

Seasonal Patterns of Soil Respiration in Three Types of Communities along Grass-Desert Shrub Transition in Inner Mongolia, China

JIN Zhao (金钊)^{1,2}, QI Yuchun*¹ (齐玉春), DONG Yunshe¹ (董云社), and Manfred DOMROES³

¹*Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101*

²*State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an 710075*

³*Institute of Geography, Mainz University, Mainz 55099, Germany*

(Received 19 December 2007; revised 25 August 2008)

ABSTRACT

The seasonal dynamics of soil respiration in steppe (*S. bungeana*), desert shrub (*A. ordosica*), and shrub-perennial (*A. ordosica* + *C. komarovii*) communities were investigated during the growth season (May to October) in 2006; their environmental driving factors were also analyzed. In the three communities, soil respiration showed similar characteristics in their growth seasons, with peak respiration values in July and August owing to suitable temperature and soil moisture conditions during this period. Meanwhile, changes in soil respiration were greatly influenced by temperatures and surface soil moistures. Soil water content at a depth of 0 to 10 cm was identified as the key environmental factor affecting the variation in soil respiration in the steppe. In contrast, in desert shrub and shrub-perennial communities, the dynamics of soil respiration was significantly influenced by air temperature. Similarly, the various responses of soil respiration to environmental factors may be attributed to the different soil textures and distribution patterns of plant roots. In desert ecosystems, precipitation results in soil respiration pulses. Soil carbon dioxide (CO₂) effluxes greatly increased after rainfall rewetting in all of the ecosystems under study. However, the precipitation pulse effect differed across the ecosystem. We propose that this may be a result of a reverse effect from the soil texture.

Key words: soil respiration, grass-desert shrub transition, *Stipa bungeana*, *Artemisia ordosica*, *Artemisia ordosica* + *Cynanchum komarovii*, Ordos Plateau

Citation: Jin, Z., Y. C. Qi, Y. S. Dong, and M. Domroes, 2009: Seasonal patterns of soil respiration in three types of communities along grass-desert shrub transition in Inner Mongolia, China. *Adv. Atmos. Sci.*, **26**(3), 503–512, doi: 10.1007/s00376-009-0503-4.

1. Introduction

The soil is a huge carbon pool. It contains 1395–2011 Pg C (1 Pg = 10¹⁵ g), which is about thrice the size of the atmosphere's carbon reservoir (Post et al., 1982; Falkowski et al., 2000; Prentice et al., 2001). Soil plays an important role in the global biogeochemistry cycle of carbon (Mielnick and Dugas, 2000; Lohila et al., 2003). Soil respiration, or the emission of CO₂ from the soil surface, is the major pathway by which soil carbon is released to the atmosphere. In fact, this

process is now recognized as one of the largest carbon fluxes in the global carbon cycle (Schlesinger and Andrews, 2000). On a global scale, soil respiration contributes about 50–75 Pg C yr⁻¹ of carbon emission to the atmosphere, which is almost equal to or greater than the estimated global terrestrial net primary productivity of 50–60 Pg C yr⁻¹ (Raich and Schlesinger, 1992). Therefore, any minor changes in soil respiration can strongly influence atmospheric CO₂ concentration (Schlesinger and Andrews, 2000; Qi et al., 2006).

Grasslands, covering nearly one-fifth of the world's

*Corresponding author: QI Yuchun, qiyc@igsnr.ac.cn

land surface area, are one of the most widespread vegetation types worldwide (Lieth, 1978). They play a significant, but poorly recognized, role in the global carbon cycle (Hall et al., 1995; Scurlock and Hall, 1998). Grasslands are reported to constitute a carbon pool of 279–642 Pg C, much of which is allocated belowground (Prentice, 1993; Mooney et al., 2001). An analysis by Scurlock and Hall (1998) shows that the world's grassland biomes are an annual carbon sink of about 0.5 Pg C; however, their contribution remains uncertain due to high-impact land management (e.g., particularly those resulting in degradation and desertification).

One form of desertification occurs by the conversion of homogeneous grasslands into shrub-dominated ecosystems, and such conversion has been noted over wide areas in the world (Grover and Musick, 1990; Schlesinger et al., 1990; Archer et al., 2001; Huenneke et al., 2002). Moreover, changes in plant type distribution and the coverage of grasslands versus shrublands have greatly affected ecosystem function and biogeochemistry cycles, including the carbon cycle (Schlesinger et al., 1990, 1996; Schlesinger and Pilmanis, 1998; Hibbard et al., 2001; Huenneke et al., 2002; Asner et al., 2003). Many studies propose that the invasion of woody vegetation into grasslands can lead to an increased amount of vegetation carbon storage in these ecosystems (Scholes and Archer, 1997; Houghton et al., 1999; Amundson, 2001). However, Jackson et al. (2002) found that woody plant encroachment into grasslands resulted in ecosystem carbon loss. In this case, soil respiration is a key process in ecosystem carbon cycling because it partly controls the potential of the ecosystem carbon sink. Incidentally, there are limited reports on soil respiration in transitional areas where there is plant conversion from grasslands to shrublands. In the southwestern part of the United States, Scott et al. (2006) reported that during the growth season (March to December), the values of net ecosystem exchange of carbon dioxide (g C m^{-2}) at three sites incurring wood-plant encroachment were -63 (grassland), -212 (grassland-shrubland mosaic), and -233 (fully developed woodland), respectively, indicating the potential for increase of carbon sequestration upon wood and shrub invasion into grasslands.

