

Effects of nitrogen fertilization on soil respiration in temperate grassland in Inner Mongolia, China

Qin Peng · Yunshe Dong · Yuchun Qi ·
Shengsheng Xiao · Yating He · Tao Ma

Received: 3 March 2009 / Accepted: 4 June 2010
© Springer-Verlag 2010

Abstract Nitrogen addition to soil can play a vital role in influencing the losses of soil carbon by respiration in N-deficient terrestrial ecosystems. The aim of this study was to clarify the effects of different levels of nitrogen fertilization (HN, 200 kg N ha⁻¹ year⁻¹; MN, 100 kg N ha⁻¹ year⁻¹; LN, 50 kg N ha⁻¹ year⁻¹) on soil respiration compared with non-fertilization (CK, 0 kg N ha⁻¹ year⁻¹), from July 2007 to September 2008, in temperate grassland in Inner Mongolia, China. Results showed that N fertilization did not change the seasonal patterns of soil respiration, which were mainly controlled by soil heat-water conditions. However, N fertilization could change the relationships between soil respiration and soil temperature, and water regimes. Soil respiration dependence on soil moisture was increased by N fertilization, and the soil temperature sensitivity was similar in the treatments of HN, LN, and CK treatments (Q_{10} varied within 1.70–1.74) but was slightly reduced in MN treatment ($Q_{10} = 1.63$). N fertilization increased soil CO₂ emission in the order MN > HN > LN

compared with the CK treatment. The positive effects reached a significant level for HN and MN ($P < 0.05$) and reached a marginally significant level for LN ($P = 0.059 < 0.1$) based on the cumulative soil respiration during the 2007 growing season after fertilization (July–September 2007). Furthermore, the differences between the three fertilization treatments and CK reached the very significant level of 0.01 on the basis of the data during the first entire year after fertilization (July 2007–June 2008). The annual total soil respiration was 53, 57, and 24% higher than in the CK plots (465 g m⁻² year⁻¹). However, the positive effects did not reach the significant level for any treatment in the 2008 growing season after the second year fertilization (July–September 2008, $P > 0.05$). The pairwise differences between the three N-level treatments were not significant in either year ($P > 0.05$).

Keywords Soil respiration · Nitrogen fertilization · Temperate grassland · China

Introduction

Soil respiration (Soil CO₂ emission) is the main pathway of carbon emission from soil to atmosphere in terrestrial ecosystems and an important source of atmospheric CO₂ (Fang et al. 1998). Annual global soil respiration is estimated at 68–100 Pg year⁻¹ of C (Raich and Schlesinger 1992; Raich and Potter 1995), accounting for almost 10% of the atmospheric CO₂ cycles (Raich and Schlesinger 1992; Raich and Potter 1995) and more than 11 times of the CO₂ released from fossil fuel combustion (Marland et al. 2000). Therefore, knowledge of soil respiration dynamics and its controlling factors in different terrestrial ecosystems is essential to find proper management policies and

Q. Peng · Y. Dong (✉) · Y. Qi · S. Xiao · Y. He
Institute of Geographic Sciences and Natural Resources
Research, Chinese Academy of Sciences, Beijing 100101, China
e-mail: dongys@igsnrr.ac.cn

Q. Peng · S. Xiao · Y. He
Graduate School of the Chinese Academy of Sciences,
Beijing 100049, China

T. Ma
College of Resource and Environment Science,
Northwestern Agricultural and Forestry University,
Yangling 712100, China

relevant technologies to decrease soil CO₂ emissions and enhance carbon sequestration.

Nitrogen has been regarded as a significant factor controlling soil respiration in N-deficient terrestrial ecosystems. Especially in the next few decades, with increasing rates of anthropogenic N deposition (Galloway et al. 1994; Mosier et al. 2002) and application of fertilizer, much N is to enter terrestrial ecosystems. This will change soil N status and plant N concentrations (Houghton 2002; Magill et al. 1997). As a result, this will affect plant growth (Nadelhoffer et al. 1999), microbial activities (Compton et al. 2004; Frey et al. 2004), litter decomposition (Magill and Aber 1998), and root respiration (Vose and Ryan 2002), and thus soil respiration is expected to change. Many studies on the effect of N additions on soil respiration have been conducted in forest ecosystems (Bowden et al. 2000, 2004; Burton et al. 2004; Micks et al. 2004), agricultural ecosystems (Ding et al. 2007; Al-Kaisi et al. 2008), and a few grassland ecosystems in Europe (Jones et al. 2006) or in North America (de Jong 1974), but little information is available for many other grassland ecosystems, especially for those in China.

