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Diurnal Variation of Soil CO_2 Efflux and Its Optimal Measuring Time-window of Temperate Meadow Steppes in Western Songnen Plain, China

YU Xiuli[1], LI Xiujun[2], XU Linshu[1], WANG Ming[1, 2], ZHANG Jitao[2], JIANG Ming[2], WANG Guodong[2]

(1. *Institute for Peat and Mire Research*, *Northeast Normal University*, *Key Laboratory of Wetland Ecology and Vegetation Restoration of National Environmental Protection*, *Changchun* 130024, *China*; 2. *Key Laboratory of Wetland Ecology and Environment*, *Northeast Institute of Geography and Agroecology*, *Chinese Academy of Sciences*, *Changchun* 130102, *China*)

Abstract: In order to study the diurnal variation of soil CO_2 efflux from temperate meadow steppes in Northeast China, and determine the best time for observation, a field experiment was conducted with a LI-6400 soil CO_2 flux system under five typical plant communities (*Suaeda glauca* (Sg), *Chloris virgata* (Cv), *Puccinellia distans* (Pd), *Leymus chinensis* (Lc) and *Phragmites australis* (Pa)) and an alkali-spot land (As) at the meadow steppe of western Songnen Plain. The results showed that the diurnal variation of soil CO_2 efflux exhibited a single peak curve in the growing season. Diurnal maximum soil respiration (Rs) often appeared between 11:00 and 13:00, while the minimum occurred at 21:00–23:00 or before dawn. Air temperature near the soil surface (Ta) and soil temperature at 10 cm depth (T_{10}) exerted dominant control on the diurnal variations of soil respiration. The time-windows 7:00–9:00 could be used as the optimal measuring time to represent the daily mean soil CO_2 efflux at the Cv, Pd, Lc and Pa sites. The daily mean soil CO_2 efflux was close to the soil CO_2 efflux from 15:00 to 17:00 and the mean of 2 individual soil CO_2 efflux from 15:00 to 19:00 at the As and Sg sites, respectively. During nocturnal hours, negative soil CO_2 fluxes (CO_2 downwards into the soil) were frequently observed at the As and Sg sites, the magnitude of the negative CO_2 fluxes were 0.10–1.55 μmol/(m^2·s) and 0.10–0.69 μmol/(m^2·s) at the two sites. The results implied that alkaline soils could absorb CO_2 under natural condition, which might have significant implications to the global carbon budget accounting.

Keywords: soil respiration; CO_2 efflux; meadow steppe; optimal measurement time; negative CO_2 efflux

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1 Introduction

Soil respiration (Rs) is a significant component of the global carbon cycle, and is likely to affect global warming (Schlesinger and Andrews, 2000). Tropical and temperate natural grasslands are one of the most widespread vegetation types in the world, storing at least 10% of the global soil carbon (Eswaran *et al*., 1993) and playing increasingly important roles in the global carbon cycle as global climate changes (Wang and Fang, 2009; Chen *et al*., 2013). Thereby, more attention should be paid to the CO_2 exchange in these grasslands. Seasonal variation of soil CO_2 efflux and influencing factors have been studied intensively in such ecosystems (Thomas *et al*., 2014; Wang *et al*., 2015), but there is little information on the diurnal patterns of Rs, which is of great im-

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Corresponding author: WANG Ming. E-mail: wangm100@nenu.edu.cn

portance to estimate the CO_2 emission and figure out factors that drive Rs (Wang *et al*., 2012). In addition, previous studies have shown that there are still large uncertainties in the magnitude and in the different driving mechanisms of Rs among grasslands under various climatic conditions, management practices and vegetation types (Schlesinger and Andrews, 2000; Wang and Fang, 2009). Therefore, studies regarding daily soil respiration and controlling factors in grasslands are still important to obtain accurate estimates of soil CO_2 efflux and to understand controls on the underlying process.

Daily average Rs is an important index for estimating the cumulative CO_2 emission (Wang *et al*., 2012). A portable gas exchange system is normally used to take a measurement of soil CO_2 efflux at a single point of time in a day and extrapolate it to estimate the daily (or even weekly or bi-weekly in some studies) average soil CO_2 efflux (Curtin *et al*., 2000; Rochette and Hutchinson, 2005; Wang *et al*., 2010). However, the method of using a non-tested single-time-point measurement as a daily average is error prone because it neglects the daily variation of CO_2 efflux and bears a risk of over or under estimation (Shi *et al*., 2012). Therefore, a time or time-window in a day is required where a single CO_2 efflux measurement will provide a good estimate of the daily average of CO_2 efflux.

