

In 2008, water samples were collected in the morning from 12 May to 20 October three times a month in both mires along linear sampling transects. Five sampling sites with 20 m intervals were arranged in each transect from the border to the center of the mire. In each site of both mires, water samples from surface and soils at 0.3-m depth were collected in the same day. In SLM, samples from soils at 1.5-m depth and from groundwater at 10-m depth were also extracted (Fig. 1). Water samples were placed in 100 mL glass vials and sent to laboratory immediately. After 8 August, surface water in SLM was exhausted by evapotranspiration, thus the latter data for surface water were absent. In SLM, soil samples at 0.3-m depth in each site were also collected once a month around the tenth day for the analysis of soil DOC and TOC. In fact, only 19 soil samples were successfully collected in SLM through the entire study period. Soil samples in PLM were absent for the difficulty to be collected. Daily standing water depths and temperatures of soils and surface water were automatically recorded by a microclimate monitoring system through the study period.

1.3 Study methods

Water samples collected were filtered through 0.45-μm filters into separate vials, and were directly analyzed for DOC, total carbon (TC) and inorganic carbon (IC) with DOC analyzer (C-VCPH, Shimadzu, Japan). TC was measured by high-temperature combustion. IC was detected

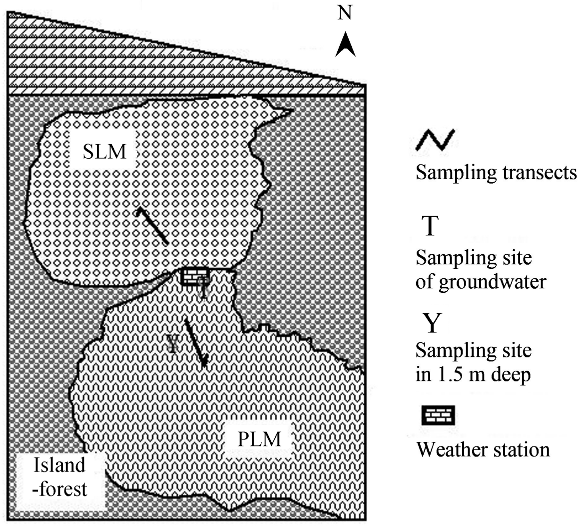

Fig. 1 Sketch map of the sampling transects and sites in the two mires.

Table 1 Comparison of ecological information between seasonally-waterlogged mire (SLM) and perennially-waterlogged mire (PLM)

	Predominant vegetation					Surface soil (0–0.3 m)			
	Type	AG-biomass[a] (g/m^2)	BG-biomass[b] (g/m^2)	Litter thickness (cm)	Bulk density (g/m^3)	Organic matter (g/Kg)	TN[c] (g/Kg)	Hydro-N[d] (g/Kg)	TP[e] (mg/Kg)
SLM	*Salix brachypoda*	269.5	20.8	10–20	0.55	226.49	8.47	0.54	15.53
PLM	*Carex lasiocarpa*	164.8	66.1	20–40	0.41	526.87	15.53	1.40	5.37

[a] AG-biomass: above-ground biomass (dry weight); [b] BG-biomass: below-ground biomass (dry weight); [c] TN: total nitrogen; [d] Hydro-N: hydrolyzable nitrogen; [e] TP: total phosphorus.

after sample acidification by 25% H_3PO_4 and 2 mol/L HCL and transformation to CO_2. DOC equals TC minus IC. As to soil samples, moist soil samples (equivalent to 10 g oven-dried weight) from the field were weighed into 40-mL lypropylene centrifuge tubes. The samples were extracted with 30 mL of distilled water for 30 min on an end-over-end shaker at approximately 230 r/min and centrifuged for 20 min at 8,000 r/min. All supernate was filtered through a 0.45-μm filter into separate vials for DOC analysis (Ghani et al., 2003). The soil TOC was determined by wet combustion.

