Environmental Management (2012) 50:39–49
DOI 10.1007/s00267-012-9869-7

Winter Soil Respiration from Different Vegetation Patches in the Yellow River Delta, China

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Received: 25 November 2011 / Accepted: 2 April 2012 / Published online: 11 May 2012

Abstract Vegetation type and density exhibited a considerable patchy distribution at very local scales in the Yellow River Delta, due to the spatial variation of soil salinity and water scarcity. We proposed that soil respiration is affected by the spatial variations in vegetation type and soil chemical properties and tested this hypothesis in three different vegetation patches (*Phragmites australis*, *Suaeda heteroptera* and bare soil) in winter (from November 2010 to April 2011). At diurnal scale, soil respiration all displayed single-peak curves and asymmetric patterns in the three vegetation patches; At seasonal scale, soil respiration all declined steadily until February, and then increased to a peak in next April. But, the magnitude of soil respiration showed significant differences among the three sites. Mean soil respiration rates in winter were 0.60, 0.45 and 0.17 μmol CO_2 m^{-2} s^{-1} for the *Phragmites australis*, *Suaeda heteroptera* and bare soil, respectively. The combined effect of soil temperature and soil moisture accounted for 58–68 % of the seasonal variation of winter soil respiration. The mean soil respiration revealed positive and linear correlations with total N, total N and SOC storages at 0–20 cm depth, and plant biomass among the three sites. We conclude that the patchy distribution of plant biomass and soil chemical properties (total C, total N and SOC) may affect decomposition rate of soil organic matter in winter, thereby leading to spatial variations in soil respiration.

Keywords Soil respiration · Winter · Vegetation patches · Spatial and temporal variation · Yellow River Delta

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Introduction

Soil respiration, the sum of autotrophic (root) respiration and heterotrophic (microbes) respiration, is the most important process of carbon loss from terrestrial ecosystems (Raich and Schlesinger 1992), accounting for up to 90 % of total ecosystem respiration (Hanson and others 2000). Furthermore, soil respiration, increasing with temperature, can create a positive feedback to global warming (Schlesinger and Andrews 2000), and slight modifications in the rate of soil respiration can result in significant changes to the global carbon (C) cycle (Giardina and Ryan 2000). Therefore, accurately estimating soil respiration, as well as determining its controlling factors, is crucial for accurate estimation of the global carbon balance and the likely consequences of climatic change (Raich and Schlesinger 1992; Fang and others 1998; Raich and others 2002).

Soil respiration for a specific ecosystem can be characterized by its magnitude and its temporal and spatial variability (Fang and others 1998), which are primarily influenced by physiological, phenological and environmental processes that vary both in time and space, as well

as with ecosystem type (Rey and others 2011). Soil temperature and soil moisture are recognized as the key environmental factors responsible for variation in soil respiration (Davidson and others 1998; Rayment and Jarvis 2000; Han and others 2007). Seasonal changes of these factors affect the productivity of terrestrial ecosystems and the decomposition rate of soil organic matter, thereby driving the temporal variations of soil respiration at individual sites (Wiseman and Seiler 2004; Jin and others 2009). Results from many studies have shown that soil respiration is exponentially correlated with changes in soil temperature when water is not limited at different temporal scales (Fang and Moncrieff 2001). However, soil respiration is also strongly influenced by soil moisture, and both soil saturation and drought suppress soil CO_2 efflux (Wiseman and Seiler 2004).

Furthermore, soil respiration can vary greatly with vegetation types, soil microbial biomass, and soil chemical properties among and within sites (Gough and Seiler 2004; Tang and Baldocchi 2005; Han and others 2007). Shifts in vegetation covers may profoundly affect soil respiration and net primary production (NPP) by influencing substrate quantity and quality supplied to the soil, fine root and rhizomorph dynamics, and soil microclimate and structure (Raich and Tufekcioglu 2000; Wang and others 2010b; Dias and others 2010). A number of studies have attempted to evaluate differences in vegetation-related controls on soil respiration (Smith and Johnson 2004; Wang and others 2010b; Dias and others 2010). For instance, there were significant differences in soil respiration rates of three ground-covers under different degrees of land degradation in a steppe semi-arid ecosystem (Rey and others 2011). Soil respiration was reduced by an average of 41 % with conversion of pasture to forest on an annual basis in Atlantic Canada (Kellman and others 2007). In some ecosystems, such as semiarid areas and mountain areas, the distribution of vegetation are markedly patchy because of the patchy distribution of resources, conditions and organisms at small scale (Maestre and Cortina 2003; Dias and others 2010). Therefore, it is necessary to obtain sufficient information on spatial variation of soil respiration in these ecosystems to accurately evaluate their soil carbon budget.

The Yellow River Delta, located in the northern Shandong province, China, is one of the most active land-ocean interaction regions in the world. As a newly formed estuarine delta, it is naturally characterized by extensive coverage of primary salinization (Zhang and others 2011), which is mainly due to the presence of a shallow, saline water table and marine sediments (Guan and others 2001). Actually, primary salinization is caused by multi-biophysical factors and their interactions, which lead to a great spatial variation in soil salinity (Zhang and others 2011). Moreover, plant growth is limited by soil salinity and water scarcity, especially in areas with shallow groundwater (Xie and others 2011). Therefore, the vegetation type and density in the Yellow River Delta exhibit a considerable patchy distribution, often at very local scales (Xie and others 2011; Wang and others 2011). Thus, the patchy distribution of vegetation and soil properties may increase the spatial variation of soil respiration in coastal ecosystems.