As one of the three largest soda saline regions in the world, the vast steppe in the western Songnen Plain is characterized by its alkaline-saline soils. Large amounts of inorganic carbon are typically stored in the semiarid meadow steppe, but the organic carbon pool is small (Ren *et al*., 2008), implying that Rs is the main process of organic carbon loss from this area. Moreover, because of the relatively small organic carbon pool in this area, Rs is one of the ecosystem properties most sensitive to climate change (West *et al*., 1994). In addition, recent studies have reported that negative soil CO_2 efflux in the night fluently occurred at some saline and alkine ecosystems (Wohlfahrt *et al*., 2008; Xie *et al*., 2009; Ma *et al*., 2013), which means that CO_2 absorption by alkaline soils and the alkaline soil may be the ′missing sink′ in the global carbon cycle. However, studies regarding Rs of the meadow steppes in the western Songnen Plain are still very scarce. Thus, using chamber-based systems, we measured diurnal variation of soil CO_2 fluxes from an alkali-spot land (As) and five typical vegetation communities (*Suaeda glauca* community (Sg), *Chloris virgata* community (Cv), *Puccinellia distans* community (Pd), *Leymus chinensis* community (Lc), and *Phragmites australis* community (Pa)) of the meadow steppe in western Songnen Plain, China. This study aimed to 1) characterize the diurnal variation of Rs and determine its controlling factors; 2) verify the negative CO_2 efflux in this saline land; 3) investigate the best time or time-window for a single efflux measurement to obtain an estimate of daily average CO_2 efflux at the meadow steppe of Songnen Plain.

2 Materials and Methods

2.1 Study area

This study was conducted at a typical temperate meadow steppe ecosystem located in Da′an sodic land experiment station of China (DSLES; 45°35′58″–45°36′28″N, 123°50′27″–123°51′31″E; 120–160 m a. s. l. in the western Songnen Plain). The study area is characterized by a temperate, semi-humid and semi-arid continental monsoon climate, with seasons alternating between dry and windy spring, humid and warm summer, windy and dry autumn and long, cold and dry winter. Its mean annual temperature is 4℃. Mean annual precipitation is 413.7 mm, of which 70%–80% occurs in July–September (Deng *et al*., 2006). In this region, the growing season is usually from early May to late September. The mean temperature and precipitation in the growing season are 17.4 ℃ and 384 mm, respectively (Fig. 1). The mean evaporation is 1791.6 mm, 4–5 times higher than the annual precipitation (Deng *et al*., 2006). The main soil type is sodic meadow soil, and further characteristics of the soil in the study area are summarized in Table 1. The distribution of the six study sites was shown in Fig. 2.

2.2 Field measurements

Soil respiration was measured with a portable CO_2 infrared gas analyzer (Li-6400) equipped with a Li-6400-09 chamber (Li-Cor Inc, Lincoln, NE, USA). To minimize soil surface disturbances, the chamber was mounted on a PVC collar (10.2 cm in diameter and 5 cm in height) sharpened at the bottom and inserted into the soil about 3 cm deep one day before the measurements. At each study site, three PVC collars were placed at random locations where the aboveground vegetation and the litter were removed one day before measurements. A measurement consisted of placing the chamber on a soil collar, scrubbing the CO_2 to subambient levels and determining soil CO_2 efflux over several 5-s periods. This procedure was repeated three more times for each flux, and each flux was measured on three collars (total of 9 measurement cycles per flux). Diurnal variations of soil CO_2 efflux were examined once every two hours from 7:00 on the first day to 7:00 on the second day each month from April to October in 2011 and 2012, and 13 times in total.