In China, grassland is the most widespread land use type, occupying about 40% of the nation's total land area (Sun 2005; Kang et al. 2007). About 78% of the grasslands are located in the northern temperate arid and semiarid area (Chen and Wang 2000); severe climate conditions together with overgrazing make most of the areas suffer from desertification or degradation, and maintain N-deficient status (Zhang and Han 2008; Cao et al. 2004; Hooper and Johnson 1999). However, how soil respiration responds to N additions from global N deposition or anthropogenic N fertilization in this N-deficient ecosystem is still unclear. Previous researches have focused on the effects of water-heat environmental factors (Luo et al. 2001; Jia et al. 2006), grazing (Cao et al. 2004), land-use change (Qi et al. 2007), and fire (Xu and Wan 2008) on soil respiration. Few details about the effect of nitrogen (N) addition on soil respiration were reported in those studies.

In order to understand how N addition affects soil respiration in this N-deficient grassland and to find suitable grassland management measures, we chose a typical semiarid temperate grassland in Inner Mongolia, China, to carry out an in situ N fertilization experiment with different levels of N input. At the same time, considering soil temperature and water conditions to be the most crucial variables regulating soil respiration of grassland in its natural state (Dong et al. 2005; Fang and Moncrieff 2001), we also studied the effects of nitrogen fertilization on the relationship between soil respiration and soil heat-water conditions.

Materials and methods

Site description

The experiment site is located at a *Leymus chinensis* steppe (43°33'10"N, 116°40'29"E, 1,265 m above mean sea level) in Baiinxile pasture, Xilin River Basin, Inner Mongolia, China. The climate is a semi-arid, temperate climate with a mean annual temperature of -0.4°C , ranging from -21.41°C in January to 18.53°C in July. The mean annual precipitation is about 350 to 450 mm (70% falling between July and September). The soil is classified as chestnut soil in Chinese classification or Calcic-orthic Aridisol in Soil Taxonomy classification. The soil depth changes between 100 and 150 cm and the A horizon is about 20–30 cm. The soil contains 60% of sand and 21% of clay sized particles. A soil property survey was made in June 2007, before initiation of the experiment (Table 1). The grass community is dominated by *Leymus chinensis*, *Stipa grandis*, *Agropyron michnoi* and *Cleistogenes squarrosa*, which also dominate the community throughout the entire Xilin Basin.

Experimental design

A plot was selected with its flat topography and uniform vegetation distribution in June 2007, which measured 35 m × 41 m. Then, 12 sub-plots (11 m × 6 m) were divided and marked as four different N fertilizer treatments with three replications each in a complete randomized block design. All of the sub-plots were separated by a 1-m-wide buffer strip in order to minimize the disturbance from neighboring treatments. The four treatments were (1) calcium ammonium nitrate N at a high level (HN; 200 kg N ha⁻¹ year⁻¹); (2) calcium ammonium nitrate N at a medium level (MN; 100 kg N ha⁻¹ year⁻¹); (3) calcium ammonium nitrate N at a low level (LN; 50 kg N ha⁻¹ year⁻¹), and (4) a zero-N control (CK). All fertilizers were applied in two splits over 1-year period: one half of the amount was applied on the 1st or 2nd of July, and the other half was applied on the 1st or 3rd of August. During each application, fertilizer was weighed, mixed with 20 L of water, and applied to each plot using a backpack sprayer. Two passes were made across each plot to ensure even distribution of fertilizers. The control plot received 20 L of water without N.

Soil respiration rates

Carbon dioxide sampling was initiated 3–4 days after each fertilization at all plots and time interval between samplings was 4–6 days during the first month (July–August). Then, the sampling frequency was reduced to three times a

