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Impacts of natural wetland degradation on dissolved carbon dynamics in the Sanjiang Plain, Northeastern China

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SUMMARY

Wetlands are important dissolved organic carbon (DOC) reservoirs, and principal sources of DOC to the fluvial environment, constituting a significant linkage between land and ocean in the context of global carbon cycle. The Sanjiang Plain, a floodplain in Northeastern China that encompasses numerous natural freshwater wetlands, has been experiencing extensive building of drainage ditches and thus elevated degradation of wetlands. This paper investigated DOC, dissolved inorganic carbon (DIC), and dissolved total carbon (DTC) in soil, the surface ponding and rivers from natural wetlands and the degraded wetland, and also in an artificial drainage ditch in the Sanjiang Plain during the growing season (May to October) of 2009. Seasonal averaged DOC concentrations were greater in soil and the surface ponding of the degraded riparian wetland than those originating from the natural riparian wetlands (i.e. Bielahong, Yalv and Nongjiang riparian wetlands). Seasonal averaged DIC concentrations in the surface ponding of the degraded wetland increased by 1.76, 0.59 and 2.05 times, compared to those in the Bielahong, Yalv and Nongjiang riparian wetlands, respectively. Similar to dissolved carbon dynamics in the field sites, the seasonal averaged DOC concentration in the degraded marshy river showed higher value (10.36 ± 1.99 mg/L), compared to those in the pristine marshy rivers. Seasonal DIC concentrations followed a trend as the degraded marshy river (15.09 ± 2.43 mg/L) – the artificial ditch (12.52 ± 1.61 mg/L) – pristine marshy rivers on average (8.53 ± 0.96 mg/L). Seasonal mean DTC concentration in the artificial ditch showed higher values than that in the natural marshy rivers, while seasonal mean DTC concentration in the degraded marshy river was greater than that in the artificial ditch. Further, seasonal DOC and DIC dynamics were similar in the artificial ditch and the degraded marshy river. These qualitative changes in the dissolved carbon dynamics in our study might have important implications that the impact of building of artificial ditches on dissolved carbon of waters more fully reflected in increases of dissolved carbon resulting from wetland degradation rather than increases in the artificial ditch itself.

1. Introduction

Dissolved organic carbon (DOC) is an important component of ecosystem carbon cycling (Kalbitz et al., 2000; Royer et al., 2007). DOC is involved in many processes such as mobilizing trace metals and hydrophobic contaminants (Bhatt and Gardner, 2009), reducing in-stream light penetration, and has the potential to produce carcinogenic trihalomethane compounds in chlorinated water treatment (Kneale and McDonald, 1999). Increases in the concentration of DOC in surface water are now a widely reported phenomenon in sub-boreal settings (Worrall and Burt, 2008)., such as rivers in both North America (Driscoll et al., 2003; Stoddard et al., 2003) and Central Europe (Hejzlar et al., 2003). Several mechanisms have been proposed to explain these increases including increasing air temperature (Freeman et al., 2001), occurrence of severe drought (Worrall and Burt, 2004), increases in atmospheric CO_2 (Freeman et al., 2004), and changes in atmospheric composition (Evans et al., 2005). Land-use change represents the most substantial human alteration of the Earth system in the past 300 years (Vitousek et al., 1997). It might also potentially exert a tremendous effect upon dissolved carbon dynamics of waters. However, the impact of land-use change on dynamics of DOC in rivers is still largely unknown (Wilson and Xenopoulos, 2009), although it has been reported that agricultural land use can increase the delivery of other nutrients such as nitrogen and phosphorus to fluvial ecosystems (Carpenter et al., 1998). Thus, it is an essential issue to further explore the effect of land-use change on dissolved carbon dynamics of rivers.