China has grasslands of area totaling $4 \times 10^6 \text{ km}^2$, or about 40% of the nation's total land surface (Chen and Wang, 2000). However, most of these areas have been affected by desertification (Ci, 1999). Shrub invasion is also very prevalent in the northwest grasslands of China (Xiong et al., 2005). To date, reports on the soil respiration of China's grasslands mainly focus on the temperate grasslands of Inner Mongolia and the Songnen Plain (Dong et al., 2000, 2005; Qi

et al., 2007), and the alpine grassland of the Tibetan Plateau (Du et al., 2006; Zhao et al., 2006). However, as earlier mentioned, information on the soil respiration of grass-desert shrub transitional areas remains limited. Therefore, further research on soil respiration and the carbon cycle for the grassland biome should be deemed crucial to accurately predict the potential carbon sinks of terrestrial ecosystems in China.

In this paper, *in situ* soil respiration was measured in three semi-arid and arid communities in Inner Mongolia, China, on Mu Us Desert sandy soil type. Two main points are addressed in this study: (1) the characteristics of soil respiration in the three identified communities, and (2) the effects of temperature, soil moisture, and precipitation on soil respiration.

2. Materials and methods

2.1 Site description

The experimental sites were set up in the Mu Us Desert in the Ordos Plateau of Inner Mongolia, China ($37^{\circ}27' - 39^{\circ}51' \text{N}$, $107^{\circ}20' - 111^{\circ}30' \text{E}$), and in the vicinity of the Ordos Sandy Grassland Research Station, which belongs to the Chinese Ecosystem Research Network. The region is considered to have an ecotone between grassland and shrubland, wherein desertification is identified as a serious problem. The climate is typically semiarid continental with marked seasonal and diurnal temperature variations and low precipitation. Annual mean precipitation is 345 mm with an annual mean evaporation of 2535 mm. From April to October, mean observed precipitation is 321.8 mm, which accounts for about 93% of the annual precipitation. The annual mean temperature is 6.7°C , with monthly mean temperatures below 5°C from November to March and between $7.4^{\circ}\text{C} - 21.9^{\circ}\text{C}$ from April to October. The area's vegetation type is primarily composed of a shrub community that is dominated by *A. ordosica* (Zheng et al., 2005).

Three study sites were selected for steppe (*S. bungeana*), desert shrub (*A. ordosica*), and shrub-perennial (*A. ordosica* + *C. komarovii*) communities. These represent the different stages of vegetation degradation and grass-desert shrub transition in the Mu Us Desert. The steppe community of *S. bungeana* is the climax vegetation type in this region, and represents a typical mild desertification. The desert shrub community of *A. ordosica* is the most widespread vegetation in this region and can be used as an index of mid-level desertification. Meanwhile, the desert shrub-perennial community of *A. ordosica* + *C. komarovii* indicates severe desertification in the area (Cheng et al., 2007).

The *S. bungeana* site lies at $39^{\circ}23' \text{N}$ and $109^{\circ}11' \text{E}$,

Table 1. Description of soils and root patterns at the three sampling sites.

Community	Soils						Roots pattern	
	Soil types	Soil textures	Depth (cm)	OC (%)	TN (%)	C/N	Depth (cm)	Percentage (%)
Steppe (<i>S. bungeana</i>)	Light chestnut soil	Fine-textured Sand+Silt: 60%–70% Clay: 30%–40%	0–5	0.49	0.06	8.17	0–20	100
			5–10	0.44	0.05	8.80	20–40	
			10–20	0.42	0.05	9.20	40–60	
			20–30	0.39	0.04	9.75		
Shrub (<i>A. ordosica</i>)	Eolian sand soil	Coarse-textured Sand+Silt: 80%–90% Clay: 10%–20%	0–5	0.54	0.04	13.50	0–20	86.2
			5–10	0.32	0.03	10.67	20–40	11.7
			10–20	0.26	0.03	8.67	40–60	2.1
			20–30	0.24	0.02	12.00		
Shrub-perennial (<i>A. ordosica</i> + <i>C. komarovii</i>)	Eolian sand soil	Coarse-textured Sand+Silt: 80%–90% Clay: 10%–20%	0–5	0.32	0.03	10.67	0–20	82.5
			5–10	0.22	0.02	11.00	20–40	13.0
			10–20	0.22	0.02	11.00	40–60	4.5
			20–30	0.19	0.02	9.50		

Notes: OC and TN refer to soil organic carbon and total nitrogen, respectively; C/N means the ratios of OC and TN.

and is 1355 m above sea level. The major species in the steppe community are *S. bungeana*, *Cleistogenes songorica*, *Lespedeza dahurica*, *Thymus serpyllum*, and *Allium mongolicum*. The *A. ordosica* site lies at 39°29'N and 110°11'E, and is 1335 m above sea level. The major species in the desert shrub community are *A. ordosica*, *Hedysarum fruticosum*, *Pennisetum centrasiaticum*, *Agropyron desertorum*, *Agropyron fragile*, *Oxytropis psammocharis*, and *Astragalus melilotoides*, among others. The *A. ordosica* + *C. komarovii* site lies near (about 500 m northeast of) the site of *A. ordosica*. The major species in the desert shrub-perennial community are *A. ordosica*, *C. komarovii*, and *Cleistogenes squarrosa*.

Information on soil properties and root patterns at the three sampling sites is presented in Table 1.

2.2 Gas sampling and flux determination

Carbon dioxide gas samples were collected using static closed opaque chambers during the growth season of May to October in 2006. Such chambers were used to eliminate the influence of plant photosynthesis, and to overcome the shortcoming of overly rapid temperature rises in the chamber during the measurements; the effectiveness of this method in measuring CO₂ efflux has been reported by Dong et al. (2000) and Lohila et al. (2003).