To date, the effects of the spatial variation of both vegetation and soil features on soil respiration in the coastal ecosystems are still poorly known because limited studies have been carried out in the field. Moreover, most often, soil respiration measurements in many ecosystems are limited to the growing season, often neglecting winter fluxes (Ruehr and others 2010; Li and others 2010). However, soil respiration in winter (non-growing season) is an important component of the annual carbon budget, because previous findings indicated that 60 % or more of growing season carbon uptake were lost during the winter in some ecosystems (Oechel and others 2000; Brooks and others 2004; Monson 2005). In this study, in order to evaluate the effect of differences in vegetation patches on spatial variation in soil respiration, we investigated the spatial and temporal dynamics of winter soil respiration in three adjacent vegetation patches, *Phragmites australis*, *Suaeda heteroptera* and bare soil, in the Yellow River Delta. Our objectives were (1) to characterize soil respiration dynamics in winter in the different vegetation patches, (2) to assess the impact of vegetation type and environmental variables on winter soil respiration, and (3) to determine and compare the magnitude of winter soil respiration for the different vegetation patches.

Materials and Methods

Study Site Descriptions

The study was conducted from November 2010 to April 2011 in three different vegetation patches (*Phragmites australis*, *Suaeda heteroptera* and bare soil) at Yellow River Delta Ecological Research Station of Coastal Wetland (37°45′50″N, 118°59′24″E), Chinese Academy of Sciences. The experimental site has a warm-temperate and continental monsoon climate with distinctive seasons and rainy summer. The annual average temperature is 12.9 °C ranging from 41.9 °C in the summer to −23.3 °C in the winter. The average annual precipitation is 550–640 mm, with nearly 70 % of the precipitation falling between May and September. The evaporation is 1962 mm, and the drought index (the ratio of annual potential evaporation to annual precipitation) is up to 3.56 (Cui and others 2009). On average, the area has 8–16 snowy days per year. The

mean annual wind speed is 2.98 m s^{-1}, and the frost-free period is 142 days (Xie and others 2011). Generally, the soil type in the Yellow River Delta gradually varies from fluvo-aquic to saline soil, and the soil texture is mainly sandy clay loam (Nie and others 2009).

Driven by the strong evaporation, salt is brought to the soil surface through capillary rise. Therefore, soil salinity is a common problem in this area. Because of spatial variation of soil salinity and water scarcity, the natural vegetation exhibits a patchy distribution, and the species composition of the vegetation is very simple and dominated by salt tolerant plants. The natural wetlands of the river delta are initially classified into four ecosystem types: (1) a mixed *Tamarix chinensis-Phragmites australis* ecosystem, (2) *Suaeda heteroptera* ecosystem, (3) unvegetated beach, and (4) open water (Yang and others 2009). The most severe salinization makes some places bare in those sites. In the areas with a lower salt content (11.0 % ± 0.9 %), *Suaeda heteroptera* are partially distributed. These *Suaeda heteroptera* increase organic matter in the soil and their secreting salt effects result in the reduction of soil salt content (9.4 % ± 1.1 %), which makes the area succeed to *Tamarix chinensis*, *Phragmites australis* or *Miscanthus sacchariflorus* ecosystem (Zhang and others 2007; Song and others 2009; Fan and others 2011). The dominant species of the research site are *Phragmites australis* and *Suaeda heteroptera*, with *Tamarix chinensis* randomly distributed among them. Due to the obvious gradient change of soil salt content, the spatial distribution patterns of vegetation in the research site are mostly identified as patches of *Phragmites australis*, *Suaeda heteroptera* or bare soil on scales of meters to tens of meters. The three study sites were selected for *Phragmites australis* community, *Suaeda heteroptera* community and bare soil site.

Soil Respiration Measurements

With a portable soil CO_2 flux system (LI-8100, LI-COR, Lincoln, NE, USA), soil respiration was measured in three different vegetation patches (*Phragmites australis*, *Suaeda heteroptera* and bare soil). The three sites were located no more than 30 m apart. In each site three collars (20 cm inside diameter) were placed at random locations where there was no living aboveground vegetation. In each measurement, respiration rates were calculated as means of the three collars for each vegetation patch. Soil respiration was measured twice a month (except for January and February) from November 2010 to April 2011. To catch the diurnal pattern, soil respiration rates were measured every 2 h from 7:00 to 17:00 at clear days. Each observation length was 120 s and the observation count was set to 2. It took 2 min for the chamber air to return to ambient conditions between the two observations. To minimize measurement errors and equipment damage all measurements were made on days without rain or snow.

Measurements of Environmental Factors

Around 100 m away from the research sites, there was a meteorological tower designed to measure meteorological parameters, such as net radiation, mean air temperature, soil temperature, and soil water content. Net radiation was measured with a four component net radiometer (CNR4, Campbell Scientific Inc., USA) positioned 1.7 m above the ground. Air temperature was measured with probes (HMP45C, Vaisala, Helsinki, Finland) at 3 m heights. Soil temperature was measured with thermistors (109SS, Campbell Scientific Inc., USA) at 10, 20, 30 and 50 cm depths below the surface. Soil water content was measured by time domain reflectometry probes (EnviroSMART SDI-12, Sentek Pty Ltd., USA) at 10, 20, 40, 60, 80 and 100 cm depths below the surface. Precipitation was measured with a tipping bucket rain gage (TE525, Texas Electronics, Texas, USA) mounted 0.7 m above the ground. These data were logged every 30 min by a CR1000 datalogger (Campbell Scientific Inc., USA).

In late October (end of growing season) of 2010, the plant aboveground biomass was measured by the harvest method. On each site of soil respiration measurement, five 0.5 m × 0.5 m squares were randomly chosen at the *Phragmites australis* and *Suaeda heteroptera* site, respectively. Live plants were clipped at 1 cm above the ground level, and root biomass was measured by taking five soil blocks (50 cm wide × 50 cm long × 20 cm deep). Plant aboveground and root biomass were oven dried at 80 °C for 48 h and weighed. At the same time, total carbon (C), total nitrogen (N) and soil organic carbon (SOC) of the 20 cm depth soil samples were analyzed in the three vegetation patches. Total soil C was analyzed using the potassium dichromate oxidation method (Wang and others 2011), total soil N was measured by the Kjeldahl method (Bremner 1960), and SOC was determined using wet combustion as described by Yeomans and Bremner (1988).