During the experimental periods, air temperature near the soil surface (℃, T_a) and soil temperature at 10, 20, 30 cm depth (℃, T_{10}, T_{20}, T_{30}) were monitored using precision thermistors (model 44008; Yellow Springs Instrument Co., Yellow Springs, OH). Relative air humidity (%, Ha) was monitored with a digital thermometer (LI-6400-09 TC, LI-Cor). Soil water content (% v/v, Ws) at 10 cm depth was measured by gravimetric method (Jackson *et al.*, 2000). Soil bulk density (BD) at each site was determined using the volumetric core method (ISSCAS, 1978). Three soil pits with depths of 20 cm were randomly dug in the buffer area near each site in July 2011 and 2012. A 500 g soil sample from 0–5 cm, 5–10 cm, and 10–20 cm was taken respectively to measure the concentration of soil organic carbon (SOC), total N, pH and electrical conductivity (EC). The soil samples were naturally dried and passed through a 2-mm sieve. SOC was measured by dichromate oxidation methods (Kalembasa and Jenkinson, 1973), total N was measured using the semimicro-Kjedahl method (Nelson and Sommers, 1982), pH and EC were determined with a glass electrode using a 1 : 5 soil-water ratio (ISSCAS, 1978).

2.3 Data analysis

All statistical procedures were performed using the software packages SPSS 11.5 (SPSS Inc., Chicago, USA) and SigmaPlot 10.0 (SPSS Inc., Chicago, USA). The correlation coefficients between soil respiration and environmental factors were calculated by the Pearson

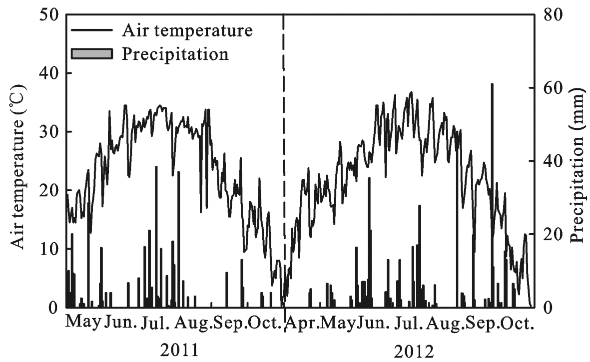


Fig. 1 Mean air temperature and precipitation in growing season in 2011 and 2012

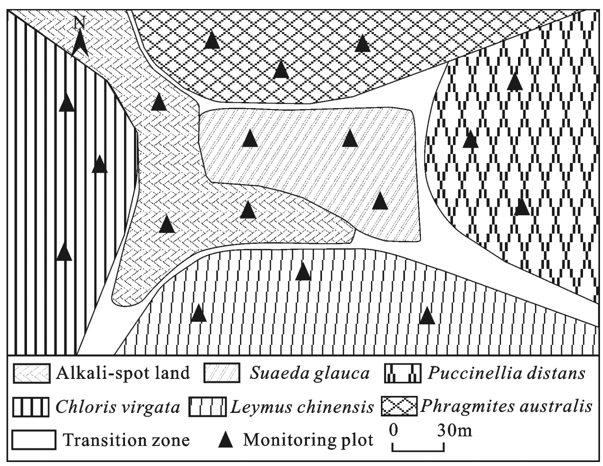


Fig. 2 Distribution of six sites in this study

Table 1 Site characteristics and mean Rs in growing season at study sites in 2011–2012

Plant community (Site code)	Alkali-spot land (As)	*Suaeda glauca* (Sg)	*Chloris virgata* (Cv)	*Puccinellia distans* (Pd)	*Leymus chinensis* (Lc)	*Phragmites australis* (Pa)
Rs (μmol/(m^2 · s))	0.07±0.01	0.40±0.01	1.47±0.12	1.48±0.17	2.38±0.36	2.76±0.42
T_{10} (℃)	18.4±0.3	18.7±0.6	17.9±0.5	18.3±0.7	17.8±0.5	16.5±0.4
W_{10} (% v/v)	19.15±1.1	19.7±1.8	22.4±3.2	23.9±4.1	22.4±3.2	27.7±3.3
BD (g/cm^3)	1.45±0.006	1.4±0.005	1.4±0.010	1.4±0.007	1.4±0.005	1.3±0.195
pH	10.6±0.19	10.2±0.11	9.7±0.32	9.9±0.02	9.4±0.31	8.4±0.18
EC (mS/cm)	2.03±0.12	1.92±0.09	0.60±0.07	0.70±0.03	0.53±0.03	0.27±0.03
SOC (g/kg)	8.12±0.62	8.7±1.6	11.9±0.5	10.2±2.1	15.2±0.1	18.9±1.4
N (g/kg)	0.46±0.02	0.70±0.03	0.70±0.04	0.61±0.05	0.69±0.03	1.01±0.08