Natural wetlands, especially those in mid-high latitudes, store large amounts of carbon (Post et al., 1982; Briggs et al., 2007),

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and the loss of DOC has been shown to be important for ecosystem carbon budgets (Roulet et al., 2007; Strack et al., 2008) and carbon pools in rivers (Wallage et al., 2006; Dawson and Smith, 2007; Baker et al., 2008). However, the increasing levels of environmental changes and human activities could affect the sustainability of natural wetlands, such as the dynamics of DOC changes. A significant threat to the sustainability of natural wetlands has been the degradation associated with the installation of open cut drainage ditches (Holden et al., 2004). For example, artificial drainage was introduced in UK blanket peatlands to lower the water table in an attempt to improve the productivity of the land for grazing and reduce downstream flood risk by establishing a moisture deficit (Holden, 2006; Wallage et al., 2006). In addition to several negative environmental problems, changes of DOC dynamics associated with drainage of wetlands and drain blocking have been observed in some of the catchments in UK (Wallage et al., 2006; Worrall et al., 2007). These conclusions, however, has been less reported in other sites around the world, especially in China.

The Sanjiang Plain, a floodplain in Northeastern China that encompasses the largest natural freshwater wetlands (Zhao, 1999), has been experiencing extensive human activity and land conversion to paddy lands and uplands over the past 50 years (Liu et al., 2005a,b). With intensively marsh reclaiming, a large number of ditch systems were built to discharge standing water so as to transform wetlands into arable land. In this way, large tracts of wetlands in the Sanjiang Plain that were drained have been degrading due to the decrease of standing water depth and input of nutrients during the agricultural activities (fertilizer, pesticide application etc.). The ditches are now used as channels to output the overflow from paddy field during the whole growing season of rice plant. Thus, the dynamics of dissolved carbon in this region can affect the carbon pools in the Amur River and even the Sea of Okhotsk in the northwest of North Pacific, as the Sanjiang Plain is located in the Amur River Basin, the world's ninth longest river. Therefore, it is critically important to track the dissolved carbon dynamics in surface water in the Sanjiang Plain, to evaluate the ecological impacts of building of artificial drainage ditches on the adjacent rivers.

The objectives of this study were (1) to determine the effects of artificial ditch establishment and the associated wetland degradation on DOC dynamics in surface ponding and rivers originating from both natural wetlands and degraded wetlands in the Sanjiang Plain, Northeastern China, (2) to test whether there are differences in DOC chemistry through the determination of specific ultra-violet absorbance index ($SUVA_{254}$) that is suggested as an index of the aromaticity of the DOC (Weishaar et al., 2003), and (3) to monitor DIC dynamics, an important part of dissolved carbon in fluvial ecosystems, which is less frequently measured (Baker et al., 2008) but has also been shown to be increasing in some rivers, such as the Mississippi river (Raymond and Cole, 2003; Raymond et al., 2008) and some urbanized catchments of UK (Baker et al., 2008).

2. Materials and methods

2.1. Study area and catchments

The Sanjiang Plain (43°49′55″–48°27′56″N, 129°11′20″–135°05′10″E), formed by the three major rivers of Amur, Ussuri, and Songhua Rivers, is located in the eastern part of Heilongjiang province, Northeastern China. The mean annual precipitation is around 600 mm and the mean annual temperature is 1.91 °C. Water and soil in marshes are completely frozen from late October to the following April and begin to melt in late April. The boreal climate conditions and low slope grade have made the largest area of freshwater wetlands in China. The major soil types in the Sanjiang Plain are albic soil, meadow soil and marsh soil and major natural vegetations vary from *Deyeucia angustifolia* to *Carex lasiocarpa* as the standing water level increases. The drainage and use of marshes for agricultural fields such as paddy land and upland occurred in the past 50 years, resulting in the apparent decrease in natural wetlands from about 3.53×10^6 h m^2 in 1954 to 0.96×10^6 h m^2 in 2005 (Song et al., 2008).

In this study, five catchments in the Sanjiang Plain were chosen (Fig. 1). There were three pristine marshy rivers originating from natural wetland, Yalv. River (Yalv. R), Nongjiang. River (Nongjiang.