Statistical Analysis

Differences among three vegetation patches (*Phragmites australis*, *Suaeda heteroptera* and bare soil) in soil respiration were evaluated with one-way ANOVA. The exponential model and standard temperature-based Q_{10} model were developed for each vegetation patch to evaluate the relationship between soil respiration and soil temperature. Linear regression was used to evaluate the relationships between soil respiration rates and soil water content. Nonlinear regression analyses were used to describe the relationships between winter soil respiration and soil

temperature and moisture within each vegetation patch. Significant differences for all statistical tests were evaluated at the level $\alpha = 0.05$. All the statistical analyses were performed by using the SPSS 13.0 package (SPSS, Chicago, IL, USA).

Results

Temporal Dynamics of Environmental Factors

In the winter (from November to next April), net radiation was 14376.41 W m^{-2} (Fig. 1a), and daily net radiation decreased gradually during autumn and winter until next February, and then increased to a peak in April (207.8 W m^{-2}). There was a close coupling between soil temperature and net radiation trends. Soil temperature at 10 cm depth ranged from −2.5 °C in January to 14.0 °C in April (Fig. 1b). Precipitation also showed large seasonal variation (Fig. 1c), and the total precipitation in winter was 14.5 mm. Seasonal fluctuations in temperature and precipitation affected soil water content. For example, mean soil water content at 10 cm depth ranged from 39.5 % in November 2010 to 16.2 % in January 2011 (Fig. 1d).

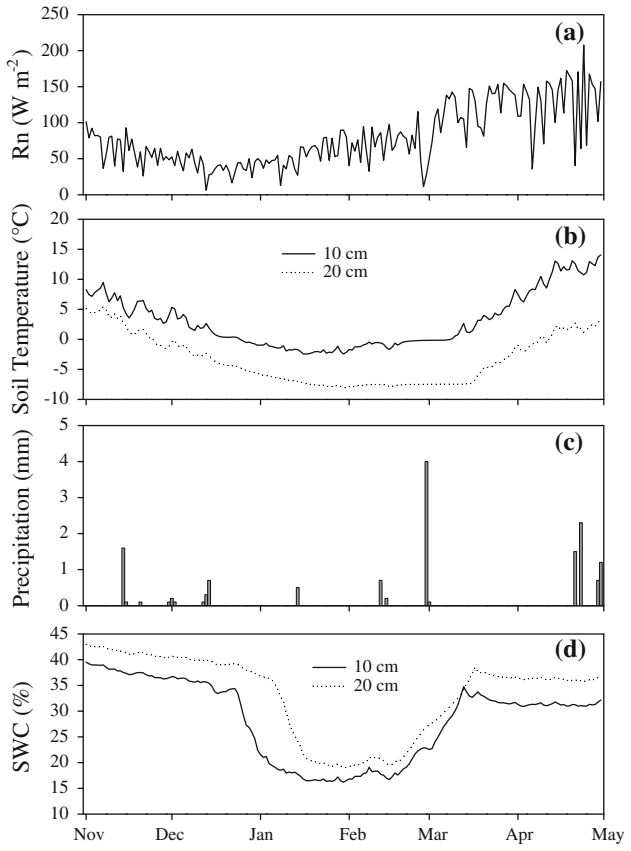

Fig. 1 Temporal dynamics of environmental factors in winter (from November 2010 to April 2011) over Yellow River Delta, China, showing **a** daily total net radiation, **b** soil temperature (10, 20 cm), **c** 24 h summed precipitation, and **d** 24 h mean soil water content (10, 20 cm)

Temporal Dynamics of Soil Respiration

At diurnal scale, soil respiration in *Phragmites australis*, *Suaeda heteroptera* and bare soil, all displayed single-peak curves and asymmetric patterns (Fig. 2). On each day, the lowest values of soil respiration in the three sites occurred in the early morning, whereas the highest values occurred around the middle of the day (11:00–13:00). The daytime variation of soil respiration followed the increasing trend of soil temperature at 10 cm depth in the morning and decreased more quickly than the temperature in the afternoon. The diurnal ranges of soil respiration in *Phragmites australis* and *Suaeda heteroptera* communities were larger than those in the bare soil in winter. Except in January and February, the diurnal range of soil respiration in the *Phragmites australis* community was larger than those in the *Suaeda heteroptera* community.

From the beginning to the end of the non-growing season, there was a similar trend in seasonal variation of soil respiration in the three vegetation patches (Fig. 3). From November, soil respiration declined steadily until next February, and then increased to a peak in April (near the beginning of growing season). The lowest value mainly occurred in January and February. This may be because soil temperature was lower than 0 °C and soil water began freezing in December (Fig. 1). Throughout the non-growing season, soil respiration in *Phragmites australis*, *Suaeda heteroptera* and bare soil sites ranged from 0.07 to 1.27 μmol CO_2 m^{-2} s^{-1}, 0.05 to 0.87 μmol CO_2 m^{-2} s^{-1}, and 0.04 to 0.43 μmol CO_2 m^{-2} s^{-1}, respectively.

Comparison of Soil Respiration Among Three Sites

With all sampling months pooled together, mean soil efflux rates were 0.60, 0.45 and 0.17 μmol CO_2 m^{-2} s^{-1} for the *Phragmites australis*, *Suaeda heteroptera* and bare soil, respectively (Fig. 4). The maximal value of soil respiration (1.27 μmol CO_2 m^{-2} s^{-1}) in *Phragmites australis* was 1.5 times higher than that of 0.87 μmol CO_2 m^{-2} s^{-1} in *Suaeda heteroptera*, and 3.0 times higher than that of 0.43 μmol CO_2 m^{-2} s^{-1} in bare soil in winter. The average soil respiration rate of each month showed significant differences ($P < 0.05$) among the three sites during the non-growing season with the exception of no significant difference observed in January. Multiple comparisons test revealed that soil respiration was significantly lower ($P < 0.001$) in the bare soil than in the *Phragmites australis* (approximately 72 %) or *Suaeda heteroptera* (approximately 62 %).