In the present study, the static closed opaque chamber was made of 8-mm thick black acrylic material with a tinfoil reflecting film attached to the external surface. The dimensions of the chambers were 50 cm (length) × 50 cm (width) × 40 cm (height). Gas was collected once every month during the early and late growth season (May and October), and twice per month in the middle months of the growth season

(June, July, August, and September). The samplings were conducted at a relatively uniform time, which is around 0900 LST to 1100 LST, because effluxes measured during this time are regarded to be representative of the daily average flux (Kessavalou et al., 1998; Du et al., 2006). Six plots were set up in each of the three communities studied. Each plot size measured 50 cm × 50 cm, and provided a gas chamber.

The average result for the six chamber measurements in each community was taken to determine soil respiration rates. In the shrub community, four plots represented bare soil and soil with biologic crusts in the interplant spaces, while the two remaining plots represented soil beneath shrubs (including the roots). Aboveground vegetation was cut to ground level one week before the sampling. In the shrub-perennial community, three plots represented soil beneath shrubs, and three other plots represented soil beneath perennials (again including roots, with aboveground vegetation cut to ground level one week before the sampling). In the steppe community, six plots were all applied on soil wherein grass was cut one week before the sampling.

During the course of measurements, the sampling chamber was placed on a stainless steel frame (collar), inserted at 5 cm into the plots, and sealed with distilled water. The lid of the chamber was installed with a fan which circulated air driven by a 12-V lead-acid battery, a highly precise temperature sensor connected with a digital thermometer, and a gas channel which consisted of a PVC tube, a silica gel pipe connected to a 100 mL syringe, and a three-way stopcock for collecting gas. Gas sampling lasted for 30 min, and the gas samples were extracted from the chamber at 0, 10, 20, and 30 min after capping. Each time, about 300 mL

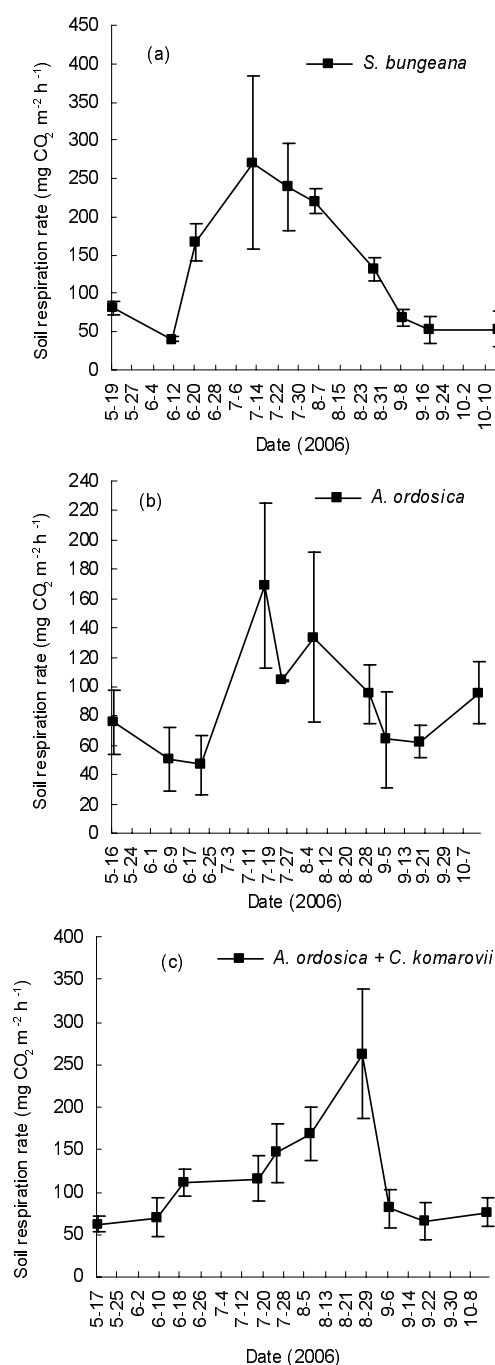


Fig. 1. Seasonal variations in soil respiration in the three communities during the growth season of 2006: (a) steppe community of *S. bungeana*, (b) desert shrub community of *A. ordosica*, and (c) desert shrub-perennial community of *A. ordosica*+*C. komarovii*. Bars denote the standard deviation of the mean (SD, $n = 6$).

of gas was extracted from the chamber and collected in polyethylene-coated aluminum gas bags; CO₂ concentrations were measured in the laboratory shortly after sampling by a LI-6252 infrared CO₂ analyzer (LICOR Inc., Lincoln, NE, USA).

The CO₂ flux was calculated by formula (1) as expressed below:

$$F = \frac{\Delta m}{\Delta t} D \frac{V}{A} = h_c D \frac{\Delta m}{\Delta t} \quad (1)$$

where F is the CO₂ flux (mg m⁻² h⁻¹), V is the volume of the sampling chamber (cm³), A is the land area covered by the chamber (cm²), D is the gas density of the chamber, and $D = P/RT$ (mol m⁻³), P is air pressure, T is the air temperature inside the chamber, R is the gas constant, $\Delta m/\Delta t$ denotes the linear slope of the concentration change with time over the measurement period, and h_c represents the height of the sampling chamber.

2.3 Temperature and soil moisture measurement

During each gas sampling, air temperature, soil temperature at depths of 0, 5, and 10 cm, gravimetric soil moisture, and internal chamber air temperature were gathered simultaneously. Air temperature inside the chamber was measured using a temperature sensor, air temperature was measured with a mechanical ventilated thermometer, and soil temperature at depths of 0, 5, and 10 cm was measured with a digital thermo detector produced by the Sinan Instruments Plant of Beijing Normal University. To determine gravimetric soil moisture, the oven-drying method was used.