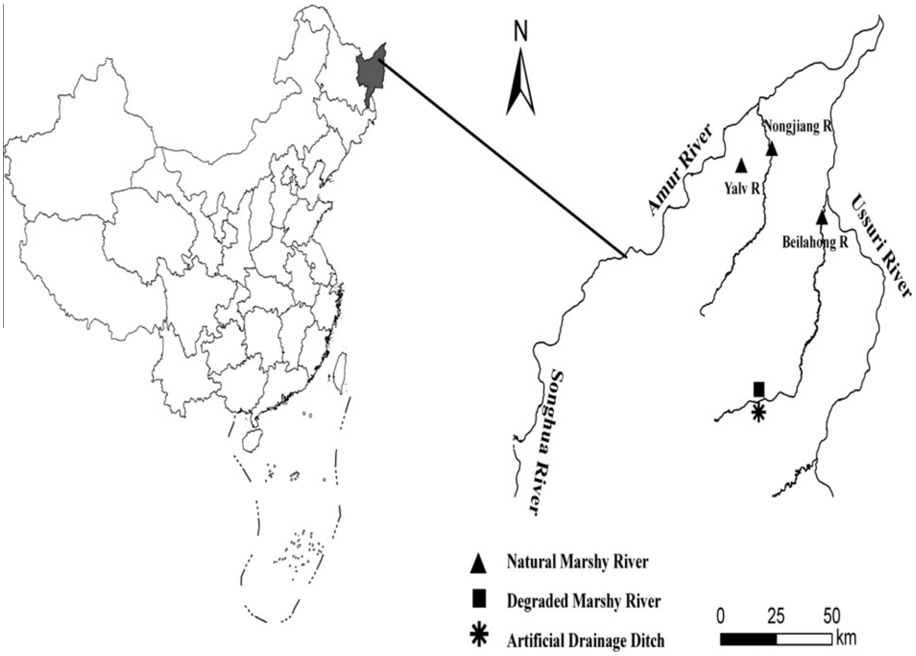

Fig. 1. Map of the sampling sites for the degraded and pristine marshy rivers, and the artificial ditch in the Sanjiang Plain, Northeastern China.

R) and Bielahong. River (Bielahong. R); one artificial drainage ditch-Bielahong. Ditch, which is the largest farmland drainage canal system in the Sanjiang Plain; and one degraded marshy river originating from degraded marsh.

2.2. Water samples collection and analysis

From May to October in 2009, surface water samples were collected for degraded marshy river, pristine marshy rivers and the artificial ditch. From the natural and degraded wetlands, surface ponding samples were simultaneously collected in three replicates during June to October. The samples were transported to laboratory and were filtered through 0.45 μm filters immediately with the first 100 mL of each sample to rinse the filter and discarded for three times, then the remaining were filtered into separate vials without any head space to minimize degassing. The water samples were analyzed for DOC, DTC and DIC with the Multi N/C 2100 Analyzer (Analytik Jena AG, Germany) using a non-dispersive infrared detector to quantitatively measure CO_2 levels. DOC concentrations were determined by DTC minus DIC. The standards for DTC were prepared from reagent grade potassium hydrogen phthalate in ultra-pure water, while DIC standards were prepared from a mixture of anhydrous sodium carbonate and sodium hydrogen carbonate. Each sample was injected at least two times to obtain a standard deviation of $\leqslant 2\%$.

2.3. Soil and litter sampling

We collected samples of litter and topsoil (0–20 cm) from the degraded and the natural riparian wetlands corresponding to the above rivers at the end of the growing season in mid-October (three soil profiles on each plot). In the laboratory, roots and gravel were removed from litter and soil samples, which further were crushed and sieved through a 2-mm screen. For extraction of DOC, 10 g of solid matter in three replicates were added by distilled water to soil ratio 3:1 (v:w) in tubes. The tubes were shaken for 30 min on an end-over-end shaker at 30 rpm. Then the tubes were centrifuged for 10 min at 8000 rpm. Filtering (0.45 μm) followed extraction immediately (Ghani et al., 2003). The extracts were analyzed for DOC using the Multi N/C 2100 Analyzer (Analytik Jena AG, Germany) as described above. Air-dried soil and litter samples were also analyzed for total organic carbon (TOC) by the Solid Module of Multi N/C 2100 Analyzer in oven furnace at 1100 °C.