In PLM, surface and soil water samples at 0.3-m depth from three days (7 June, 29 July and 8 September) were analyzed for pH, total nitrogen (TN), redox potential (Red), electric conductivity (EC) and the basic eleven ions (Cl^-, F^-, NO_3^-, SO_4^-, HCO_3^-, Na^+, K^+, Mg^{2+}, Cu^{2+}, Fe^{2+}, NH_4^+) with a series of automatic apparatuses. Red was measured *in situ* by ISTEK-P105 ORP Determinator (SMITH-BLAIR, Korea) when water sample was collected. Correlation analysis between these elements and DOC were conducted by SPSS 11.5 to find the factors that affected the distribution characteristics of DOC. Unless noted otherwise, statistical significance was set at the 95% level.

2 Results and discussion

2.1 Dynamics of DOC in the mires

There were significant seasonal trends in DOC concentrations of the surface and soil water at depth of 0.3 m in the both mires as shown in Fig. 2. It experienced a single apex of fluctuation of DOC through the whole growing season. In the two mires, DOC concentrations increased steadily since mid-May and reached the maximum values in the early August. The maximum values of surface water DOC in SLM and PLM were 67.97 and 51.42 mg/L, respectively, while that of DOC in soil water at 0.3-m depth were 52.39 and 50.90 mg/L correspondingly. Later, DOC concentrations began to decline rapidly with the advent of autumn and reached the minimum in mid-September almost synchronously. In the surface water, the average value of the DOC in SLM (47.82 mg/L) was remarkably higher than that in PLM (34.84 mg/L), whereas that in soil water at 0.3-m depth had little difference (20.25 mg/L for SLM and 26.51 mg/L for PLM). Although representing the same seasonal pattern, correlation analysis for DOC concentrations indicated that there was no remarkable linear relationship between the surface and soil water at 0.3-m depth in both mires. In addition, limited spatial variations in the DOC concentrations were observed in both mires in view of the standard errors of all the samplings, and the standard errors for the majorities were less than 7.5 mg/L.

Main DOC sources include partially degraded primary plant material (cellulose, lignin, etc.) along with the products of microbially-mediated decomposition, below ground tissue decomposition and soil carbon turnover (Scheffer and Aerts, 2000; Fenner et al., 2004). Secretions from living plants also form an important DOC source which represents a pool of readily degraded organic matter substrates, such as amino acids and sugars, and this DOC source mainly exists in the soil rhizosphere (Paterson et al., 1997). But there is scant information regarding the release and exudation of DOC by living *Salix brachypoda* and *Carex lasiocarpa* into surface water. Correlation analysis indicates that DOC of top 0.3-m soil has no relation with DOC in soil water (n = 19, p = 0.317), nor with DOC in surface water (n =13, p = 0.827) in SLM. As shown in Fig.