Table 1 Soil physiochemical properties of the sampling site

Soil sampling depth (cm)	Organic C (%)	Total N (%)	C/N	NH ₄ ⁺ -N (mg kg ⁻¹)	NO ₃ ⁻ -N (mg kg ⁻¹)	Soil bulk density (g cm ⁻³)
0–10	1.995	0.188	10.625	1.43	1.91	1.22
10–20	1.496	0.160	9.333	1.38	1.47	1.28
20–30	1.301	0.131	9.912	0.85	0.75	1.28

month during the rest of the growing season (September, May and June) and once a month in the non-growing season. The CO₂ gas sampling was taken using a static closed opaque chamber technique (Clayton et al. 1994; Dong et al. 2000; Zou et al. 2004). In this study, the static closed opaque chamber was made of 8-mm-thick black acrylic material with a tinfoil reflecting surface covering each side. The inner dimension of the chamber was 50 × 40 × 30 cm (Dong et al. 2000; Qi et al. 2007). The day before each sampling, all the green and standing-dead vegetation were clipped to the ground level. During the course of measurement, the sampling chambers were put into the groove of a stainless steel chamber base which was inserted into the soil to a depth of 5 cm, and the groove was sealed with distilled water. All the samples were taken at a relatively uniform time, mostly at around 09:00–11:00 in the morning. Gas sampling lasted for 21 min, and gas samples were extracted from the chamber at 0, 7, 14, and 21 min, respectively, after capping. Each time, about 100 mL of gas was extracted from the chamber through a syringe and collected in polyethylene-coated aluminum gas bags. Shortly after the sampling, the gas bags were brought to the laboratory, and CO₂ concentration was measured with a Li-6252 infrared carbon dioxide analyzer (LICOR Inc., Lincoln, NE, USA).

Environmental factors

Air temperature, soil temperatures (at 0, 5, and 10 cm below the soil surface), and the internal temperature of the chamber were recorded at the time of the gas sampling. Temperature in the chamber was measured with a temperature sensor; air temperature was measured with a DHM2 mechanical ventilated thermometer; and soil temperatures at 0, 5 and 10 cm were measured with a SN2202 digital thermodetector produced by the Sinan Instruments Plant of Beijing Normal University. In order to determine soil water content, soil cores were also collected from three depths (0–10, 10–20 and 20–30 cm) simultaneously; they were immediately placed in labeled airtight bags and transferred to the laboratory. Each soil core was weighed to obtain its field-dry weight and dried for 24 h at 105°C. Then, the gravimetric soil moisture content of soil samples was calculated.

Data analysis

The method used to calculate CO₂ fluxes and cumulative fluxes was that described by Dong et al. (2000). Annual average CO₂ emission for each treatment was calculated as the mean of the annual cumulative fluxes of the three chambers. Each sampling date was considered the midpoint of a sampling period, and the annual cumulative flux was the sum of C respired during the whole observed year from July 2007 to June 2008. One-way analysis of variance (ANOVA) with Tukey's HSD test was used to test the differences in cumulative respiration rates among N treatments. One-way ANOVA with LSD was also performed to determine the pairwise differences in temperature sensitivity of soil respiration between all N treatments. Correlation and linear or non-linear regression analyses were used to explore the relationships between soil temperature or soil moisture and soil respiration rates. All analyses were performed with the SPSS 13.0 software package (SPSS Inc., Chicago, USA) and graphs were prepared with Origin 8.0 (Origin Lab Corporation, USA). Statistically significant differences were tested at *P* values <0.05 unless otherwise stated.

Results

Seasonal variations of soil respiration rates

The seasonal variations in the soil respiration rates were similar in the fertilized and unfertilized plots during the study period, with highest fluxes observed in summer from July to August, and lowest fluxes in snow-cover season from November to January (Fig. 1). The maximum CO₂ emission rates were 448.12 ± 17.46, 489.69 ± 35.98, 396.53 ± 20.14, and 200.26 ± 24.41 mg m⁻² h⁻¹ for HN, MN, LN, and CK treatments, respectively. These maxima were reached quickly within 1–2 weeks after the first fertilization on 1 July 2007. The peak rates were sustained for about 3 weeks in all treatments. Then, decreasing CO₂ effluxes with small fluctuations were observed after the nitrogen fertilization in August. Soil respiration remained low in all plots from the fall season to early spring of the next year. The lowest negative fluxes were observed in the