2.4. Determination of $SUVA_{254}$ (specific ultra-violet absorbance index)

$SUVA_{254}$ is defined as the UV absorbance at 254 nm divided by the DOC concentration measured in milligrams per liter (mg/L), and is reported in units of L/(mg m) (Weishaar et al., 2003). $SUVA_{254}$ has been suggested as an index of the aromaticity of DOC and changes with differences in the chemical composition of DOC (Peichl et al., 2007). UV measurements were made on a UV-7504 spectrophotometer using distilled water as a blank. A quartz cell with a 1.0-cm path length was used. The absorbance readings at 254 nm were converted to standardized measurements of absorbance units per metre (au m^{-1}) by multiplying the liquid cell width, following the procedure of Weishaar et al. (2003).

2.5. Statistical analysis

The SPSS 11.5 and Origin 7.5 statistical packages were used in the statistical analysis. The difference in DOC, $SUVA_{254}$ and DIC among different sites tested by repeated measures ANOVA. In analyses where $P < 0.05$, the comparisons were considered statistically significant.

3. Results

3.1. Concentration of dissolved carbon in litters and soil

As shown in Table 1, DOC concentration in 0–20 cm topsoil of degraded riparian wetland was significantly higher compared to those of the naturally riparian wetlands ($P < 0.05$). Apparent differences were also found among all the three naturally riparian wetlands possibly due to different organic matter accumulation and hydro-climatic regimes among them. However, no significant differences were observed among the three naturally riparian marshes ($P > 0.05$).

Concentrations of DOC in litters of the studied plots varied within the range from 4.41 to 7.02 g kg^{-1} with no significant differences between naturally riparian and the degraded wetlands. However, DOC concentration in the litter of the degraded riparian wetland was higher than the naturally riparian wetlands. Calculated as percentage of TOC in litters, the ratio of DOC to TOC ranged from 0.96% to 1.59%, and the mean value from the degraded marsh was higher than that of the naturally riparian marshes.

3.2. Seasonal variation of dissolved carbon in surface ponding

Fig. 2 shows the seasonal patterns of DOC and DIC dynamics by month in surface pondings of naturally and degraded riparian wetlands. For the four field sites, monthly DOC concentrations peaked at the beginning of the growing season (June), except Bielahong riparian wetland which showed the highest value in August. The averages of DOC concentrations were 16.02 ± 4.00 mg/L, 9.61 ± 1.07 mg/L, 14.21 ± 2.45 mg/L and 15.96 ± 5.88 mg/L for the surface ponding of degraded, Bielahong, Yalv and Nongjiang riparian wetlands, respectively, with the highest seasonal mean value

Table 1
Characteristics of dissolve carbon dynamics in 0–20 cm topsoil and litters under different types of riparian wetlands in the Sanjiang Plain, Northeastern China.

Plot	Soil	Litter	
	DOC (mg/kg)	DOC (g/kg)	DOC/TC (%)
Degraded R. wetland	86.49 (±4.05)	7.02 (±0.97)	1.59
Yalv R. wetland	37.13 (±5.76)	5.65 (±0.44)	1.23
Nongjiang R. wetland	46.53 (±8.30)	6.27 (±0.47)	1.43
Bielahong R. wetland	57.19 (±6.52)	4.41 (±0.13)	0.96

Values expressed as mean (mean ± SE).

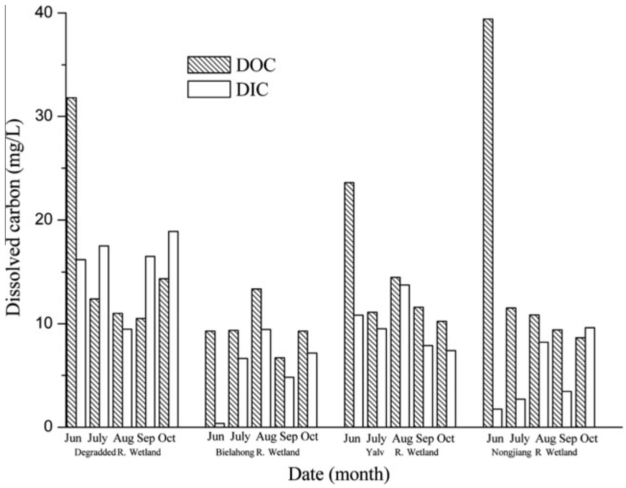

Fig. 2. Seasonal dynamics of dissolved carbon concentrations in the surface ponding under degraded and naturally riparian wetlands in the Sanjiang Plain.