2.4 Data analysis

Statistical analyses were conducted using Statistical Program for Social Sciences (SPSS 11.0, SPSS Inc., 2001). Correlation analysis was used to examine the relationships among soil surface moisture, temperature, and CO₂ effluxes. Regression and curve fitting analysis was used to determine the effects of soil surface moisture and temperature on CO₂ flux.

3. Results

3.1 Seasonal dynamics of soil respiration

Soil respiration measured in the steppe (*S. bungeana*), desert shrub (*A. ordosica*), and shrub-perennial (*A. ordosica* + *C. komarovii*) communities during the growth season of 2006 were found to have similar patterns of variation (Figs. 1a, b, and c). The peak values mostly occurred in July and August, and the soil respiration rates were lower before mid-June and after early September. In the steppe community, the soil respiration rates varied from 40.33 to 270.95 mg CO₂ m⁻² h⁻¹ during the growth season, with the peak value occurring in mid-July. As compared to the steppe, the desert shrub and shrub-perennial commu-

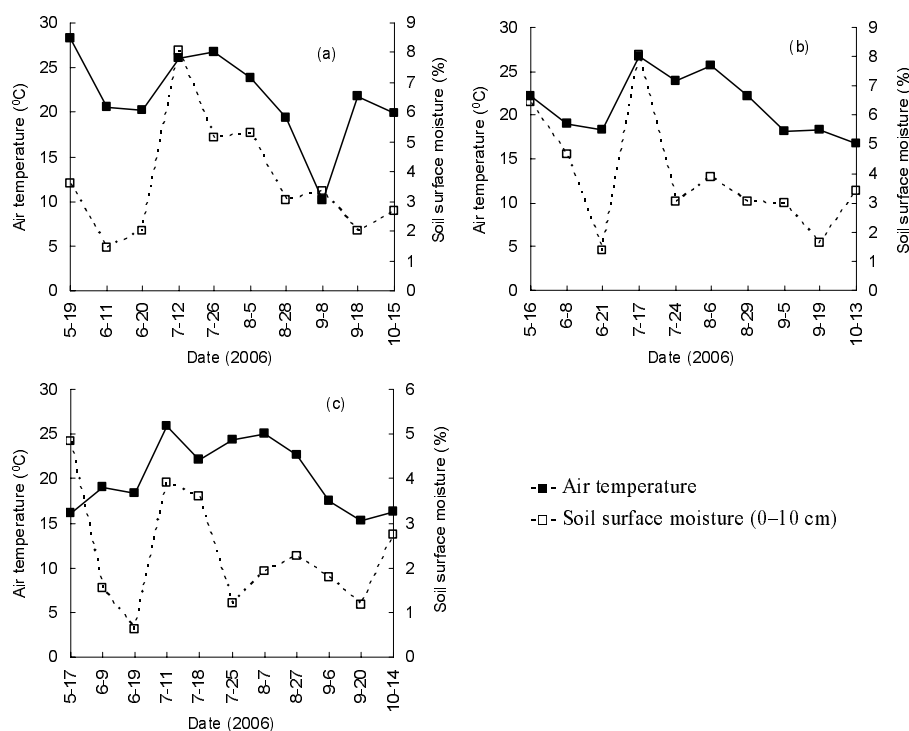


Fig. 2. Seasonal variations in air temperature and surface soil moisture in the three communities during the growth season of 2006: (a) steppe community of *S. bungeana*, (b) desert shrub community of *A. ordosica*, and (c) desert shrub-perennial community of *A. ordosica*+*C. komarovii*. Data points represent the mean values ($n = 6$). SWC refers to soil water content.

nities showed less variation and lower soil respiration rates. In the shrub community, the soil respiration rates varied from 50.45 to 168.84 mg CO₂ m⁻² h⁻¹, with the peak value also occurring in mid-July. However, the soil respiration rates in the desert shrub-perennial community varied from 62.33 to 262.12 mg CO₂ m⁻² h⁻¹, with the peak values occurring in late August.

The seasonal characteristics of soil respiration in the three communities indicate that moderate temper-

ature and adequate soil moisture during July and August triggered plant activity and soil crust formation. This consequently led to the higher soil respiration observed during the period.

3.2 Effects of temperature and surface soil moisture on soil respiration

In this study, seasonal variations in air temperature and soil moisture at a depth of 0 to 10 cm of the three sampling sites were analyzed (Figs. 2a–c). Correlation

Table 2. Correlation analysis of environmental factors with soil respiration rates.

Community	Correlations					
	Air temperature	Soil surface temperature	5 cm soil temperature	10 cm soil temperature	0–10 cm SWC	10–20 cm SWC
Steppe (<i>S. bungeana</i>)	0.48	0.26	0.39	0.50	0.83**	0.38
Desert shrub (<i>A. ordosica</i>)	0.83**	0.20	0.08	0.01	0.61	0.46
Shrub-perennial (<i>A. ordosica</i> + <i>C. komarovii</i>)	0.69*	0.38	0.45	0.34	0.47	0.46

Notes: SWC refers to soil water content (** denotes $p < 0.01$; * denotes $p < 0.05$).

analysis showed seasonal soil respiration in the steppe varied closely with the variation in soil water content at a depth of 0 to 10 cm. However, variation in air temperature was shown to influence seasonal soil respiration in the desert shrub and shrub-perennial communities (Table 2). To better understand the reasons for such variation in CO₂ effluxes, statistical relationships between the environmental factors and soil respiration rates were analyzed (Table 3). The results indicate that the soil respiration dynamics of the arid and semi-arid communities studied were greatly influenced by temperatures and surface soil moistures, which varied between the different community types. Soil water content at a depth of 0 to 10 cm was found to be the key environmental factor affecting the variation in soil respiration in the steppe; changes in soil water content could explain 68% of the variations in soil respiration rates. In contrast, air temperature is observed as the key environmental factor affecting the variations in soil respiration in the desert shrub and shrub-perennial communities, accounting for 41%–68% of the variations in soil respiration rates.