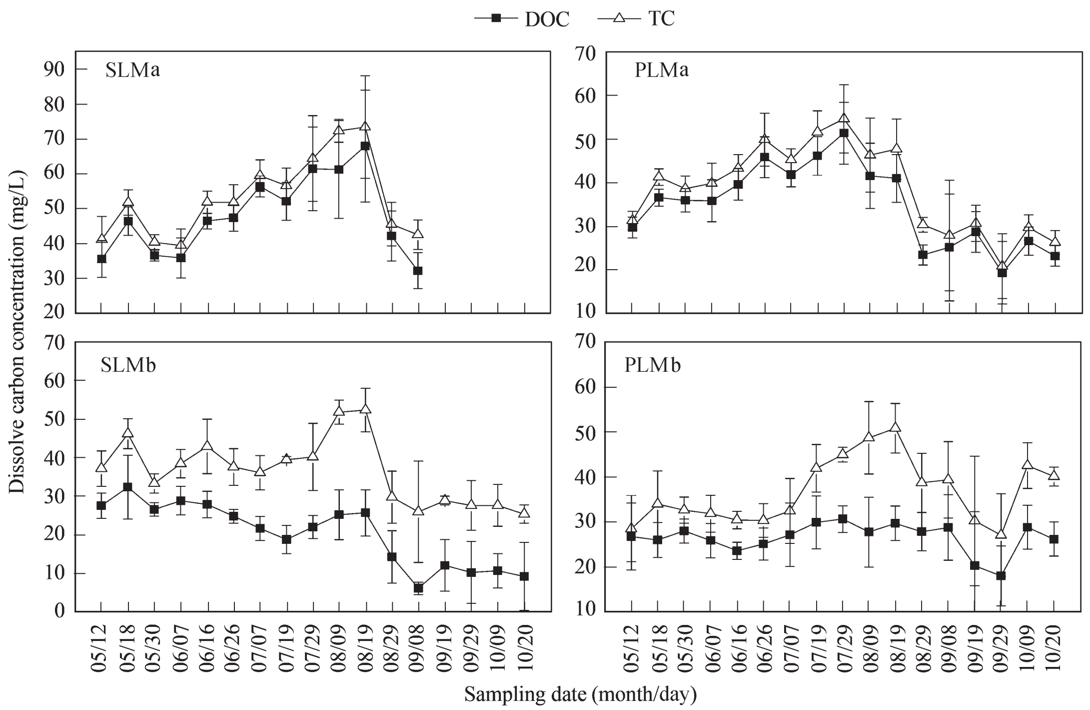

Fig. 2 DOC concentrations in two mires in the surface and soil waters at 0.3-m depth through the study period. (a) surface water; (b) soil water at 0.3-m depth.

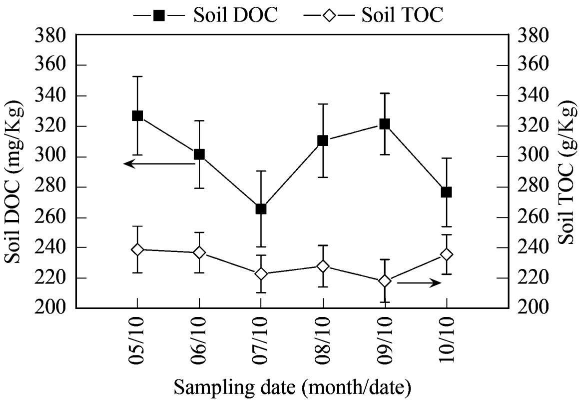

Fig. 3 Seasonal trends of TOC and DOC of top soil in SLM.

3, DOC of top soil reached its minimum on July 10, which reflected the disparate seasonal trends comparing with DOC in soil and surface water. TOC of top soil also had no correlation with DOC in soil water and surface water for TOC was correspondingly stable in the top soil. Therefore, the change of DOC and TOC in top soil could not directly explain the DOC dynamics in soil pore and surface water although they are the important DOC sources.

In both mires, the DOC concentrations in surface waters showed highly positive correlations with TC ($R > 0.975$) as well as in soil waters at 0.3-m depth ($R > 0.76$). Averagely, DOC took nearly 90% to TC in the surface waters while it reached 53.9% and 72.1% in the soil at 0.3-m depth for SLM and PLM, respectively. DOC was the main compound of the dissolved carbons in the most of mire-wetlands in the Sanjiang Plain. Besides of the high percentage to TC, the DOC proportion in surface water varied slightly through the entire growing season while that in the soil water at 0.3-m depth declined gradually, especially in SLM (Fig. 4). The phenomenon highlighted the inherent discrepancies between surface water and soil layers in organic carbon utilization and cycles in the mire ecosystems.

In SLM, DOC and TC from soil at 1.5-m depth and groundwater were also measured. As shown in Fig. 5, DOC concentrations in the two positions were much lower than the top layers, which, in the most of data, were below 10 mg/L. The depth of 1.5-m below the soil surface was just in the range of aquiclude with much lower content of organic carbon than upper soils, which would be a reason for lower DOC concentrations as well as in the deeper soil layers. In the soil water at 1.5-m depth, the higher DOC concentrations only last for half of month in the spring and then decreased dramatically to a very low level with smoother trend (Fig. 5a). In fact, the conversion was concurrent with frost-thaw process which was supposed to be the important period in DOC accumulation and consume in the boreal areas, and at the end of the process DOC usually experienced a change from high to low level (Grogan et al., 2004). In the groundwater of 10-m deep, DOC concentrations had maintained at lower level all the time except of a short-term small rise in the spring, and the average concentration was only 5.18 mg/L (Fig. 5b). As to the proportion to TC, DOC in the soil water at 1.5-m depth was about 77.8% on average while that in groundwater only 18% which proved that of the carbon cycle pattern inorganic carbon dominated in deep of mire soils in the study area.