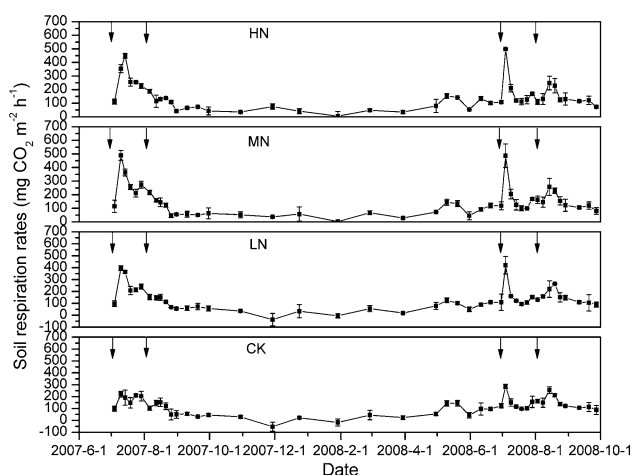


Fig. 1 Soil respiration rates from soil fertilized with $200 \text{ kg ha}^{-1} \text{ year}^{-1}$ (HN), $100 \text{ kg ha}^{-1} \text{ year}^{-1}$ (MN), $50 \text{ kg ha}^{-1} \text{ year}^{-1}$ (LN) and $0 \text{ kg ha}^{-1} \text{ year}^{-1}$ (CK). Solid arrows indicate fertilization dates

LN and the CK plots and near-zero fluxes were observed in the MN and the HN plots. In the late spring (May) in 2008, the CO_2 fluxes began to increase and reached maxima of 498.45 ± 4.53 (HN), 487.21 ± 87.05 (MN), $421.07 \pm 74.05 \text{ mg m}^{-2} \text{ h}^{-1}$ (LN), and $287.15 \pm 17.52 \text{ mg m}^{-2} \text{ h}^{-1}$ (CK) again shortly (5 days) after the fertilization on July 1. This peak lasted for a shorter time than in the first year, no more than about 2 weeks. Several days after the second fertilization in August 2008, another small peak appeared, but the values were close to one another in all treatments.

Cumulative soil respiration rates

All three levels of N fertilization enhanced soil respiration and the enhancement was in the order $\text{MN} > \text{HN} > \text{LN}$ (Fig. 2). The mean total values of cumulative soil respiration rates from the HN, MN, and LN treatments over the period were 332 , 342 and 314 g m^{-2} , respectively, which were 1.39, 1.43, and 1.31 times that of the CK treatment (239.00 g m^{-2}) in the 2007 growing season after fertilization (July–September 2007). When the mean annual total soil CO_2 emissions were calculated for the entire year after the first year fertilization (July 2007–June 2008), the values were $710 \text{ g m}^{-2} \text{ year}^{-1}$ (in HN), $715 \text{ g m}^{-2} \text{ year}^{-1}$ (in MN), and $577 \text{ g m}^{-2} \text{ year}^{-1}$ (in LN), respectively, which were 53, 57, and 24% higher than the one for the CK plots ($465 \text{ g m}^{-2} \text{ year}^{-1}$). In contrast, the mean cumulative soil respiration values for the treatments were 313 g m^{-2} (HN), 316 g m^{-2} (MN), and 306 g m^{-2} (LN), which were 7.9, 8.9, and 5.5% higher than the CO_2 emission from CK (290 g m^{-2}) in the period after the second year fertilization (July–September 2008).

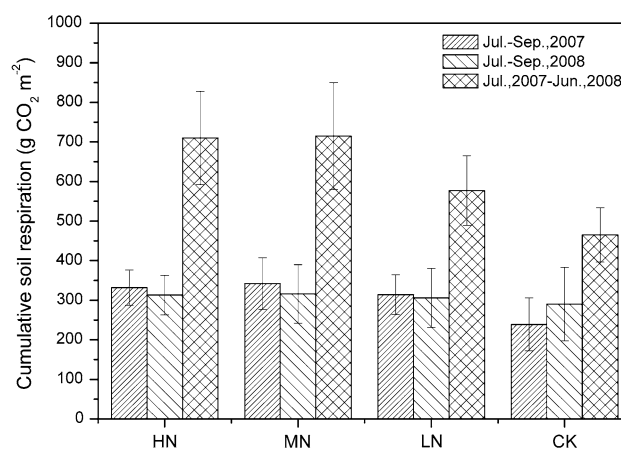


Fig. 2 The mean total values of cumulative soil respiration rates from the three N treatments and CK treatment over the growing seasons after fertilization from July to September in 2007 and 2008, and the annual cumulative soil respiration from July 2007 to June 2008

One-way ANOVA (Table 2) for mean cumulative soil respiration rates (data not shown) showed that the positive effects on soil respiration were significant in the HN and MN treatments ($P < 0.01$) and were marginally significant in the LN treatment ($P = 0.059$) relative to the CK treatment over the first growing season following fertilization (July–September 2007).