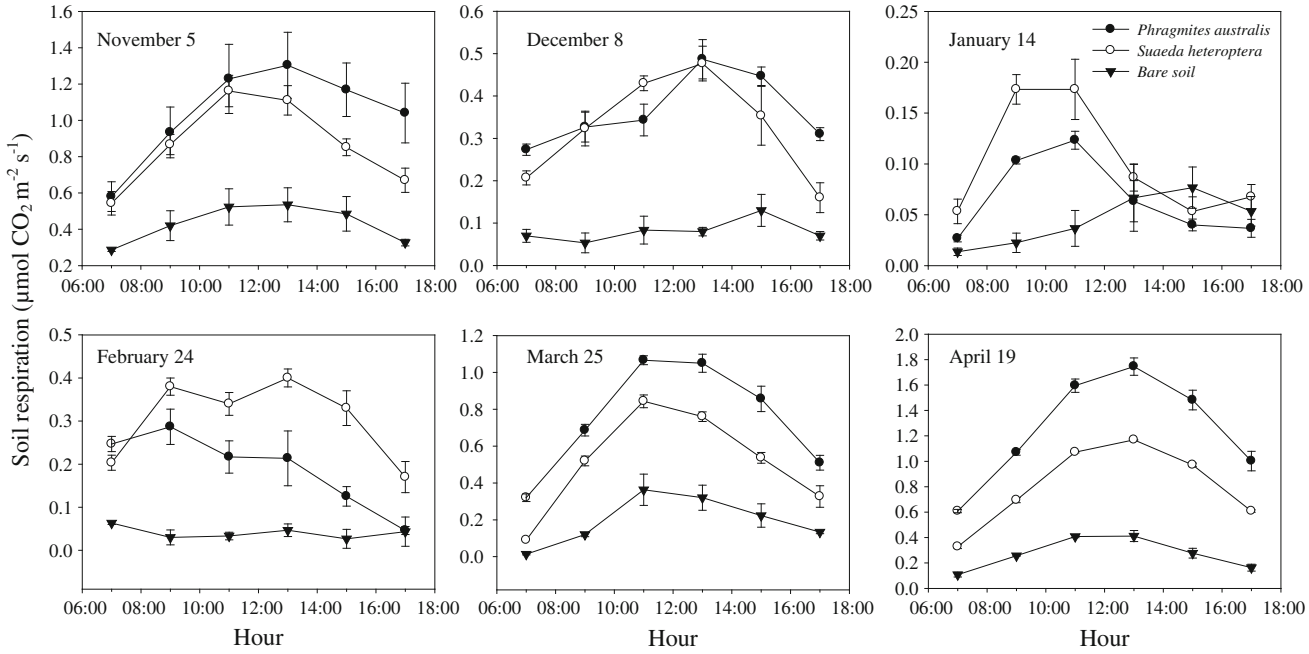

Fig. 2 Daytime variation in soil respiration on November 5, December 8, January 14, February 24, March 25 and April 19 at *Phragmites australis*, *Suaeda heteroptera* and bare soil sites. Data are mean values and standard error on each sampling day ($n = 3$)

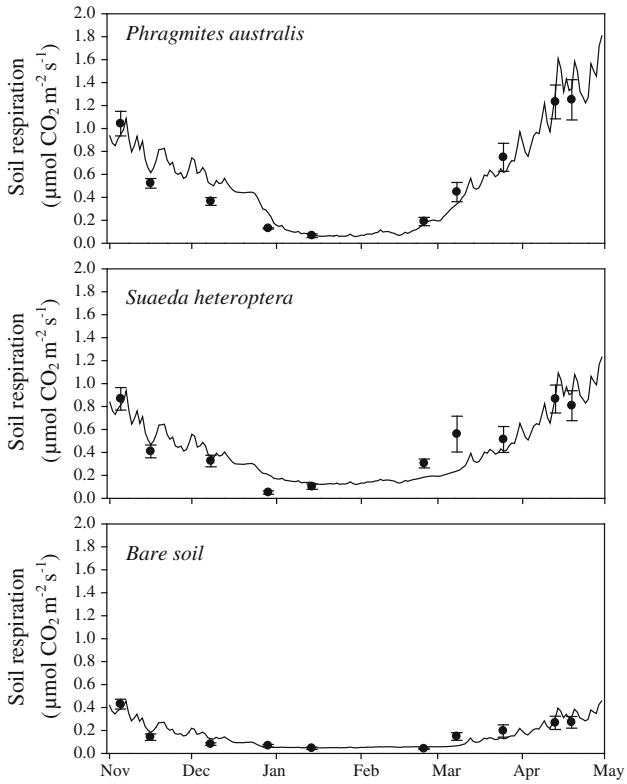

Fig. 3 Measured and modeled soil respiration in winter at *Phragmites australis*, *Suaeda heteroptera* and bare soil sites. Measured values of soil respiration are represented by the *black dots* and *bars* (±1 SE), and modeled values of soil respiration are calculated using the equation $SR = ae^{bT}W^c$ and are represented by the *black line*

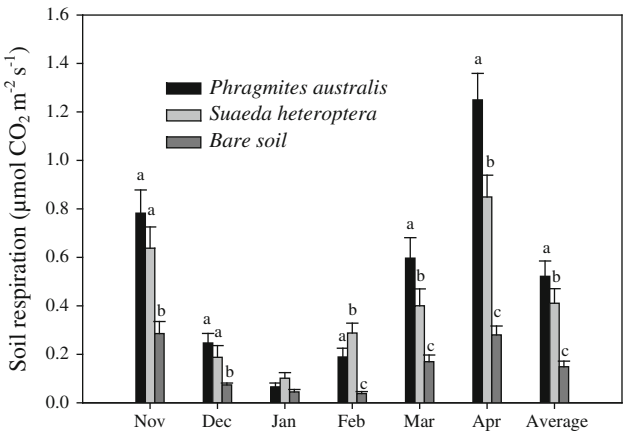

Fig. 4 Mean soil respiration in winter at *Phragmites australis*, *Suaeda heteroptera* and bare soil sites. Each *bar* represents the mean soil respiration for the 3 collars per month. Standard error of each mean is represented over each *bar*. *Different letters* denote significant ($P < 0.05$) differences among the three sites (Tukey test after one way-ANOVA)