Notes: Rs means average soil respiration rate in the growing season. T_{10} means soil temperature at 10 cm depth; W_{10} means soil water content in the topsoil (0–10 cm); Total N and SOC represent total nitrogen and soil organic carbon in the top 20 cm depth soil, respectively; EC and BD mean electric conductivity, bulk density in the top 20 cm depth soil. Given data represent the mean ± standard error for three replicates method. To quantify the deviations of soil CO_2 efflux at different measurement times (of day) (R_{real}) with the daily average value of Rs (R_{mean}), the coefficient of deviation was calculated as: Deviation = $(R_{real} - R_{mean}) / R_{mean} \times 100\%$ (Yao *et al*., 2011; Shi *et al*., 2012).

3 Results and Analyses

3.1 Diurnal variation of soil CO_2 efflux

The diurnal patterns of Rs were similar in different measuring days of these six study sites, and could be expressed as single peak curves (Fig. 3). In general, Rs rates reached to the maximum (1.46–5.61 μmol/(m^2·s)) at 11:00–13:00 and fell to the minimum (–1.55–0.53 μmol/(m^2·s)) at 21:00–23:00 or before dawn, coinciding with the highest and the lowest temperature. The Rs in the daytime was significant greater than that in the nighttime. The Rs rates in the growing season ranged from –1.55 to 1.46, –0.69 to 1.98, 0 to 5.61, 0 to 4.25, 0.37 to 4.81, and 0.53 to 5.15 μmol/(m^2·s) for the As, Sg, Cv, Pd, Lc and Pa sites, respectively.

3.2 Controlling factors of diurnal variation of Rs

Rs showed different dependency on environment factors at different study sites (Table 2). At the As and Sg sites, Ta was most closely related to Rs and could explain 70.5% and 79.6% of the diurnal variations of Rs. Meanwhile, Rs was negatively correlated with Ha, which indicated Ha was the other controlling factor in regulating the diurnal variations of Rs at the two sites. At the other four sites, the relationship between Rs and Ta, T_{10}, T_{20} and T_{30} all reached very significant level ($P < 0.01$), among which the correlation coefficients with T_{10} were significantly higher than other factors, suggesting that T_{10} was the main controlling factor of the diurnal variations of Rs at the four sites.