All the effects induced by the three levels of N fertilization in contrast to the CK treatments were significant ($P < 0.05$) during the first whole observed year following 2007 fertilization (July 2007–June 2008). However, the increases were insignificant over the period after the second year fertilization in 2008 ($P > 0.05$). In addition, when the cumulative soil respiration rates were compared with each other in the three levels of nitrogen fertilizer treatments, no significant differences were observed in both years ($P > 0.05$).

Relationships between soil respiration rates and temperature and water conditions

The seasonal variations of mean soil moisture content and temperature in the experiment sites were shown in Fig. 3. Soil moisture content varied from 2.45 to 21.68% in the whole study period. It presents a typical seasonal variation pattern. Due to precipitation events and snow-thawing, soil moisture content was generally higher in the months from April to late September than those in the other months. Soil temperature varied from -17.2 to 41.3°C . The relatively higher temperature appeared in the months of growing season from May to September than other months. In these months, soil temperature was always above 10°C , but in other months from October to April, soil temperature decreased and was relatively low.

Table 2 Tukey’s HSD *P*-values for differences in mean cumulative soil respiration rates between four different N treatments in three different measurement periods

Treatments	July–September 2007				July–September 2008				July 2007–June 2008			
	HN	MN	LN	CK	HN	MN	LN	CK	HN	MN	LN	CK
HN	–	0.610ns	0.823ns	0.044*	–	0.971ns	0.765ns	0.542ns	–	0.808ns	0.252ns	0.003**
MN	0.610ns	–	0.463ns	0.020*	0.971ns	–	0.741ns	0.525ns	0.808ns	–	0.158ns	0.001**
LN	0.823ns	0.463 ns	–	0.059	0.765ns	0.741ns	–	0.671ns	0.252ns	0.158ns	–	0.033*
CK	0.044*	0.020*	0.059	–	0.542ns	0.525ns	0.671ns	–	0.003*	0.001*	0.033*	–

* Statistically significant at *P* < 0.05, ** statistically significant at *P* < 0.01
 ns statistically insignificant

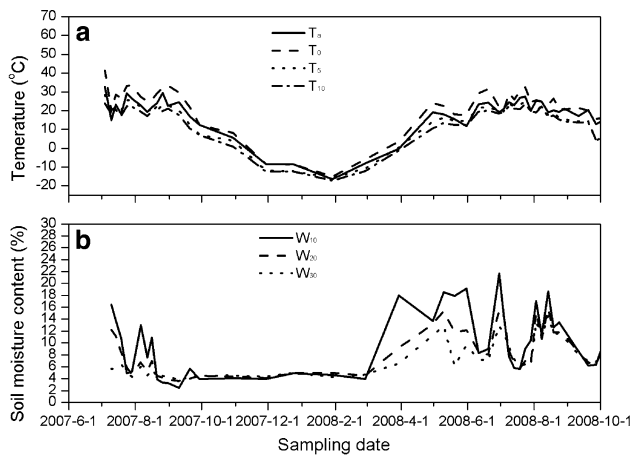


Fig. 3 Temperature and soil moisture conditions in the observed period

Pearson correlation analysis (Table 3) revealed that the seasonal variations of soil respiration rates were mainly controlled by soil temperature and water conditions. During the entire year after fertilization from July 2007 to June 2008, soil respiration rates showed significant correlation with temperature, especially with soil temperature at the depth of 10 cm (*T*₁₀). However, the relationship between them was masked by soil moisture in the growing season after fertilization (July–September) in both years, and the soil moisture in the 10–20 cm layer (*W*₂₀) was the most important control factor for soil respiration.

The relationship between soil moisture (*W*₂₀) and soil respiration rate (*R*) was fitted by a significant positive linear regression ($R = a + bW_{20}$, *P* < 0.05) in the growing seasons of both years (Table 4). The linear functions explained as much as 47.3–81.9% of the variations in soil respiration for 2007 and 31.3–62.8% for 2008. The slopes of the *R*-*W*₂₀ linear regression equation, *b*, represented moisture dependence parameters. The higher slope of the regression line in MN treatments suggested that soil respiration was more sensitive to soil moisture than in the other treatments. Thus, in this study, N fertilization

enhanced the moisture sensitivity of soil respiration in both growing seasons, because the slope values were 36.795–44.273 in 2007 and 16.267–19.164 in 2008 in N fertilized treatments in contrast to 17.183 in 2007 and 13.329 in 2008 in non-fertilized treatments. In addition, moisture sensitivity was higher in the growing season of 2007 than in that of 2008.