Effects of Soil Temperature and Moisture on Soil Respiration

Correlation analysis revealed that soil respiration was more significantly related to soil temperature and soil water content at the depth of 10 cm than at the other depths in winter (Table 1). Therefore, soil temperature and soil water

Table 1 Correlation coefficients of winter soil respiration to soil temperatures and soil water content at *Phragmites australis*, *Suaeda heteroptera* and bare soil sites of the Yellow River Delta

Vegetation type	Soil temperature (°C)					Soil water content (%)				
	10 cm	20 cm	30 cm	40 cm	50 cm	10 cm	20 cm	40 cm	60 cm	80 cm
Phragmites australis	0.860**	0.858**	0.684**	0.782**	0.658**	0.534**	0.439**	0.342**	0.283*	0.15
Suaeda heteroptera	0.798**	0.794**	0.672**	0.735**	0.641**	0.520**	0.391**	0.348**	0.342**	0.2
Bare soil	0.732**	0.728**	0.678**	0.676**	0.625**	0.556**	0.469**	0.465**	0.468**	0.346**

* and ** are significant at the 0.01 level and the 0.05 level (2-tailed) respectively

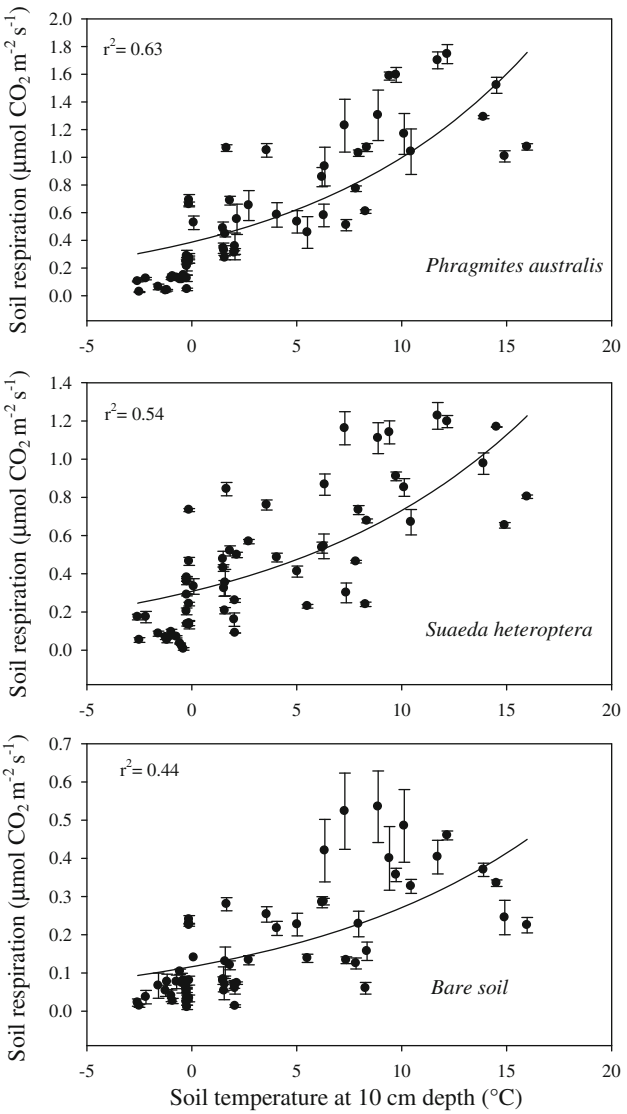

Fig. 5 Responses of soil respiration (mean ± SE) to soil temperature at 10 cm depth in winter at *Phragmites australis*, *Suaeda heteroptera* and bare soil sites of Yellow River Delta. *Black lines* are the best fit exponential relationship

content at 10 cm depth were used to investigate the influence of soil temperature and water on soil respiration. In winter, the relationships between soil respiration rate and soil temperature at 10 cm depth were well fit by exponential growth regression model ($P < 0.001$) for all of the 3 different ecosystems (Fig. 5; Table 2).

$$SR = ae^{bT} \quad (1)$$

where SR is mean soil respiration rate (μmol CO_2 m^{-2} s^{-1}), T is soil temperature at 10 cm depth (°C), and a, b are fitted parameters and they are showed in Table 2.

The Q_{10} value was calculated by

$$Q_{10} = e^{10b} \quad (2)$$

Soil temperature alone explained 63, 54 and 44 % of the variations in soil respiration at the *Phragmites australis*, *Suaeda heteroptera* and bare soil sites, respectively. The apparent Q_{10} value against 10 cm soil temperature was 2.58, 2.38 and 2.33 at *Phragmites australis*, *Suaeda heteroptera* and bare soil sites, respectively, suggesting the different response of soil respiration to soil temperature among different vegetation sites.

Furthermore, there were significant, positive, linear relationship between soil respiration and soil moisture (Eq. (3)) for *Phragmites australis*, *Suaeda heteroptera* and bare soil sites, which explained only 24–28 % of the variance in soil respiration (Fig. 6; Table 2).

$$SR = aW + b \quad (3)$$

where W is soil volumetric water content at 10 cm depth (%), and a, b are fitted parameters and are presented in Table 2.

Thus, taking this water content into account improved the explained temporal variation of soil respiration in winter in all vegetation types. The combined use of soil temperature and soil water content functions (Eq. (4)) could explain 58–68 % of the variation in soil respiration during the non-growing season (Fig. 3; Table 2), indicating that soil temperature and soil water content played a complicated role in influencing soil respiration in this study.

$$SR = ae^{bT}W^{c} \quad (4)$$

where a, b, c are fitted parameters and they are showed in Table 2.