Changes of the DOC concentrations along the vertical profile in SLM were remarkable (Fig. 6). From the surface to groundwater, DOC concentrations declined about 5–8 times and the most rapidly turnaround happened in the upper 1.5-m soils, which was a similar trend from June to October. Although there were no data from the soil layers deeper than 1.5 m in PLM, similar results could be conjectured from the fact that the uniform deeper soil properties extended across the whole experimental fields and direct hydraulic connections of groundwater were exist between the two neighboring mires. In PLM, DOC contents in deeper soil layers must be approximately equal to that in SLM. Therefore, the mire soils in the upper 1.5-m deep would be the most important space storing DOC and the key layer related to the exchange of dissolved carbons between soil and water pools.

2.2 Controlling factors of DOC distribution in the mires

2.2.1 Temperature

Temperature is the primary factor controlling the decomposition of organic carbon and bacterial metabolism in ecosystems, and hence closely associated with DOC dynamics (Fröberg et al., 2006). For samples in surface

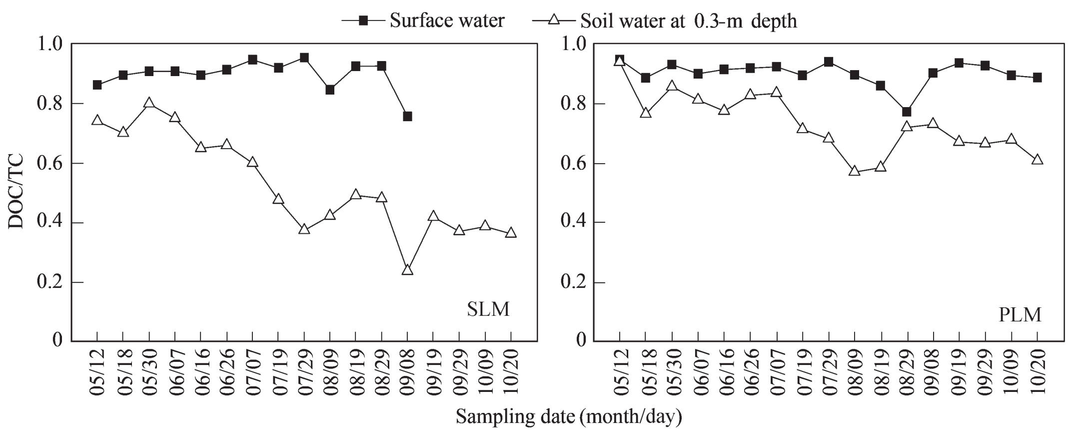

Fig. 4 Proportion of DOC to TC in surface and soil waters in SLM and PLM through the study period.

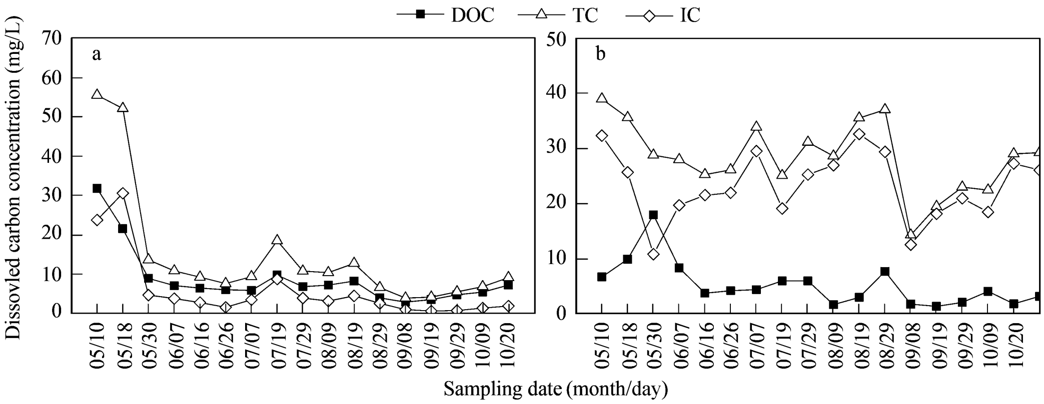

Fig. 5 Dissolved carbon concentrations in soil waters at 1.5-m depth and groundwater in SLM through the study period.