3.3 Optimal measuring time of mean daily CO_2 efflux

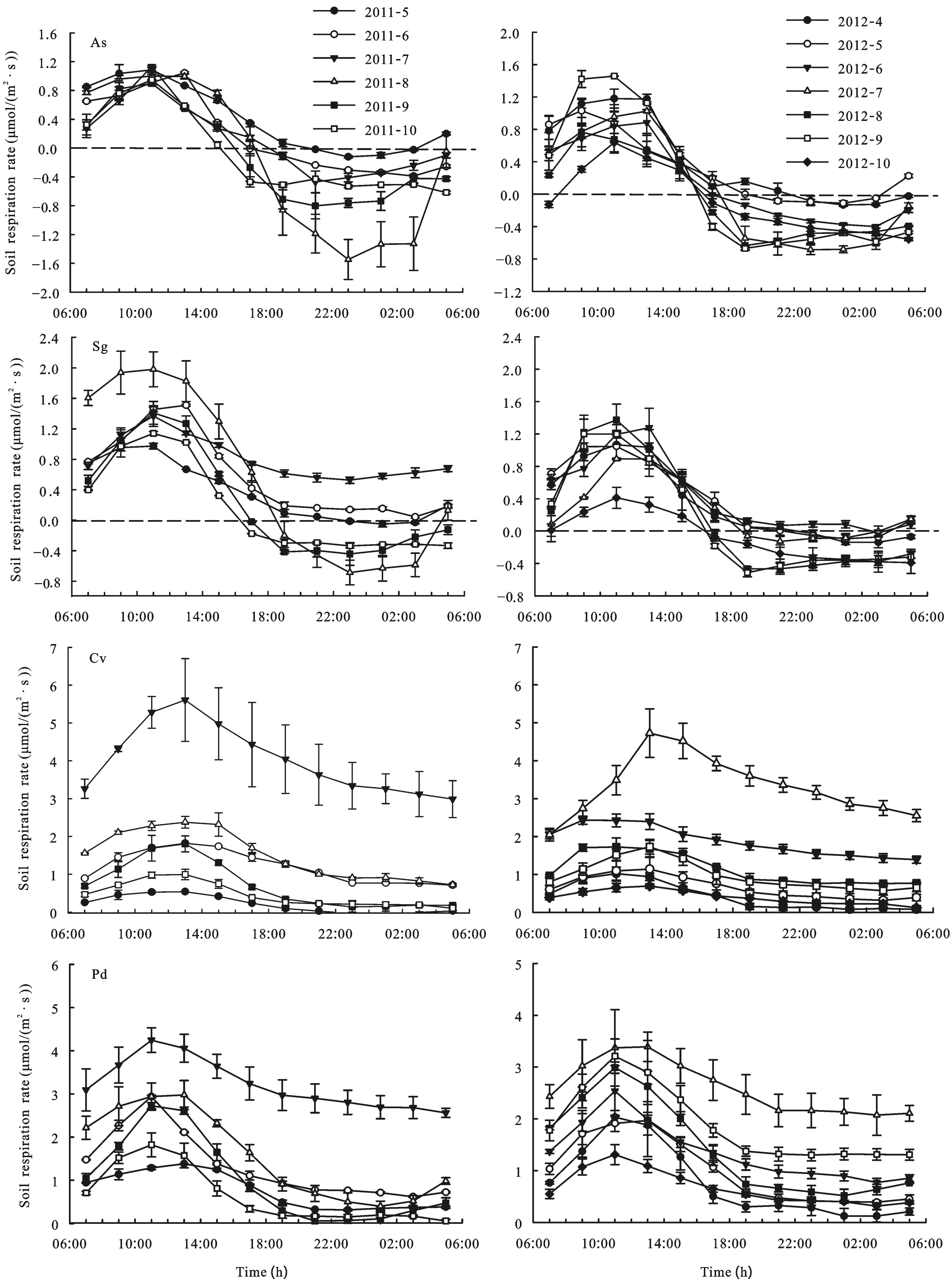
The mean daily soil CO_2 efflux, calculated from 13 individual measurements over each 24 h measurement campaign, was close to those at 7:00–9:00 and 17:00–19:00 at the Cv, Pd, Lc and Pa sites. These two time-windows (7:00–9:00 and 17:00–19:00) represented the optimal time period to make soil CO_2 efflux measurements for the estimation of mean daily CO_2 efflux. However, at the As site, the lowest deviation generally occurred at 15:00–17:00. At the Sg site, the mean daily soil CO_2 efflux was close to the mean of 2 individual soil CO_2 efflux, which was monitored from 15:00 to 19:00 (Table 3).

3.4 Negative CO_2 fluxes

There was a strange phenomenon arose in the diurnal pattern of soil respiration over the two growing seasons: during nocturnal hours, negative soil CO_2 fluxes (downwards into the soil) were frequently observed at the As and Sg sites (Fig. 3). The magnitude of the negative CO_2 fluxes were 0.10–1.55 μmol/(m^2·s) and 0.10–0.69 μmol/(m^2·s) at the As and Sg sites, respectively. The As site had big negative CO_2 fluxes which were slightly higher than the magnitude of its CO_2 emissions (Fig. 3), so that the mean daily value of Rs at the As site even demonstrated the negative CO_2 fluxes.