Soil respiration rates (*R*) and soil temperature at the depth of 10 cm (*T*) had significant exponential relationship ($R = ae^{bT}$, Table 5) during the entire measuring period although positive linear relationship existed between soil respiration and moisture. The functions explained approximately 27.3–50.1% of the variations in soil respiration. The fitted *Q*₁₀ values, known as the multiplier to the respiration rate for a 10°C increase in temperature and obtained from the *b* coefficient ($Q_{10} = e^{10b}$) were similar for CK, LN, and HN treatments with mean value range of 1.70–1.74. However, in the MN treatment, the value of *Q*₁₀ was slightly reduced to 1.63 (*P* < 0.05).

Discussion

The effect of nitrogen fertilization on seasonal variations of soil respiration rates

Nitrogen fertilizations had little effect on the seasonal variations of soil CO₂ effluxes during the study period (Fig. 1). Whether in the non-fertilized plots or in the fertilized plots, soil respiration showed a strong seasonal variation, with higher CO₂ effluxes in summer and lower CO₂ effluxes in winter. This agrees with the results of Mo et al. (2008) and Bowden et al. (2004). Similar seasonal variations of soil respiration rates mainly resulted from the similar seasonality of temperature and soil moisture conditions which reflected the semiarid, continental temperate climate of our study site and were not changed by different levels of N treatments (Data not shown).

Table 3 Correlation coefficients of soil respiration and soil temperature or moisture

Treatments	Periods	Correlation coefficients						
		T_a	T_0	T_5	T_{10}	W_{10}	W_{20}	W_{30}
HN	A	0.003	0.014	0.321	0.337	0.738**	0.880**	0.646*
	B	-0.008	-0.107	0.205	0.245	0.456	0.557*	0.423
	C	0.452*	0.443*	0.520**	0.525**	0.287	0.340	0.029
MN	A	-0.182	-0.126	0.232	0.263	0.818**	0.904**	0.634*
	B	-0.024	-0.154	0.182	0.222	0.560*	0.661**	0.537*
	C	0.380*	0.382*	0.477*	0.487**	0.314	0.336	0.013
LN	A	-0.134	-0.099	0.249	0.277	0.782**	0.905**	0.596*
	B	-0.064	-0.169	0.149	0.186	0.562*	0.661**	0.550*
	C	0.485**	0.486**	0.572**	0.579**	0.297	0.339	0.031
CK	A	0.082	0.090	0.435	0.472	0.582*	0.687**	0.515
	B	-0.058	-0.116	0.170	0.203	0.753**	0.792**	0.716**
	C	0.634**	0.623**	0.707**	0.712**	0.340	0.384*	0.152

A the 2007 growing season after fertilization, B the 2008 growing season after fertilization, C the first entire year after 2007 fertilization from July 2007 to June 2008, W_{10} 0–10 cm soil water content, W_{20} 10–20 cm soil water content, W_{30} 20–30 cm soil water content, T_a air temperature, T_0 surface ground temperature, T_5 soil temperature at 5 cm depth, T_{10} soil temperature at 10 cm depth

* Correlation is significant at the 0.05 level (2-tailed), ** correlation is significant at the 0.01 level (2-tailed)

Table 4 Linear regression functions between soil respiration rate and soil moisture at the depth of 10–20 cm

Treatments	A				B			
	Functions	b	R^2	P	Functions	b	R^2	P
HN	$R = -66.04 + 39.179W_{20}$	39.179	0.775	0.000	$R = 4.787 + 16.586W_{20}$	16.586	0.311	0.031
MN	$R = -92.92 + 44.273W_{20}$	44.273	0.802	0.000	$R = -17.639 + 19.164W_{20}$	19.164	0.437	0.007
LN	$R = -61.85 + 36.795W_{20}$	36.795	0.819	0.000	$R = 2.277 + 16.267W_{20}$	16.267	0.437	0.007
CK	$R = 18.05 + 17.183W_{20}$	17.183	0.473	0.006	$R = 19.139 + 13.329W_{20}$	13.329	0.628	0.000

Table 5 Exponential regression functions between soil respiration rate and soil temperature at 10 cm depth and Q_{10}

Treatments	Functions	R^2	P	Q_{10}
HN	$R = 55.7352e^{0.0554T}$	0.425	0.000	1.74 a
MN	$R = 63.3409e^{0.0489T}$	0.273	0.006	1.63 b
LN	$R = 52.9772e^{0.0534T}$	0.429	0.000	1.71 a
CK	$R = 43.9088e^{0.0533T}$	0.501	0.000	1.70 a