Table 2 Effects of soil temperature (T) and soil water content (W) on the variation of soil respiration rate (SR) during the non-growing season at *Phragmites australis*, *Suaeda heteroptera* and bare soil sites of the Yellow River Delta

Vegetation type	Regression equation									
	$SR = ae^{bT}$			$SR = aw + b$			$SR = ae^{bT}W^{c}$			
	a	b	R^2	a	b	R^2	a	b	c	R^2
Phragmites australis	0.387	0.095	0.63 ($P = 0.000$)	0.037	−0.511	0.26 ($P = 0.000$)	0.018	0.089	0.898	0.68 ($P = 0.000$)
Suaeda heteroptera	0.308	0.087	0.54 ($P = 0.000$)	0.026	−0.323	0.24 ($P = 0.000$)	0.009	0.082	1.032	0.61 ($P = 0.000$)
Bare soil	0.116	0.085	0.44 ($P = 0.000$)	0.012	−0.177	0.28 ($P = 0.000$)	0.0001	0.081	1.972	0.58 ($P = 0.000$)

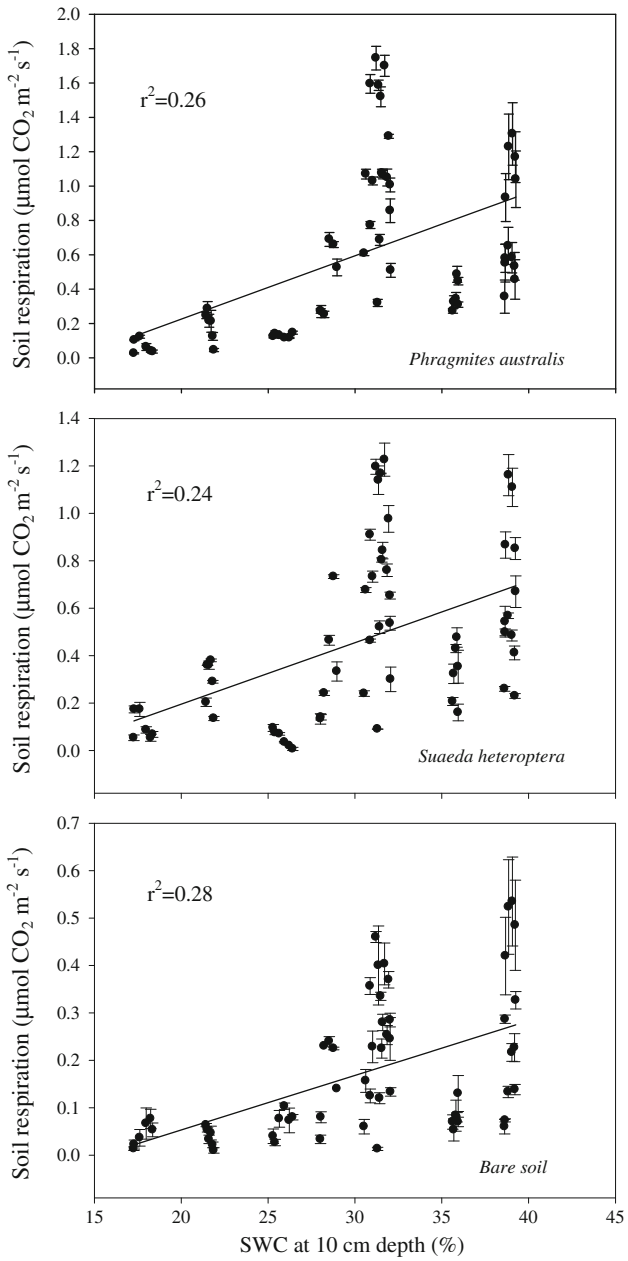

Fig. 6 Relationship between soil respiration (mean ± SE) and soil water content at 10 cm depth in winter at *Phragmites australis*, *Suaeda heteroptera* and bare soil sites of Yellow River Delta. *Black lines* are the linear fit. *Bars* represent standard errors of the means

Effects of Soil C and N Storage and Biomass on Soil Respiration

The total C, total N and SOC varied greatly among vegetated and bare soil patches, and there were significant differences ($P < 0.05$) in soil total C, total N and SOC storages among different ground-cover types (Fig. 7). Lower mean soil respiration at bare soil site appeared to be associated with its lower total C, total N and SOC content, and lower biomass values than vegetated sites. The mean soil respiration revealed positive and linear correlations ($P < 0.05$) with total C, total N and SOC storages at 0–20 cm depth, and plant biomass among the *Phragmites australis*, *Suaeda heteroptera* and bare soil sites (Fig. 7).

Discussion

Winter Soil Respiration

Most soil respiration measurements were conducted during the growing season, because of the assumption that microbial activity in frozen or snow-covered soils was negligible (Fahnestock and others 1999; Wang and others 2010a). However, many studies have convincingly demonstrated that soil respiration still existed and sometimes even increased, because soil microbial activity occurred even at freezing temperatures (Nobrega and Grogan 2007; Li and others 2010; Wang and others 2010a). In addition, during the non-growing season, most decomposable organic matter was typically available to soil microbes after leaf litter fall in terrestrial ecosystems (Hobbie and Chapin 1996). Thus, respiratory losses in winter might offset a major portion of the carbon fixed during the growing season and could be critical in determining annual carbon cycling (Nobrega and Grogan 2007; Wang and others 2010a). For instance, Monson (2005) reported that the amount of carbon lost in winter could be as much as 50–90 % of the carbon gained in the previous summer in subalpine forests. The accumulated CO_2 efflux from snow-covered soils was 62 g C m^{-2} or approximately 12 % of total annual soil respiration (Schindlbacher and others