4 Discussion

Similar to other studies on soil respiration of grassland ecosystem (Dong *et al*., 2000; Wang *et al*., 2014; Wang *et al*., 2015), in diurnal scale, soil respiration exhibited a single peak curve variation at the meadow steppe of Songnen Plain, and reached highest at noon and lowest in the late night or before dawn. There was almost no change on soil water content in a day, and the diurnal variation of soil respiration was tightly consistent with Ta and T_{10}, which indicated that the diurnal variation of soil respiration was mainly influenced by air temperature and soil temperature at 10 cm depth. However, as there was no or very thin plant roots, heterotrophic respiration was the main component of Rs at the As and Sg sites. But for other four sites, the autotrophic respiration from roots and rhizosphere largely contributed to the Rs, as roots and rhizomes lie horizontally about 10 cm under the ground surface, and are highly branched (Wang *et al*., 2004). Precious studies have suggested that the autotrophic respiration was more sensitive to changes in soil temperature than heterotrophic respiration (Luo and Zhou, 2010), which is more easily influenced by the air temperature (Bauer *et al*., 2008). Therefore, Ta had stronger controlling on the daily variation of Rs at the As and Sg sites, while the T_{10} regulated that of the other four sites.


As
Sg
Cv
Pd
2011-5
2011-6
2011-7
2011-8
2011-9
2011-10
2012-4
2012-5
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Soil respiration rate (μmol/(m² · s))
Time (h)

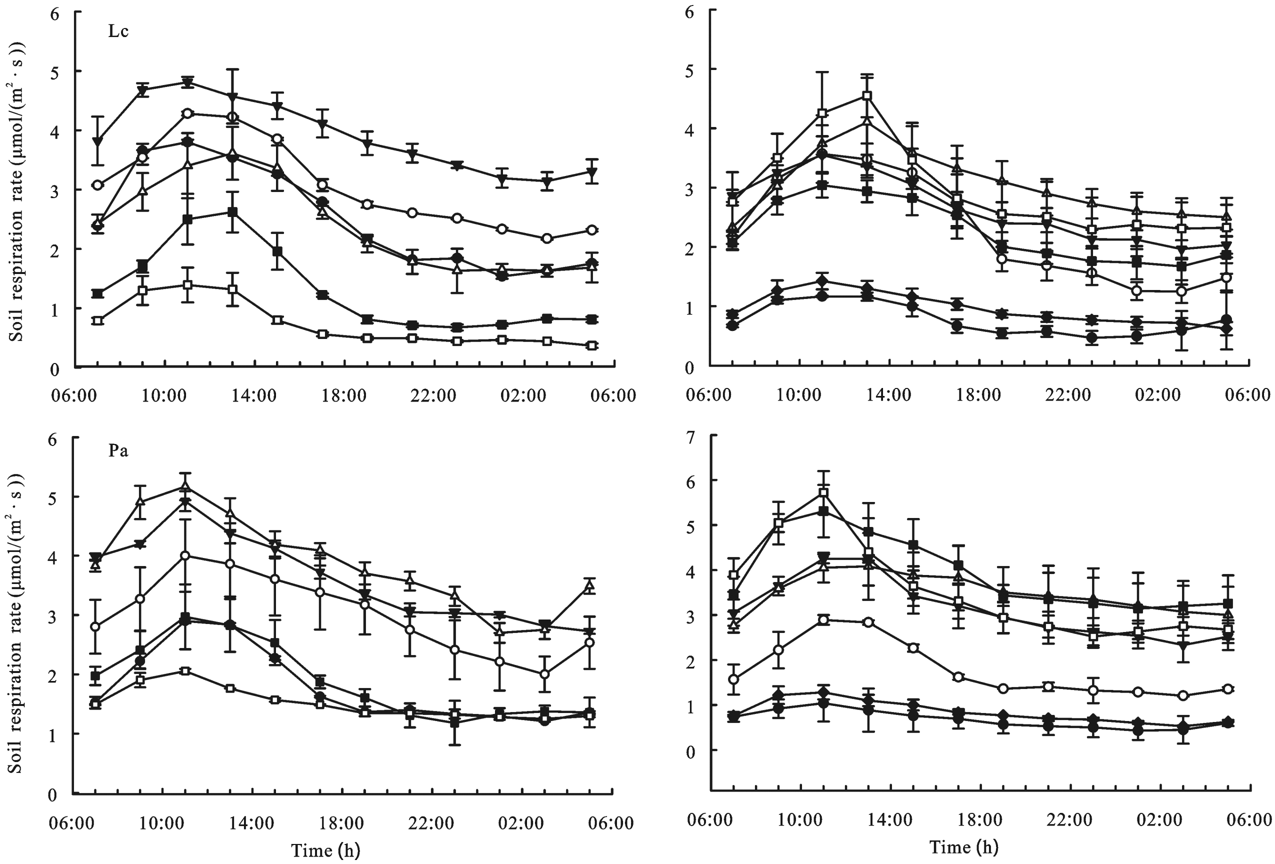

Fig. 3 Diurnal patterns of Rs at alkali-spot land and five vegetation sites in growing season. site codes are given in Table 1, Standard errors are shown as error bars