Q_{10} values, known as the multiplier to the respiration rate for a 10°C increase in temperature and obtained from the b coefficient ($Q_{10} = e^{10b}$). Different letters in the last column indicate significant difference ($P < 0.05$) in Q_{10} values

The effect of nitrogen fertilization on temperature or moisture dependency of soil respiration rates

Nitrogen fertilizations had little influence on the seasonal variations of soil respiration or the conditions of soil moisture and soil temperature alone. However, it can alter the relationships between them to some degree. The slopes of linear functions representing moisture dependence parameters were generally higher in N-fertilized plots than

in non-fertilized plots (Table 4). This suggested that N fertilization resulted in soil respiration rates more sensitive to soil moisture than those of the CK treatment. The differences in soil moisture dependency might be attributed to the changes in the respiring communities involved in soil respiration due to N additions (Phillips and Fahey 2007; Olsson et al. 2005; Liljeroth et al. 1990). Respiration of microbial communities and plant roots has different soil moisture dependencies (Joffre et al. 2003). Besides, the alteration of C allocation pattern between above-ground plants and below-ground roots caused by N fertilization can change water evaporation and plant evapotranspiration and thus could influence the responses of soil respiration to soil moisture (Coleman et al. 2004).

Furthermore, a significant decline ($P < 0.05$) in Q_{10} between CK, LN, HN (1.70–1.74), and MN (1.63) was found (Table 5). Similarly, lower temperature sensitivity upon N fertilization was reported by Mo et al. (2008) for a mature tropical forest in southern China. The decrease in temperature sensitivity under specific N treatment may be due to the alterations of quality and quantity of soil

substrates (Luo et al. 2001). Soil labile-C and resistant-C have different temperature sensitivity (Davidson et al. 2006; Eliasson et al. 2005), and their proportion can be changed by N addition (Wang et al. 2004; Malhi et al. 2003). Wang et al. (2004) and Craine et al. (2007) have found that soil labile-C would increase with N addition, and thus could make the temperature sensitivity of soil respiration decrease. However, Conant et al. (2008) observed that the difference of temperature sensitivity caused by the change of the substrates such as labile- and resistant-C was not evident until a substantial portion of the labile-C was lost in the incubation soil. These reports supply a partial explanation for the phenomenon we observed, and it is possible that only the MN treatment leads to a large change of substrate in soil, thus causing a reduction of temperature sensitivity of soil respiration. Additionally, Boone et al. (1998) reported that roots also exerted a key role in regulating temperature dependency of soil respiration. The mechanisms affecting Q_{10} are complex, and its exact characteristics are difficult to explain.

The effect of nitrogen fertilization on cumulative CO_2 effluxes

Considering the cumulative soil respiration rates, the rates of soil respiration could be enhanced by all three levels of N fertilization in the order $\text{MN} > \text{HN} > \text{LN}$ (Fig. 2). The positive effects of N fertilization on soil respiration rates were significant in the first year but not in the second year. Short-term increases in soil CO_2 fluxes have been reported in many field experiments (Bowden et al. 2004; Gallardo and Schlesinger 1994) and incubation experiments (Söderström et al. 1983). The positive effects have been attributed to increased microbial biomass and activity (Lovell and Hatch 1998) as well as root production (Magill et al. 1997) after fertilization. The short-term CO_2 increases that occurred in our study also may be related to stimulation of the two basic components (microbial respiration and root respiration) associated with soil respiration and it could mean that N was limiting in the current study sites in the first year.

The exact reason for the insignificant increase in soil respiration following the second year N fertilization has not yet been identified. It can be explained by several possible mechanisms: (1) the experimental sites are not strongly N limited after 1 year of fertilization and (2) the observed pattern is a result of multiple factors other than N availability (Aber et al. 1989; Burton et al. 2004). Micks et al. (2004) reported that microbial respiration was seldom affected by N fertilization in a C-limited status. Burton et al. (2004) also found no responses in root biomass and root respiration due to N additions and they attributed this to the limitation of other nutrient resources in the NO_3^- -N