3.3 Precipitation pulses of soil respiration

In 11 July 2006, soil respiration rates and soil water content at a depth of 0 to 10 cm were measured following a 10-day dry period of the three communities under study. Fortunately, a rainfall event of 17 mm transpired in 12 July 2006, and the soil respiration rates were immediately measured after precipitation. The results indicate that precipitation could greatly increase soil respiration when conditions have been

dried for a long time (Table 4). Before precipitation, the soil moisture (0 to 10 cm) was poor (2.09%–3.56%), and the soil respiration rate was relatively low (144.35–215.54 mg CO₂ m⁻² h⁻¹). In contrast, after precipitation, the soil moisture and soil respiration rates greatly increased. The increases in soil respiration were 1.34, 3.23, and 1.93 times for the steppe, desert shrub, and shrub-perennial communities, respectively (Table 4). The effects of the precipitation pulse were higher in the two desert shrub communities than in the steppe.

4. Discussion

4.1 Soil texture, plant roots distribution, and responses of soil respiration

The roles of temperature and soil moisture as independent or confounded factors influencing soil respiration are well documented in a number of studies (Kirschbaum, 1995; Davidson et al., 1998; Fang and Moncrieff, 2001; Fang et al., 2005). In the present study, soil respiration in the three arid and semi-arid communities showed different responses to temperature and surface soil moisture. For the steppe community, the seasonal dynamics of soil respiration were significantly influenced by surface soil moisture at a depth of 0 to 10 cm. In contrast, for the desert shrub and shrub-perennial communities, seasonal variations in soil respiration were markedly driven by air temperature change. The different responses of soil respiration to temperature and soil moisture may be attributed to the different soil textures and distribution patterns of plant roots in the three communities. For

Table 3. Multiple regression and curve fitting analysis between soil respiration rates and main environmental factors during the growth season of 2006 at the three sampling sites.

Sampling site	Independent variable	Fitted equation	<i>F</i>	<i>p</i>	<i>R</i> ²
Steppe (<i>S. bungeana</i>)	<i>M</i> and <i>T</i>	$Y=2.302 T+33.074 M-38.581$	8.08	0.015	0.70
	<i>M</i>	$Y=35.71 M+1.769$	17.23	0.003	0.68
	<i>M</i>	$Y=131.101 \ln (M)-21.361$	13.33	0.006	0.63
	<i>M</i>	$Y=-0.412 M^2+39.547 M-5.267$	7.55	0.018	0.68
	<i>M</i>	$Y=31.552 M^{1.041}$	11.52	0.009	0.59
	<i>M</i>	$Y=39.845 e^{0.270M}$	11.26	0.010	0.59
Desert shrub (<i>A. ordosica</i>)	<i>M</i> and <i>T</i>	$Y=8.055 T+3.357 M-93.284$	8.19	0.015	0.70
	<i>T</i>	$Y=9.255 T-105.726$	17.00	0.003	0.68
	<i>T</i>	$Y=0.196 T^{1.991}$	11.72	0.009	0.59
	<i>T</i>	$Y=10.858 e^{0.096T}$	13.94	0.006	0.64
	<i>T</i>	$Y=583.86 e^{-40.28/T}$	9.72	0.014	0.55
Shrub-perennial (<i>A. ordosica</i> + <i>C. komarovii</i>)	<i>M</i> and <i>T</i>	$Y=13.125 T-1.021 M-140.328$	4.585	0.053	0.57
	<i>T</i>	$Y=9.827 T-83.937$	6.26	0.034	0.41
	<i>T</i>	$Y=0.495 T^{1.788}$	12.73	0.006	0.59
	<i>T</i>	$Y=17.906 e^{0.087T}$	11.69	0.008	0.57
	<i>T</i>	$Y=648.16 e^{-35.81/T}$	13.47	0.005	0.60

Note: *M* is the soil surface moisture (0–10 cm); *T* is air temperature; *F* is the *F*-statistic of the fit; *p* is the significance level of the *F*-test; and *R*² is the goodness of fit of the regression equation.

Table 4. Soil respiration and soil moisture change pre- and post-precipitation (storm total=17 mm) from 11–12 July 2006.

Community		Pre-precipitation	Post-precipitation	Post/Pre
Steppe	<i>R</i>	202.86	270.95	1.34
(<i>S. bungeana</i>)	<i>M</i>	3.56	8.06	2.26
Desert shrub	<i>R</i>	144.35	466.74	3.23
(<i>A. ordosica</i>)	<i>M</i>	3.45	7.46	2.16
Shrub-perennial	<i>R</i>	215.54	416.81	1.93
(<i>A. ordosica</i> + <i>C. komarovii</i>)	<i>M</i>	2.09	4.68	2.24

Note: *R* is the soil respiration rate ($\text{mg CO}_2 \text{ m}^{-2} \text{ h}^{-1}$), and *M* is the soil surface moisture (0–10).

the grassland of *S. bungeana*, the soil is fine textured and has high clay content. The soil types of the other arid ecosystems generally display high water-retention capacity, and their water availability is greater at the soil surface layer, where the majority of microbial activity occurs (Foster, 1988; Hook and Burke, 2000; Austin et al., 2004). The plant roots in the steppe are mostly distributed in the surface soil layer (0 to 20 cm), thereby utilizing surface soil moisture; however, water availability is often poor due to the high evaporation and low precipitation in this region. Therefore, plant growth and soil microbial activity in the steppe are mostly controlled by the surface soil water conditions.