occurring at the degraded site. However, no significant seasonal differences were found for DOC between the surface pondings from degraded and naturally riparian wetlands. From June to October, DIC concentration in the surface ponding of the degraded wetland fluctuated between 9.48 mg/L and 18.88 mg/L, while DIC in surface ponding of naturally riparian wetlands showed lower values with ranges of 0.35–9.45 mg/L for Bielahong riparian wetland, 7.41–13.74 mg/L for Yalv riparian wetland, and 1.75–9.61 mg/L for Nongjiang riparian wetland, respectively. Seasonal mean values of DIC concentrations were 15.71 ± 1.63 mg/L (the degraded site), 5.69 ± 1.53 mg/L (Bielahong. site), 9.88 ± 1.14 mg/L (Yalv. site) and 5.15 ± 1.57 mg/L (Nongjiang. site). Wetland degradation enhanced DIC concentration by 1.76, 0.59 and 2.05 times, compared to Bielahong, Yalv and Nongjiang riparian wetlands, respectively. Significant differences in DIC concentrations were found between the surface pondings from degraded riparian wetland and Bielahong, Yalv, Nongjiang riparian wetlands ($P = 0.000$; $P = 0.013$; $P = 0.000$). Overall, both DOC and DIC concentrations were higher in the surface ponding from degraded riparian marsh than those from naturally riparian marshes.

SUVA$_{254}$ in the surface ponding of degraded and Bielahong riparian wetlands showed large variations during the whole observed time, while seasonal patterns of SUVA$_{254}$ in the surface ponding of Yalv and Nongjiang riparian wetland changed more slowly (Fig. 3). Significant difference in SUVA$_{254}$ was observed between the surface pondings from the degraded riparian wetland and the Yalv. riparian wetland ($P = 0.034$), while no significant differences were found among the other sites ($P > 0.05$). The seasonal mean SUVA$_{254}$ was clearly lower in the surface ponding of the degraded riparian wetland (3.10 ± 0.28 L/mg m) than that in the natural riparian wetlands (3.20 ± 0.30, 3.82 ± 0.09 and 3.61 ± 0.12 L/mg m), suggesting that aromatic carbon content of DOC was less in the surface ponding from degraded wetland than that from natural ones. It implied that although wetland degradation resulted in higher DOC concentration in surface ponding, the increased DOC showed higher instability.

3.3. Seasonal variations of dissolved carbon in rivers and the artificial ditch

As shown in Fig. 4, seasonal patterns of DOC concentrations in the artificial ditch were similar to that in the degraded marshy river. In the two sites, DOC concentrations peaked in May when extra water from rice paddy drains intensely, and then showed an apparent decrease, with the lowest value occurring in September for the artificial ditch and in August for the degraded marshy river. For the three pristine marshy rivers, seasonal DOC dynamics showed inverted v shape with the vertex occurring in July for Bielahong. R and Yalv. R, and in August for Nongjiang. R, while the nadir occurred in May for Yalv. R and Nongjiang. R, and in September for Bielahong. R. The highest and lowest values for DOC concentrations in the five sites were 19.15 mg/L in May and 1.87 mg/L in September, and they both appeared in the artificial ditch. As shown in Table 2, seasonal mean DOC concentration in the artificial ditch (8.21 ± 2.44 mg/L) was lower than that in the Bielahong. R (9.28 ± 0.89 mg/L) and Yalv. R (9.44 ± 1.53 mg/L), but higher than that in the Nongjiang. R (7.17 ± 0.82 mg/L), while mean DTC concentrations in the three pristine marshy rivers all showed lower values than that in the artificial ditch. Compared to the other sites, the seasonal averaged DOC concentration in the degraded marshy river showed the highest value (10.36 ± 1.99 mg/L).