Table 2 Correlations between Rs and environmental factors in growing season in 2011 and 2012

Site	H_a (%)	T_a (℃)	T_{10} (℃)	T_{20} (℃)	T_{30} (℃)
As	–0.604**	0.705**	0.301**	0.017	–0.005
Sg	–0.626**	0.796**	0.485**	0.232**	0.235**
Cv	0.022	0.703**	0.749**	0.715**	0.686**
Pd	–0.170*	0.682**	0.774**	0.568**	0.548**
Lc	–0.106	0.698**	0.783**	0.661**	0.733**
Pa	–0.156*	0.747**	0.766**	0.781**	0.769**

Notes: T_a is air temperature near soil surface (℃); T_{10}, T_{20}, T_{30} mean soil temperature at 10, 20 and 30 cm depth, respectively (℃); H_a is relative air humidity (%); site codes are given in Table 1. * $P < 0.05$, ** $P < 0.01$, $n = 468$

In this study, the mean daily soil CO_2 efflux, calculated from 12 individual measurements over each 24 h measurement campaign, was close to those at 7:00–9:00 and 17:00–19:00 at the Cv, Pd, Lc and Pa sites. Although the measurements conducted at approximately 17:00–19:00 at night may represent mean daily soil CO_2 efflux equally well as measurements in the morning (7:00–9:00), it is generally not practical to carry out measurements at night using manual chambers. Therefore, the time-window between 7:00 and 9:00 could be used as the optimal measuring time to represent the mean daily soil CO_2 efflux at the Cv, Pd, Lc and Pa sites. Our result was inconsistent with the general measured time in forest, agriculture, and wetland ecosystems, in which the mean daily CO_2 efflux mostly occurred between 9:00 and 11:00 (Wang, 2005; Shi *et al*., 2012; Wang *et al*., 2012). If the Rs rate from 9:00–11:00 was used to represent the mean daily value, the mean daily CO_2 efflux would be overestimated by 7%–119%, 3%–45%, 16%–76% and 14%–137% for the Cv, Pd, Lc

Table 3 Deviations (%) of soil CO_2 efflux at different measurement times (of day) with daily average Rs rates at study sites

Measurement date	Measurement time (h)											
	As		Sg		Cv		Pd		Lc		Pa	
	9:00-11:00	15:00–17:00	9:00–11:00	15:00–19:00	7:00–9:00	9:00–11:00	7:00–9:00	9:00–11:00	7:00–9:00	9:00–11:00	7:00–9:00	9:00–11:00
2011-5	166	30	145	5	11	103	9	36	–13	44	0	79
2011-6	87	–10	166	62	–8	42	–12	25	–5	38	4	72
2011-7	70	–19	186	66	9	29	–2	17	8	23	1	42
2011-8	146	–4	197	82	–38	–17	–21	3	–23	–1	–6	17
2011-9	111	–23	169	–25	–15	51	–12	29	–9	23	28	70
2011-10	95	–30	150	–36	–17	17	10	43	–7	18	–6	38
2012-4	187	0	138	–20	–2	36	–10	45	–11	31	–18	60
2012-5	164	–2	168	28	7	119	–14	25	–5	45	24	49
2012-6	77	–22	98	8	–26	21	–7	9	0	16	12	72
2012-7	98	28	6	18	–19	7	10	16	–2	20	–4	14
2012-8	97	–6	214	–27	4	41	2	30	1	23	41	73
2012-9	316	26	208	–58	–3	60	4	27	–6	29	5	79
2012-10	–21	–24	–20	–74	2	57	–1	26	6	76	10	137

Note: site codes are given in Table 1

and Pa sites, respectively, which indicated that this time window could be a poor representation of the mean daily soil CO_2 efflux for this meadow steppe. This optimal time for Rs measurement (7:00–9:00) was also found in the studies of Jia *et al*. (2006) and Wang *et al*. (2014) at the meadow steppes. However, different from the four sites above, the optimal measuring time at the As and Sg sites was 15:00–17:00 and 15:00–19:00, respectively. These inconsistent time windows may be attributed to the negative CO_2 efflux unstable occurred in the night in the growing season. Considering the strong correlations between Rs and temperature, temperature may not only control the soil CO_2 emission, but also affect the negative CO_2 efflux (CO_2 absorption by the alklaine soil) (Ma *et al*., 2013), which finally changed the optimal measuring time of the As and Sg sites.