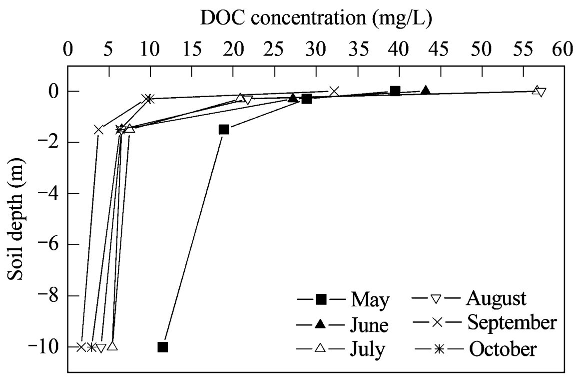

Fig. 6 Monthly vertical distribution of DOC concentrations in SLM.

waters and soil waters at 0.3-m depth, there was no obvious relationship between DOC concentrations and daily water or soil temperature when the data in the entire study period were taken into account. But the DOC concentrations before 8 August, when were in the increasing stage, exhibited pronounced positive correlations with average temperature of the day before sampling for the surface waters in both mires and for the soil water only in PLM (Fig. 7). The different results for the soil waters between the two mires might come from the discrepancies of soil content of organic carbon and hydraulic connection with surface water. Soils in PLM took more advantages in the two aspects which would lead to the consistent result with surface water. In the declining stage after August, DOC in all sites put up a more sharpen descending trend than water temperature with accelerative declining began from September. To sum up, the influences of temperature on DOC were supposed to be time-limited and more effectual to surface water. Not all the seasonality of the DOC could be explained by temperature. Mann and Wetzel (1995) had also confirmed that the relationships varied greatly with different positions even in the same riparian wetland, and it was more difficult to be understood than as expected.

2.2.2 Standing water depth

Fluctuation in standing water levels was the key hydrological process in mires and other riparian wetlands to control the source or sink for nutrients and DOC (Lilian and Gljnter, 2001). On the sampling transect of PLM, water depth ranged from 30 to 100 cm from the bounder to the center. The monthly changes of DOC concentra-

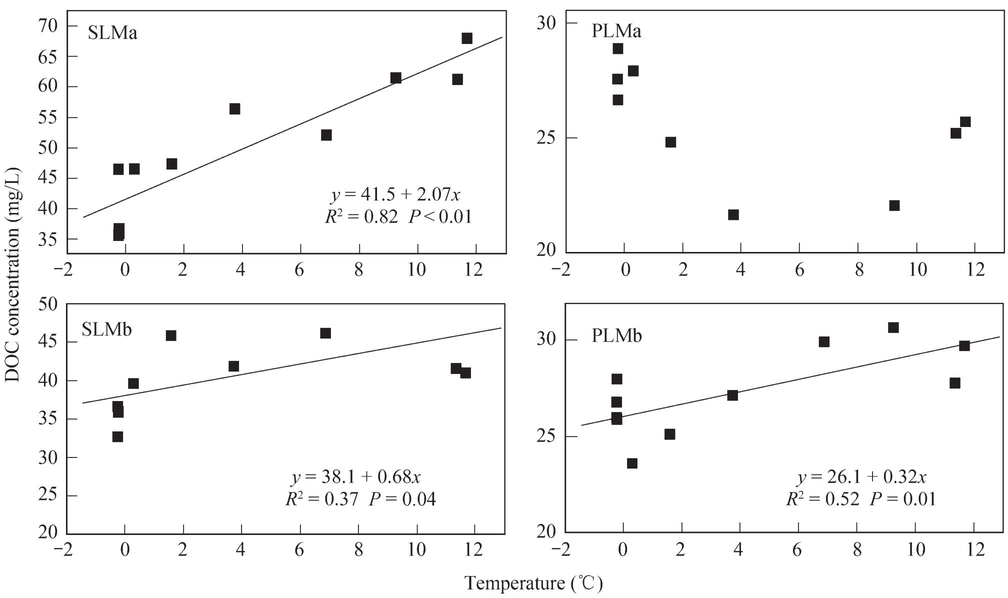

Fig. 7 Relationship between DOC concentrations and average temperature of the day before sampling. a: surface water; b: soil water at 0.3-m depth.