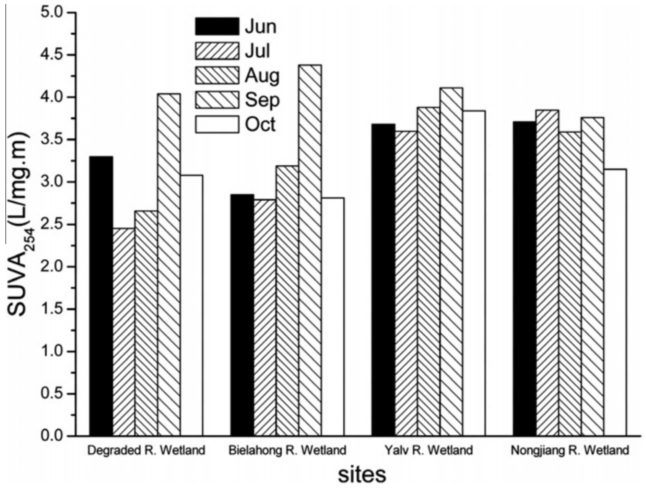

Fig. 3. Seasonal dynamics of SUVA$_{254}$ in surface ponding under degraded and naturally riparian wetlands in the Sanjiang Plain.

Seasonal fluctuations of DIC concentration in the degraded marsh river showed different patterns compared to those in the pristine marshy rivers, while it appeared almost the same trends with that in the artificial ditch, with the lowest values occurring in August and the highest values in June. No significant differences were observed between the artificial ditch and degraded marshy river, and between the artificial ditch and the naturally marshy rivers ($P > 0.05$), while significant differences in DIC concentrations were found between the degraded marshy river and Bielahong. R and Nongjiang. R ($P = 0.014$; $P = 0.003$). Furthermore, the seasonal mean DIC concentrations in the artificial ditch and the degraded marshy river both showed higher values than those in the three natural marshy rivers. The highest value for DIC concentration among the five sites was detected in the degraded marshy river in June (21.23 mg/L), while the lowest value was 3.74 mg/L which occurred in the Nongjiang.R in July. The decreasing order of averaged seasonal DIC concentration was the degraded marshy river (15.09 ± 2.43 mg/L) – the artificial ditch (12.52 ± 1.61 mg/L) – naturally marshy rivers on average (8.53 ± 0.96 mg/L) (Table 2). To quantify the distribution of DIC and DOC in DTC, we took the ratio of DIC to DTC. As shown in Table 2, DIC/DTC was 60.11% and 63.86% for the degraded river and the artificial ditch, respectively, while it ranged from 46.83% to 51.59% for the pristine marshy rivers.

The seasonal patterns of SUVA$_{254}$ throughout the observation period for the five sites showed almost the same trends for the sites of degraded marshy. R, Bielahong. D and Bielahong. R (Fig. 4). In the three sites, SUVA$_{254}$ increased from the beginning of the growth season, peaked at August or September, and then showed downward trends. The maximum value of SUVA$_{254}$ was 7.47 L/mg m appearing in the artificial ditch, while the minimum value was only 2.25 L/mg m that also occurred in the artificial ditch. Further, the seasonal averaged SUVA$_{254}$ in the artificial ditch showed the highest value, compared to that in the degraded and pristine marshy rivers. To quantify the seasonal variation of SUVA$_{254}$, we took the coefficient of variance (CV) as the index. In the five sites, the highest CV existed for SUVA$_{254}$ from the artificial ditch (46.97%), followed by the degraded marshy river (36.01%), while the lowest CV was 13.94% occurring for Nongjiang river. It suggested that the chemical structure of DOC in surface water from the artificial ditch showed the strongest seasonal variation, followed by Yalv. R, Nongjiang. R, and the degraded marshy river. DOC in Bielahong. R had the most stable chemical structure during the whole growing season.

4. Discussion

In our study, substantial variations in dissolved carbon were observed between the degraded wetland site and the natural wetland