Negative soil CO_2 fluxes were frequently observed during the night in the two growing seasons at the As and Sg sites (Fig. 3). Since the alkali-spot land was bare and the vegetation covered Sg site was removed before the measurement, the chamber measuring soil respiration was installed on a bare soil surface. Hence, the negative CO_2 fluxes were not contributed from photosynthesis, and in fact, this was impossible as negative CO_2 fluxes were most frequently observed during nocturnal hours. Rs usually refers to a suite of complex processes contributing to CO_2 efflux from the surface of soils. These processes include respiration by plant roots, microorganisms and soil fauna, and decomposition of soil organic matter (Qi *et al*., 2002). Thus, Rs, by definition, cannot be negative, no matter how small it might be at a bare saline site. Hence, there must be a significant, unrecognized process of CO_2 exchange between this saline soil and the atmosphere above, in addition to the processes of soil respiration that are predominantly microbial and root metabolic activities. This negative soil CO_2 flux was also reported at American Mojave desert (Wohlfahrt *et al*., 2008) and at the southern periphery of the Gubantonggut desert (Xie *et al*., 2009), where soil type was also saline or alkaline. As these negative CO_2 fluxes into the soil were detected mostly at the saline land or desert site where the soil was extremely saline, Xie *et al*. (2009) reasoned that these negative CO_2 fluxes stemmed from the salinity of the soil. Moreover, Ma *et al*. (2013) indicated that an inorganic CO_2 diffusion and dissolution process, derived from the change in the size of the reservoir of dissolved inorganic carbon in the soil solution, may explain negative CO_2 fluxes in saline-alkaline soils. However, Schlesinger *et al*. (2009) considered that the net uptake of carbon in the Mojave Desert, reported from the dome experiments by Jasoni *et al*. (2005) and Wohlfahrt *et al*. (2008), was vastly in excess of NPP of that ecosystem. If the uptake is retained in soil organic matter, its rate of increase would exceed that found in nearly all studies of temperate-zone forest and grassland ecosystems (Post and Kwon, 2000). And such large uptake would seem unlikely to have escaped notice at such a well studied site. Hence, gas exchange measurements should be used with caution and better validation if they are expected to indicate the magnitude of carbon sink in these ecosystems (Schlesinger *et al*., 2009).

Although debate centered around the negative CO_2 flux of saline soil, the ′anomalous′ negative flux might have significant implications to global carbon cycle, which worth wide attention of the concerned scientific community. This suggested that more types of soil salinity/alkalinity and long term monitoring were required, and the mechanism of this absorption was still worthy further study.

5 Conclusions

This study identified the diurnal variations of soil respiration and its optimal measuring time-window at the meadow steppe in the western Songnen Plain. The main conclusions are as follows.

(1) The diurnal patterns of soil respiration exhibited single peak curves, with lower values in the early mornings and late evenings and the peak CO_2 flux occurring around midday or mid afternoon. Air temperature and soil temperature at the 10 cm depth were the main controlling factors which regulated the daily variation of soil respiration.

(2) The soil respiration rate from 7:00 to 9:00 in the morning could be used as the daily mean soil CO_2 efflux at the Cv, Pd, Lc and Pa sites. But for As and Sg sites, the mean daily soil CO_2 efflux was close to the soil CO_2 efflux from 15:00 to 17:00 and the mean of 2 individual soil CO_2 efflux between 15:00 and 19:00, respectively.

(3) Negative soil CO_2 fluxes were frequently observed during the night over the two growing seasons at the As and Sg sites, which illustrated the CO_2 absorption by alkaline soils.

The results could not only supply fundamental data of soil CO_2 flux in saline and alkaline land to the global carbon cycle, but also provide important evidences and basis for figuring out the ′missing sink′ of carbon.

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