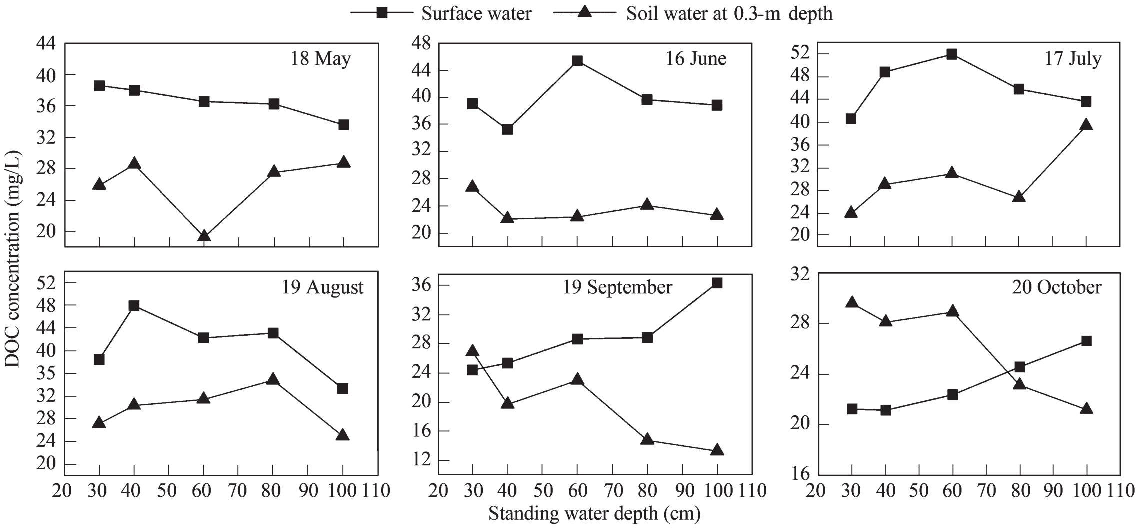

Fig. 8 Relationship between DOC concentrations and standing water depth along the sampling transect in PLM.

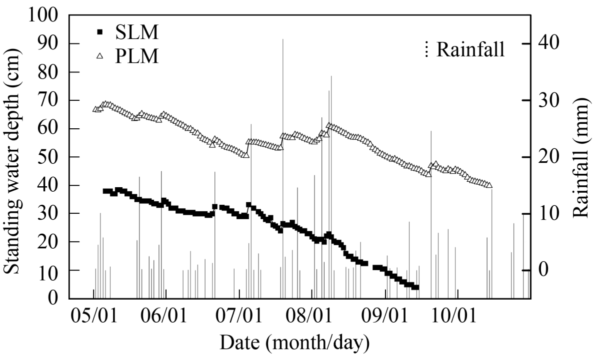

Fig. 9 Standing water depths of SLM and PLM and rainfall during the study period. Standing water depths were measured in the middle of the two sampling transects.

tions with water depth along the transect are shown in Fig. 8. As a whole, no pronounced spatial change was observed, which was consistent with the study of Xi et al. (2007) in the same area. Only in early spring and later autumn, DOC showed identifiable spatial trends changing with water depths. Along the transects, the surface DOC concentrations declined slowly in mid-May but raised in mid-September and October, whereas DOC in the soil waters showed opposite tendency correspondingly. The opposite responses to water depths from surface water and top soils confirmed further the discrepancies of dissolved carbon cycles between water and soil pools. In the whole summer, it was no direct relationship between DOC concentration and water depth. Standing water depths worked effectually only in conditions of low temperature in spring or autumn, hence it could be inferred that temperature was more powerful factor controlling DOC dynamics in the top layer of mires.