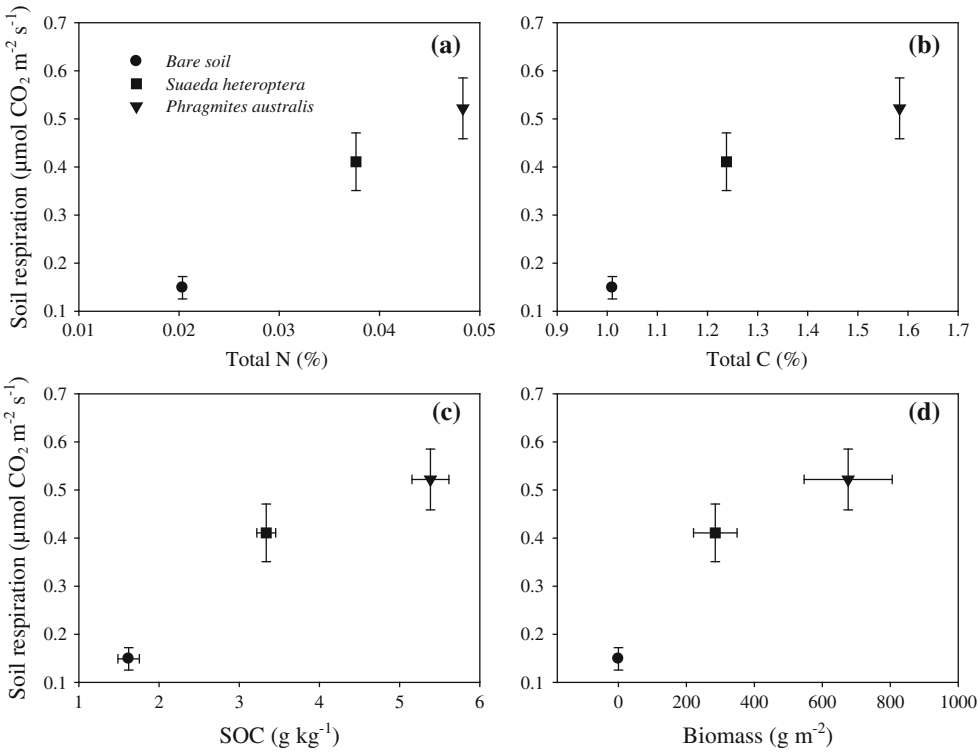

Fig. 7 Relationships of soil respiration with **a** total N, **b** total C, **c** soil organic carbon (SOC), and **d** biomass during the non-growing season at *Phragmites australis*, *Suaeda heteroptera* and bare soil sites of Yellow River Delta. *Bars* represent standard errors of the means

2007). In a maize agroecosystem in Northeast China, the average soil respiration of the non-growing season accounted for 11 % of the gross primary production (GPP) of the growing season (Li and others 2010). At our study site, accumulated CO_2 efflux in winter (181 days) was 374.5, 279.8 and 100.4 g CO_2 m^{-2} at *Phragmites australis*, *Suaeda heteroptera* and bare soil sites, respectively. Therefore, understanding the dynamics of winter soil respiration and its controls can contribute to accurately estimating annual carbon budgets and calculating belowground carbon allocation by plants.

For our study site, in the three vegetation patches, soil respiration all declined steadily from November until next February, and then increased to a peak in April, which was consistent with Li and others (2010) in a maize agroecosystem in Northeast China, Wang and others (2010a) for seven ecosystems of a forest-steppe ecotone in north China, and Ruehr and others (2010) in a mixed mountain forest in Switzerland. In the Yellow River Delta, mean soil efflux rates in winter were 0.60, 0.45 and 0.17 μmol CO_2 m^{-2} s^{-1} for the *Phragmites australis*, *Suaeda heteroptera* and bare soil, respectively, which were in the range comparable to those measured in other temperate ecosystems. For example, Wang and others (2010a) found that overall mean winter season soil CO_2 effluxes were 0.15–0.26 μmol CO_2 m^{-2} s^{-1} for seven ecosystems in a forest-steppe ecotone of north China. During the non-growing season, from November to April of the next year, average monthly soil respiration varied from 0.52–0.70 μmol CO_2 m^{-2} s^{-1} in a maize agroecosystem in Northeast China (Li and others 2010). In a semi-arid northern mixed-grass prairie in North Dakota, averaged winter respiration rate was 0.48 μmol CO_2 m^{-2} s^{-1} (Frank and others 2002). Elberling (2007) reported that soil CO_2 efflux during the winter was 0.11–0.28 μmol CO_2 m^{-2} s^{-1} for three dominating types of vegetation (Dryas, Cassiope, and Salix) at Svalbard.

Effect of Soil Temperature and Moisture on Soil Respiration

In the winter, when plant activity was strongly reduced, soil respiration was typically dominated by heterotrophic respiration (Schindlbacher and others 2007; Ruehr and others 2010), which was the result of decomposition of litter and soil organic matter. Our findings showed that temperature was the major controlling factor for the seasonal patterns of winter soil respiration among different vegetation patches, which was consistent with results reported from many other terrestrial ecosystems (Schindlbacher and others 2007; Li and others 2010; Ruehr and others 2010). The magnitude of seasonal variation in soil respiration due to soil temperature varied from 44 % at bare soil site to 63 % at *Phragmites australis* site (Fig. 5), indicating that the temporal variation of soil respiration observed in our site was dominantly controlled by the changes of soil temperature. However, there were still unknown factors which impact soil respiration such as soil

moisture, biomass of fine roots, and litters (Fang and others 1998). The Q_{10} values were 2.58 at the *Phragmites australis* site, 2.38 at the *Suaeda heteroptera* site and 2.33 at the bare soil site, suggesting the vegetation type affecting the response of soil respiration to soil temperature. The differences in Q_{10} values ($P < 0.001$) in our study might primarily result from the differences in the characteristics of SOC quality, substrate quality, or microbial activities among different vegetation covers (Davidson and others 2006), which was consistent with Li and others (2008), Arevalo and others (2010), and Sheng and others (2010). In addition, our estimates of Q_{10} among these three vegetation covers were close to the average value of 2.4 found in temperate ecosystems (Fang and Moncrieff 2001; Wang and others 2006, 2010a).