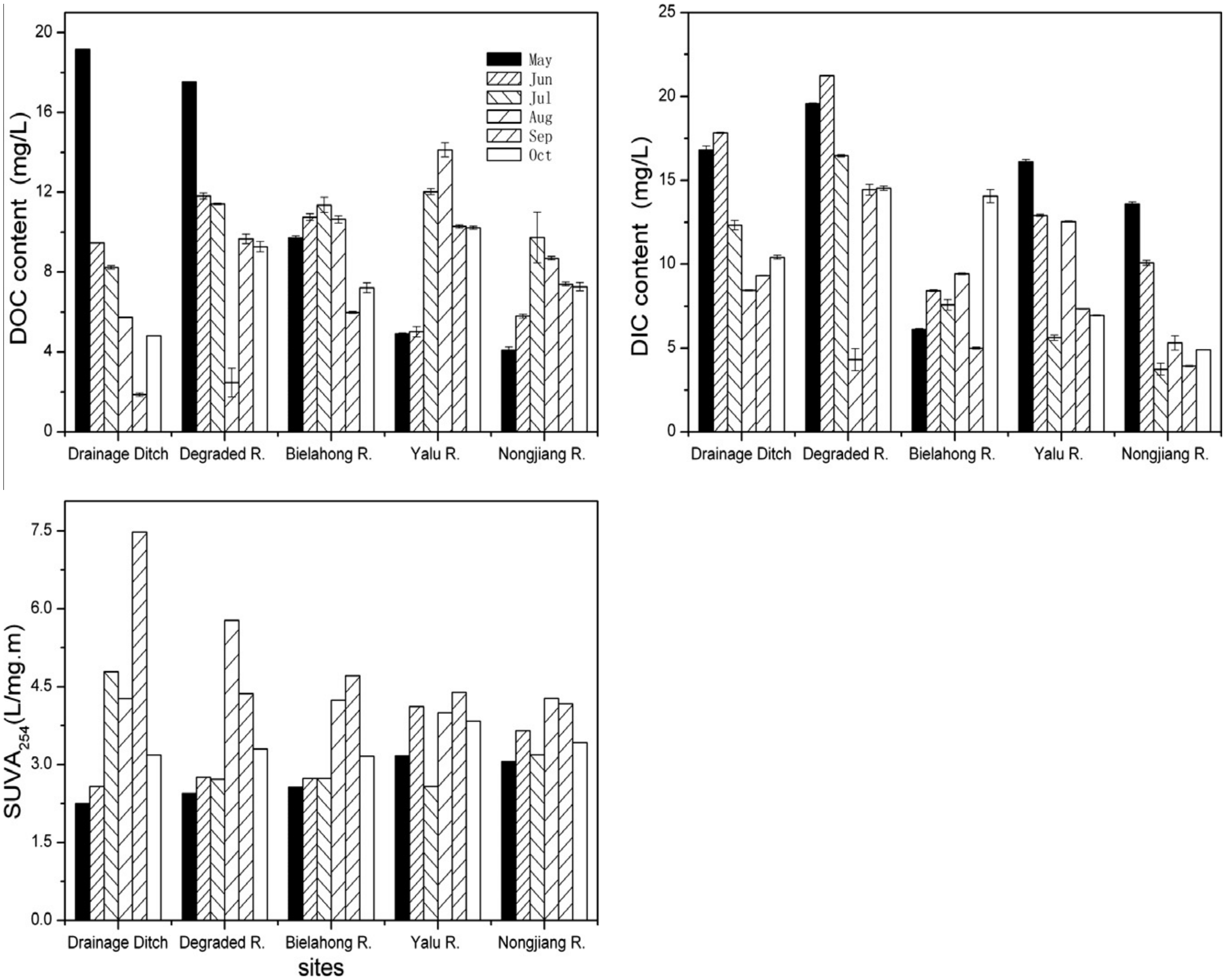

Fig. 4. Seasonal dynamics of DOC, DIC and $SUVA_{254}$ in the degraded and pristine marshy rivers, and the artificial ditch in the Sanjiang Plain.

Table 2
The distribution characteristics of dissolved carbon in marshy rivers, degraded river and the artificial ditch in the Sanjiang Plain.