In contrast, the desert shrub and shrub-perennial communities are located in semi-mobile or stabilized sand dunes where soil is coarse textured and made of traveling sands. These sandy soils have less runoff, and have more and deeper infiltration because of their lower water storage capacity (Austin et al., 2004). The plant roots of the shrub-perennial community are distributed more deeply in these soil layers, especially for the perennials *C. komarovii*. Although surface soil water is easily lost, the deeper soil layers can hold abundant water supplies and thus maintain plant growth (Gibbens and Lenz, 2001). These indicate that surface soil moisture is not the driving variable for soil respiration in desert shrub ecosystems; in contrast, the soil respiration pattern is mostly influenced by changes in air temperature.

4.2 Precipitation pulses of soil respiration

In semiarid and arid regions, precipitation is notably low, and water availability is the key factor influencing ecosystem function and processes (Noy-Meir, 1973). Plant growth and soil microbial activity are often significantly triggered by discrete precipitation events. A small rainfall event (generally of size <5 mm) can stimulate the activity of soil microbes and trigger soil respiration, which can then immediately lead to strong carbon flux to the atmosphere (Austin et al., 2004). Moreover, such precipitation may physically displace soil pore spaces, which were

previously filled by soil air (mainly as CO_2) during interpulse times, thus freeing the carbon present in large soil pools of inorganic carbonates (Schlesinger, 1985). Moreover, large rainfall events not only stimulate strong soil CO_2 efflux, but they also trigger the activity and growth of vascular plants and carbon accumulation in ecosystems. Plant responses to precipitation are also noted to be more complicated compared to the effect of soil respiration (Huxman et al., 2004).

In the present study, precipitation greatly increased soil respiration rates. The three identified communities showed different intensities of response to a precipitation pulse. For the steppe of *S. bungeana*, the response to a pulse was smaller than for the desert shrub communities, and the different responses were attributed to the communities' different soil textures. In water limited ecosystems in coarse-textured soils, Austin et al. (2004) suggested that carbon and nitrogen mineralization linearly increases along a gradient of precipitation; in contrast, fine-textured soils are suggested to have a saturating relationship with increasing precipitation. The difference in potential carbon and nitrogen mineralization between coarse- and fine-textured soils may be due to the relative difference in their water-retention capacity. Our investigation found that soil was fine textured in the steppe community, while soil was coarse textured in the two other desert communities. As compared to their counterparts, the fine-textured soils of arid and semi-arid regions tend to accommodate greater water-storage by virtue of lower permeability. Thus, although soil microbial activity and plant growth could be greatly triggered by a large rainfall event, a sudden increase in soil water content concurrent with poor soil permeability can constrain soil microbe activities. As such, the precipitation pulse effect on respiration for the steppe was lower than those of the two other desert communities.

Soil respiration is usually weak in desert ecosystems because of their low precipitation and poor soil organic carbon and nitrogen contents. Precipitation triggers soil respiration pulses, and the soil carbon flux rate can increase by 30 times immediately after an

event of soil rewetting (Sponseller, 2007). Therefore, knowledge of precipitation pulses is essential in ensuring an accurate estimation of soil CO₂ efflux in arid ecosystems. According to the effects calculated in this study, the values of carbon release during the growth season were much higher when including the impact of precipitation pulses. Since most of the other reported values on CO₂ efflux in arid ecosystems do not take into account infiltration pulse events, extreme difficulty can be expected when attempting to accurately estimate amounts of soil respiration. Presently, a combined approach using modeling and field-based collections covering a range of seasonal moisture conditions is deemed necessary to enable long-term representation of fluxes (Luo and Reynolds, 1999; Reynolds et al., 2000, 2004).

5. Conclusions

During the growth season of May to October, the steppe, desert shrub, and shrub-perennial communities of arid and semi-arid regions in Inner Mongolia, China clearly displayed the dynamics of seasonal soil respiration. Soil CO₂ efflux varied across the community types, with variations in efflux manifesting through different temperatures and moisture conditions. In the steppe community of *S. bungeana*, soil water content at a depth of 0 to 10 cm was the key environmental factor triggering soil respiration changes, accounting for 68% of the variation in soil respiration rates. In contrast, soil respiration was significantly influenced by air temperature in the desert shrub (*A. ordosica*) and shrub-perennial (*A. ordosica* + *C. komarovii*) communities, in which air temperature changes accounted for 41% to 68% of the variations in soil respiration rates.

The different responses of soil respiration to temperature and soil moisture were attributed to the different soil textures and distribution patterns of plant roots in the three communities studied. In desert ecosystems, precipitation triggered soil respiration pulses and soil CO₂ effluxes, with a great increase in flux values after rainfall rewetting. Moreover, in the three communities, the difference in the precipitation pulse effect may be attributed to the reversal of the soil texture effect. As such, in semiarid and arid regions, precipitation pulses need to be considered when calculating annual carbon budgets, since they can profoundly influence the estimation of total soil CO₂ effluxes.

Acknowledgements. This research was supported by the National Natural Science Foundation of China (Grant Nos. 40730105, 40501072, and 40673067), the

Ministry of Science and Technology of China (Grant Nos. 2007BAC03A11 and 2002CB412503), and The Knowledge Innovation Program of the Institute of Geographical Sciences and Natural Resources Research of the Chinese Academy of Sciences (The effect of human activities on regional environmental quality, health risk, and environmental remediation). We likewise thank Ms. Diane Elizabeth Allen for her valuable comments and for the proofreading of the manuscript. Moreover, we extend our gratitude to anonymous referees for their helpful reviews and constructive suggestions, which improved our manuscript considerably.