Winter soil respiration also showed positive relationships with soil moisture in the *Phragmites australis*, *Suaeda heteroptera* and bare soil sites, and the contribution of soil moisture to soil respiration ranged from 24 to 28 % among these three vegetation covers (Fig. 6). These significant correlations between soil respiration and soil moisture observed in this study were in accordance with those in other terrestrial ecosystems (Chen and others 2010; Jin and others 2010). For example, in a maize agroecosystem of Northeast China, the relationship between soil respiration and soil water content in the non-growing season was expressed as a quadratic equation (Li and others 2010). At the Ordos Plateau of Inner Mongolia, China, the linear soil moisture model could explain 42 and 23 % of seasonal variations in soil respiration for the grass site and desert shrub site, respectively (Jin and others 2010). Moisture could limit soil respiration when the soil was too dry or too wet, because water saturation limited oxygen diffusion, and low soil moisture restricted microbial metabolism through desiccation and reduced substrate access or diffusion (Davidson and others 1998; Xu and others 2004; Chen and others 2010). For instance, at an old-field grassland with very high mean soil moisture content, a negative relationship between soil respiration and soil moisture was observed (Wan and others 2007). Moreover, in the winter, there was an alternate process of freezing and thawing in the soil, which could lead to a variation of many factors (e.g., soil microbial popular, soil temperature and moisture), and subsequently to influencing soil microbial activity and soil respiration (Li and others 2010). In our study, in December and February, when soil temperature was lower than 0 °C and air temperature was higher than 0 °C, the process of freezing and thawing would happen. Thus, changes in soil water moisture might affect the response of soil respiration to soil temperature. Therefore, the models of soil respiration during the non-growing season should take into account soil temperature as well as soil moisture to calculate respiration rates (Li and others 2010). In our study, the combined effect of T and W (58–68 %) was strongly significant compared with the individual impact of T (44–63 %) and W (24–28 %), which was consistent with some previously reported results (Chen and others 2010; Li and others 2010; Zhang and others 2010).

Comparison of Soil Respiration Among Three Vegetation Patches

Because of spatial variation of soil salinity and water scarcity in the Yellow River Delta, the vegetation type and density exhibited a considerably patchy distribution, often at very local scales (Xie and others 2011; Wang and others 2011). Based on the analysis of measurements, it was clear that the average soil respiration rates showed significant differences ($P < 0.05$) among the three different vegetation patches (Fig. 7). The differences in vegetation-related controls on soil respiration have been evaluated in different places for different ecosystems (Wang and others 2010a; Dias and others 2010; Zhang and others 2010; Yan and others 2011). Spatial variations in vegetation type and soil physical and chemical properties might affect productivity of terrestrial ecosystems, C allocation pattern, and decomposition rate of soil organic matter, thereby ultimately leading to spatial variations in soil respiration (Jin and others 2009; Rey and others 2011; Yan and others 2011).

In our research, differences in soil respiration among the three vegetation patches could be largely explained by the patchy distribution of plant biomass and soil chemical properties (total C, total N and SOC). On one hand, differences in plant biomass among sites could contribute well to differences in heterotrophic respiration (Hanson and others 2000). In the winter, because plant activity was strongly reduced, soil respiration was not affected by photosynthesis and productivity. However, soil respiration could be regulated by soil carbon substrate supply, which, in turn, might cause variation of heterotrophic respiration. Plant biomass could influence soil respiration by affecting soil C pool size and C inputs derived from canopy litter input, root biomass and soil organic matter (Raich and Tufekcioglu 2000). In our study, there was a positive relationship between soil respiration and plant biomass among the *Phragmites australis*, *Suaeda heteroptera* and bare soil sites (Fig. 7), implying the distinct influence of substrate availability and input on the soil respiration. Our result was essentially consistent with those from Sheng and others (2010), Zhang and others (2010), and Yan and others (2011). There was a general agreement that heterotrophic respiration increases with increasing biomass, possibly due to increased C inputs from litter and roots (Johnson and others 2008).

On the other hand, heterotrophic respiration could be greatly affected by soil chemical properties such as C pool variables and N stocks (Arevalo and others 2010; Wang and others 2010a; Rey and others 2011). The soil chemical properties under different vegetation covers could be related to decomposability of SOC and its sensitivity to soil temperature (Chen and others 2010; Yan and others 2011). In our study, the three sites experienced similar temperature and precipitation events, but among them the soil total C, total N and SOC storages differed significantly. Our results demonstrated that seasonal mean soil respiration rate was positively correlated with soil total C, total N and SOC, respectively. This result was in agreement with several recent studies suggesting that difference in the supply of substrate for heterotrophic respiration may be responsible for the observed variation in soil respiration among the different ecosystems (Wang and others 2010a, b; Rey and others 2011). Our results also showed higher total C, total N, and SOC in vegetated soil patches than bare soil patches, thereby, leading to much larger soil respiration from the soil beneath plant cover than from bare soil. Such a finding was mostly confirmed by many previous researches (e.g., Jin and others 2009; Rey and others 2011).

Conclusions

Our results showed that there was significant spatial and temporal variation in winter soil respiration in the Yellow River Delta. Though winter soil respiration presented the same patterns from November 2010 to April 2011 in the three vegetation patches, the magnitude of soil respiration showed significant differences among the three sites. The combined effect of soil temperature and soil moisture dominated the temporal patterns of soil respiration, and the patchy distribution of plant biomass and soil chemical properties (total C, total N and SOC) accounted for the spatial variations in soil respiration among the three vegetation covers. This study confirmed that the magnitude and variability of soil respiration were affected by the spatial variations in vegetation type and soil chemical properties. Therefore, modeling soil respiration should take into account the influence of patchy distribution of vegetation type and soil property.

Acknowledgments This research was funded by the National Science and Technology Support Program of China (No. 2011BAC02B01), the Chinese Academy of Sciences (No. kzcx2-yw-223), the CAS/SAFEA International Partnership Program for Creative Research Teams (Representative environmental processes and resources effects in coastal zone), and the 100 Talents Program of the Chinese Academy of Sciences. We also thank Dr. Hongfang Dong, Yuhong Liu, Xiaobing Chen and Baohua Xie for their helpful work during this study.

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