Types	Location	DTC	DOC	$SUVA_{254}$	DIC	DIC:DTC
Artificial ditch	Bielahong. D	20.74 (3.83)	8.21 (2.44)	4.09 (0.78)	12.52 (1.61)	63.86% (0.05)
Marshy river	Bielahong. R	17.71 (1.53)	9.28 (0.89)	3.36 (0.37)	8.43 (1.30)	46.83% (0.04)
	Yalv. R	19.68 (1.51)	9.44 (1.53)	3.68 (0.28)	10.24 (1.71)	51.59% (0.07)
	Nongjiang. R	13.99 (0.99)	7.17 (0.82)	3.63 (0.21)	6.93 (1.64)	47.08% (0.08)
Degraded marshy. R	Qianfeng Farm	25.46 (4.29)	10.36 (1.99)	3.56 (0.52)	15.09 (2.43)	60.11% (0.02)

DOC, DIC and DTC were measured in mg/L; $SUVA_{254}$ was measured in L/(mg m).

sites. Seasonal averaged DOC concentration in the degraded marshy river was much higher compared to that in both the intact marshy rivers and the artificial ditch. It indicated that wetland degradation in the Sanjiang Plain might lead to an increased loss of DOC from wetlands and then enhanced the output of DOC to Amur River. This corroborates well with the findings of (Wallage et al., 2006) who demonstrated that wetland degradation caused by installation of artificial drainage ditches in the UK resulted in significant increased loss of DOC in catchment waters. In particular, the averaged values of DTC from the artificial ditch in our study were higher than that in the natural marshy rivers, while the averaged DTC in the artificial ditch was lower than that in the degraded marshy river. It implied that impacts of farming activities on riverine dissolved carbon dynamics more fully reflected in increased loss of dissolved carbon through waters resulting from wetland degradation. The seasonal mean $SUVA_{254}$ in the artificial ditch showed the highest value. It demonstrated that DOC at the artificial ditch contained significantly more aromatic carbon for every carbon unit (e.g. per mg C) than that at the natural or degraded sites, which implied that DOC sampled in water of the artificial ditch was obtained from a more aromatic source than the other sites.

DIC/DTC in the rivers and artificial ditch in our study ranged from 46.83% to 63.86%, demonstrating that DIC was an abundant specie of the waters we sampled in the Sanjiang Plain. Baker et al. (2008) has similar findings that with the exception of peat-rich headwaters, DIC concentration from various British rivers was always greater than DOC, with the highest DIC concentrations occurring in highly urbanized catchments. In our study, seasonal averaged DOC/DIC in the natural marshy river all showed higher values than that in the degraded marshy river and artificial ditch. It highlighted the fact that DIC became more dominant in the dissolved carbon concentration of the degraded marshy river and artificial ditch, compared to that in the natural marshy sites in the Sanjiang Plain. That might result from irrigation activities and the application of fertilizers such as urea in the rice paddy, as Kelly (1997) found that DIC concentrations could be increased by irrigation activities associated with redox-sensitive fertilizers.

Similar to DOC dynamics in rivers, seasonal averaged DOC concentrations were higher from litter, soil, and surface ponding in the degraded wetland site than those from the natural wetland sites. Higher averaged DIC/DTC (51.28%) was found in the surface ponding of degraded riparian wetland, compared to that in the Bielahong. riparian wetland (34.37%), Yalv. riparian wetland (41.73%) and Nongjiang. riparian wetland (29.20%). It showed the consistent patterns with the differences between the degraded marshy river and the natural marshy rivers, which implied that dissolved carbon dynamics in point scale might be a good predictor in-stream water to explore the dynamics of dissolved carbon as affected by wetland degradation.

5. Conclusions

For the first time, concentrations of DOC, DIC and DTC in the degraded marshy river, pristine marshy rivers and artificial ditches at the Sanjiang Plain in Northeastern China were measured. This work will substantially enrich the database related to the regional and global carbon cycle. The quality dataset will facilitate the incorporation of these species into models of carbon cycles linked land and watersheds. The presented results lead us to three major conclusions: (1) An increased loss of DOC and an associated rise in the level of DIC of the river from the degraded wetland were observed, compared to those in natural marshy rivers and the artificial ditch. (2) Establishment of the artificial ditch modified the partitions of dissolved carbon forms, such that DIC became more dominant in the DTC concentrations in the artificial ditch and degraded marshy river, compared to those in natural marshy rivers. (3) The averaged DOC concentrations were also higher from litter, soil, and surface ponding in the degraded wetland site than those from the natural wetland sites. Dissolved carbon dynamics in point scale might be a good predictor of dissolved carbon dynamics in-stream water affected by wetland degradation.

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