As a matter of fact, standing water depth was the most significant difference in the ecological factors between SLM and PLM. Snow melt in spring and rainfalls in summer were the main water sources to the mires, and the average standing water depth in PLM was averagely 30 cm higher than that in SLM through the study period (Fig. 9). Hydrological condition of perennially-waterlog in PLM had resulted in a much higher soil organic carbon content than in SLM as shown in Table 1. Nevertheless, DOC content in surface water showed opposite direction. Two reasons could perhaps explain this phenomenon: (1) organic carbon content was no longer the limiting factor in the condition of overmuch supply of organic matter in both mires, and the ratio of C/N in soil (15.5/1 in SLM, 19.7/1 in PLM) was more important to the production of DOC; (2) a higher standing water depth would dilute DOC content and bring down the average temperature of surface water. Differences in DOC content between the two mires caused by many complicated ecological processes, and more detail researches were needed to reveal the puzzle.

2.3 Relationships between DOC and other variables

The mobility through soil-water surface and microbial availability of the DOC in mires were most related to the characteristics of the basic biogeochemical elements in solutions and other environment variables (Catherine et al., 2008). Although DOC mobility was greatly related to pH as previously indicated (Sommer, 2006), DOC concentrations had no relationship with pH in our samples. The fact is that pH values of surface water and upper soils were consistent and changed little (5.54–6.29) through the period. The redox potentials with minimum value –264, had negative relationship with DOC concentration. It was proved again that the redox condition controlled by the waterlogging was most essential in the biogeochemical processes of organic decomposition and transformation in the mires. Under the lenitic condition of mires like in PLM, biogeochemical variables should be more important to DOC dynamics than the hydrological processes. Some ions including Fe^{2+}, HCO_3^- and Cl^- also had significant relationships with DOC (Table 2). Relationships between DOC concentrations and TN concentrations were also rather weak, which was a consilient conclusion with Xi *et al.* (2007). Actually, in the study region, there were generally low free ions and TN concentrations which might restrict their contents in DOC. High TOC/TN ratio in top

Table 2 Correlations between DOC and the elements in surface and soil waters in PLM

	Cl^-	NO_3^-	HCO_3^-	K^+	Mg^{2+}	Cu^{2+}	Fe^{2+}	TN	Red	pH	EC
DOC	0.58	–0.561	–0.756	–0.076	0.228	0.359	0.518	0.375	–0.692	–0.183	0.411
Significance (2-tailed)	0.026	0.091	0.00	0.758	0.348	0.131	0.019	0.083	0039	0.883	0.73
Significance level	0.05	–	0.01	–	–	–	0.05	–	0.05	–	–
n	27	27	27	27	27	27	27	27	27	27	27

soils, usually more than 15.5/1, was an outstanding feature of the mires in the Sanjiang Plain, and it was another important reason for the accumulation of organic substances in the boreal mires besides the lower temperature.

3 Conclusions

Mires in the study area were the most important sources of DOC which experienced pronounced seasonal variation in both seasonally-waterlogged and perennially-waterlogged mires. The DOC concentration was the greatest in the surface water and was averagely 47.82 and 34.84 mg/L in SLM and PLM, respectively, during the growing season. Vertically, DOC concentrations declined form the surface to groundwater, and the upper soils layers above 1.5-m depth were the uppermost storage of DOC in the mires.

The DOC production from organic soils and litters were mail related to the seasonal dynamics, and were controlled by the hydrological conditions and temperature as well as availability of nitrogen and other nutrients. But the influences on DOC from the hydrologic conditions and temperature exited remarkable seasonality and were rather complicated. As to the surface water, DOC concentrations varied positively with temperature before 8 August, and in early spring and later autumn. DOC showed identifiable spatial trends changing with standing water depths in PLM. It seemed that actions from water depth came to the surface only in the condition of low temperature. Temperature should be the most powerful factor controlling DOC dynamics in the mires of boreal area, but not effectual all the time through the growing season. The redox potential showed a negative relationship with DOC values while TN and the majority of free ions. In addition, high soil C/N ratio (TOC/TN) and low redox potentials would be the important factors leading to DOC accumulation in the mires in the Sanjiang Plain.

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