REFERENCES

- Amundson, R., 2001: The carbon budget in soils. *Annual Review of Earth and Planetary Sciences*, **29**, 535–562.
- Archer, S., T. W. Boutton, and K. A. Hibbard, 2001: Trees in grasslands: biogeochemical consequences of woody plant expansion. *Global Biogeochemical Cycles in the Climate System*, Schulze et al., Eds., A Harcourt Science and Technology Company, California, U.S.A., 115–138.
- Asner, G. P., S. A. Archer, R. F. Hughes, J. N. Ansley, and C. A. Wessman, 2003: Net changes in regional woody vegetation cover and carbon storage in North Texas rangelands, 1937–1999. *Global Change Biology*, **9**, 316–335.
- Austin, A. T., Y. Laura, J. M. Stark, J. Belnap, A. Porporato, U. Norton, D. A. Ravetta, and S. M. Schaeffer, 2004: Water pulses and biogeochemical cycles in arid and semiarid ecosystems. *Oecologia*, **141**, 221–235.
- Chen, Z. Z., and S. P. Wang, 2000: *Typical Grassland ecosystem in China*. 1st ed., Science Press, Beijing, 412pp. (in Chinese)
- Cheng, X., S. An, J. Chen, B. Li, Y. Liu, and S. Liu, 2007: Spatial relationships among species, above-ground biomass, N, and P in degraded grasslands in Ordos Plateau, northwestern China. *Journal of Arid Environments*, **68**, 652–667.
- Ci, L. J., 1999: The status quo of desertification in China and its restoration strategy. *Forestry of China*, **5**, 14–15.
- Davidson, E. A., E. Belk, and R. D. Boone, 1998: Soil water content and temperature as independent or confounded factors controlling soil respiration in a temperate mixed hardwood forest. *Global Change Biology*, **4**, 217–227.
- Dong, Y. S., S. Zhang, Y. C. Qi, Z. Z. Chen, and Y. B. Geng, 2000: Fluxes of CO₂, N₂O and CH₄ from a typical temperate grassland in Inner Mongolia and its daily variation. *Chinese Science Bulletin*, **45**, 1590–1594.
- Dong, Y. S., Y. C. Qi, J. Y. Liu, Y. B. Geng, M. Domroes, X. H. Yang, and L. X. Liu, 2005: Variation characteristics of soil respiration fluxes in four types of grassland communities under different precipitation

- intensity. *Chinese Science Bulletin*, **50**, 583–591.
- Du, R., D. R. Lu, and G. C. Wang, 2006: Diurnal, seasonal, and inter-annual variations of N₂O fluxes from native semi-arid grassland soils of Inner Mongolia. *Soil Biology and Biochemistry*, **38**, 3474–3482.
- Falkowski, P., and Coauthors, 2000: The global carbon cycle: A test of our knowledge of earth as a system. *Science*, **290**, 291–296.
- Fang, C., and J. B. Moncrieff, 2001: The dependence of soil CO₂ efflux on temperature. *Soil Biology and Biochemistry*, **33**, 155–165.
- Fang, C., P. Smith, J. B. Moncrieff, and J. U. Smith, 2005: Similar response of labile and resistant soil organic matter pools to changes in temperature. *Nature*, **433**, 57–59.
- Foster, R. C. 1988: Microenvironments of soil microorganisms. *Biology and Fertility of Soils*, **6**, 189–203.
- Gibbens, R. P., and J. M. Lenz, 2001: Root systems of some Chihuahuan desert plants. *Journal of Arid Environments*, **49**, 221–263.
- Grover, H. D., and H. B. Musick, 1990: Shrubland encroachment in Southern New Mexico, U.S.A.: An analysis of desertification process in the American Southwest. *Climatic Change*, **117**, 305–330.
- Hall, D. O., D. S. Ojima, W. J. Parton, and J. M. O. Scurlock, 1995: Response of temperate and tropical grasslands to CO₂ and climate change. *Journal of Biogeography*, **22**, 537–547.
- Hibbard, K. A., S. Archer, D. S. Schimel, and D. V. Valentine, 2001: Biogeochemical changes accompanying woody plant encroachment in a subtropical savanna. *Ecology*, **82**, 1999–2011.
- Hook, P. B., and I. C. Burke, 2000: Biogeochemistry in a shortgrass landscape: Control by topography, soil texture and microclimate. *Ecology*, **81**, 2686–2703.
- Houghton, R. A., J. L. Haeckler, and K. T. Lawrence, 1999: The US carbon budget: Contributions from land-use change. *Science*, **285**, 574–578.
- Huenneke, L. F., J. P. Anderson, M. Remmenga, and W. H. Schlesinger, 2002: Desertification alters patterns of aboveground net primary production in Chihuahuan ecosystems. *Global Change Biology*, **8**, 247–264.
- Huxman, T. E., K. A. Snyder, D. Tissue, J. Leffler, W. T. Pockman, D. R. Sandquist, D. L. Potts, and S. Schwinning, 2004: Precipitation pulses and carbon fluxes in semiarid and arid Ecosystems. *Oecologia*, **141**, 254–268.
- Jackson, R. B., J. L. Banner, E. G. Jobbagy, W. T. Pockman, and D. H. Wall, 2002: Ecosystem carbon loss with woody plant invasion of grasslands. *Nature*, **418**, 623–626.
- Kessavalou, A., J. W. Doran, A. R. Mosier, and R. A. Drijber, 1998: Greenhouse gas fluxes following tillage and wetting in a wheat fallow cropping system. *Journal of Environmental Quality*, **27**, 1105–1116.
- Kirschbaum, M. U. F., 1995: The temperature dependence of soil organic matter decomposition, and the effect of global warming on soil organic C storage. *Soil Biology and Biochemistry*, **27**, 753–760.
- Lieth, H. F. H., 1978: *Patterns of Primary Productivity in the Biosphere*. Hutchinson Ross, Stroudsburg, P A, 342pp.
- Lohila, A., M. Aurela, K. Regina, and T. Laurila, 2003: Soil and total ecosystem respiration in agricultural fields: Effect of soil and crop type. *Plant and Soil*, **251**, 303–317.
- Luo, Y., and J. F. Reynolds. 1999: Validity of extrapolating field CO₂ experiments to predict carbon sequestration in natural ecosystems. *Ecology*, **80**, 1568–1583.
- Mielnick, P. C., and W. A. Dugas, 2000: Soil CO₂ flux in a tallgrass prairie. *Soil Biology and Biochemistry*, **32**, 221–228.
- Mooney, H., J. Roy, and B. Saugier, 2001: *Terrestrial Global Productivity: Past, Present and Future*. San Diego, Academic Press, 573pp.
- Noy-Meir, E., 1973: Desert ecosystems: Environment and producers. *Annual Review of Ecology and Systematics*, **4**, 23–51.
- Post, W. M., W. R. Emanuel, P. J. Zinke, and A. G. Stangenberger, 1982: Soil carbon pools and world life zones. *Nature*, **298**, 156–159.
- Prentice, I. C., 1993: Biome modeling and the carbon cycle. *The Global Carbon Cycle*. NATO ASI Series I15, *Global Environmental Change*, M. Heiman, Eds., Springer-Verlag, Berlin, 219–238.
- Prentice, I. C., and Coauthors, 2001: The carbon cycle and atmospheric carbon dioxide. *Climate Change 2001: The Scientific Basis*, Houghton et al., Eds., Cambridge University Press, Cambridge, 183–237.
- Qi, Y. C., Y. S. Dong, M. Domroes, Y. B. Geng, L. X. Liu, and X. R. Liu, 2006: Comparison of CO₂ effluxes and their driving factors between two temperate steppes in Inner Mongolia, China. *Adv. Atmos. Sci.*, **23**(5), 726–736, doi: 10.1007/s00376-006-0726-6.
- Qi, Y. C., Y. S. Dong, J. Y. Liu, M. Domroes, Y. B. Geng, L. X. Liu, X. R. Liu, and X. H. Yang, 2007: Effect of the conversion of grassland to the spring wheat field on the CO₂ emission characteristics in Inner Mongolia, China. *Soil and Tillage Research*, **94**(2), 310–320.
- Raich, J. W., and W. H. Schlesinger, 1992: The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate. *Tellus(B)*, **44**, 81–99.
- Reynolds, J. F., P. R. Kemp, K. Ogle, and R. J. Fernández, 2004: Modifying the “pulse-reserve” paradigm for deserts of North America: Precipitation pulses, soil water, and plant responses. *Oecologia*, **141**, 194–210.
- Reynolds, J. F., P. R. Kemp, and J. D. Tenhunen, 2000: Effects of long-term rainfall variability on evapotranspiration and soil water distribution in the Chihuahuan Desert: A modeling analysis. *Plant Ecology*, **150**, 145–159.
- Schlesinger, W. H., 1985: The formation of caliche in soils of the Mojave Desert, California. *Geochim Cosmochim Acta*, **49**, 57–66.
- Schlesinger, W. H., and J. A. Andrews, 2000: Soil respi-

- ration and the global carbon cycle. *Biogeochemistry*, **48**, 7–20.
- Schlesinger, W. H., and A. M. Pilmanis, 1998: Plant-soil interactions in deserts. *Biogeochemistry*, **42**, 169–187.
- Schlesinger, W. H., J. A. Raikes, A. E. Hartley, and A. F. Cross, 1996: On the spatial pattern of soil nutrients in desert ecosystems. *Ecology*, **77**, 364–374.
- Schlesinger, W. H., J. F. Reynolds, G. L. Cunningham, L. F. Huenneke, W. M. Jarrell, R. A. Virginia, and W. G. Whitford, 1990: Biological feedbacking global desertification. *Science*, **247**, 1043–1048.
- Scholes, R. J., and S. A. Archer, 1997: Tree-grass interactions in savannas. *Annual Review of Ecology and Systematics*, **28**, 517–544.
- Scott, R. L., T. E. Huxman, D. G. Williams, and D. Goodrich, 2006. Ecohydrological impacts of woody-plant encroachment: Seasonal patterns of water and carbon dioxide exchange within a semiarid riparian environment. *Global Change Biology*, **12**, 311–324.
- Scurlock, J. M. O., and D. O. Hall, 1998: The global carbon sink: A grassland perspective. *Global Change Biology*, **4**, 229–233.
- Sponseller, R. A., 2007: Precipitation pulses and soil CO₂ flux in a Sonoran Desert ecosystem. *Global Change Biology*, **13**, 426–436.
- Xiong, X. G., X. G. Han, and Y. J. Bao, 2005: Discussion on the research into sandy desertification, accompanying by thickening of semiarid grasslands in Inner Mongolia, China. *Acta Prataculturae Sinica*, **14**, 1–5. (in Chinese)
- Zhao, L., Y. N. Li, S. X. Xu, H. K. Zhou, S. Gu, G. R. Yu, and X. Q. Zhao, 2006: Diurnal, seasonal and annual variation in net ecosystem CO₂ exchange of an alpine shrubland on Qinghai-Tibetan plateau. *Global Change Biology*, **12**, 1940–1953.
- Zheng, Y. R., Z. X. Xie, L. H. Jiang, Y. Z. Wu, and H. Shimizu, 2005: Model simulation and comparison of the ecological characteristics of three degraded grassland types in China. *Belgian Journal of Botany*, **138**, 109–118.