amended plots. In our study sites, the immediate positive effects on soil respiration following N addition may be due to abundant C substrates. However, after 1 year of fertilization, with large amounts of CO_2 emitted from the soil, much of the available soil C resource could have been consumed. Meanwhile, in our present system, the accumulation of soil organic carbon is relatively slow due to the restriction of low water and temperature conditions in the observed period (Fig. 3). Thus, if the exogenous C input could not compensate for the loss of soil C, the previous N-limited status possibly changed into a limitation by C resources. With the limitation of these resources, the two basic parts of soil respiration (microbial respiration and root respiration) can respond less to the N addition than the one in the previous untreated, N-limited soils. Xu and Wan (2008) conducted a field experiment in Duolun, a grassland adjacent to our sites, and found that CO_2 emissions from urea ($\text{CO}(\text{NH}_2)_2$)-treated plots are significantly larger than the control in both years of their study, which is opposite to our observed 2 year CO_2 emission patterns. The different results support the hypothesis that C substrate could be a limiting factor in our study sites. Additionally, the pattern observed in our study that the highest amounts of CO_2 tended to be emitted in MN treatment but not in HN treatment also indicated that the limitation of other elements such as C could happen; under insufficient C resources, we would not necessarily observe more CO_2 emission from the soils after excessive N addition (Aber et al. 1989).

Besides, another possible mechanism may be related to the interactions among various processes associated with soil respiration such as root production and microbial biomass in response to nitrogen fertilization. Nitrogen fertilization can modify below-ground soil processes in both microbes and plant roots, and not always in consistent ways. On the one hand, positive effects of N fertilization on microbial respiration or root respiration have been reported (Hart and Stark 1997; Zhang and Zak 1998; Lovell and Hatch 1998); on the other hand, negative effects on the two components of soil respiration have also been shown (Compton et al. 2004; Bowden et al. 2004). Given the wide variation in their potential responses, opposing processes might be elicited by N fertilization and counteract each other, resulting in no net change in soil respiration across treatments.

Conclusions

This study has demonstrated that all levels of N fertilization did not change seasonal variations of soil respiration, which are still controlled by climatic factors such as temperature and soil water conditions. However, N fertilization influenced the dependence of soil respiration on these climatic

factors to some degree. Furthermore, different stimulations of soil respiration due to different levels of N fertilization have also been observed in our study sites. Such information could provide a better basis for improved C and N management decision-making in semiarid grassland.

However, the stimulation of soil respiration due to N fertilization was not significant in the second year. Meanwhile, the alteration of moisture or temperature dependency of soil respiration rates was not very clear and was the same as all N treatments. Therefore, long-period studies and corresponding mechanistic studies must be conducted to clarify the interaction between N fertilization and soil respiration.

Acknowledgments This work was financially supported by the National Natural Science Foundation of China (Grant No: 40730105, 40673067 and 40501072), and the Ministry of Science and Technology of China (Grant No: 2007BAC03A11). We are grateful to the Inner Mongolia Grassland Ecosystem Research Station (IMGERS) for providing the experimental sites to the research team.

References

- Aber JD, Nadelhoffer K, Steudler P et al (1989) Nitrogen saturation in northern forest ecosystems. *Bioscience* 39:378–386
- Al-Kaisi MM, Kruse ML, Sawyer JE (2008) Effect of nitrogen fertilizer application on growing season soil carbon dioxide emission in a corn-soybean rotation. *J Environ Qual* 37:325–332
- Boone RD, Nadelhoffer KJ, Canary JD et al (1998) Roots exert a strong influence on the temperature sensitivity of soil respiration. *Nature* 396:570–572
- Bowden RD, Rullo G, Stevens GR et al (2000) Soil fluxes of carbon dioxide, nitrous oxide, and methane at a productive temperate deciduous forest. *J Environ Qual* 29:268–276
- Bowden RD, Davidson E, Savage K et al (2004) Chronic nitrogen additions reduce total soil respiration and microbial respiration in temperate forest soils at the Harvard Forest. *For Ecol Manage* 196:43–56
- Burton AJ, Pregitzer KS, Crawford JN et al (2004) Simulated chronic NO_3^- addition reduces soil respiration in northern hardwood forests. *Glob Change Biol* 10:1080–1091
- Cao G, Tang Y, Mo W et al (2004) Grazing intensity alters soil respiration in an alpine meadow on the Tibetan plateau. *Soil Biol Biochem* 36:237–243
- Chen Z, Wang S (2000) Typical steppe ecosystems of China. Science Press, Beijing
- Clayton H, Arah JRM, Smith KA (1994) Measurements of nitrous oxide emissions from fertilized grassland using closed chambers. *J Geophys Res* 99:16599–16607
- Coleman MD, Friend AL, Kern CC (2004) Carbon allocation and nitrogen acquisition in a developing *Populus deltoides* plantation. *Tree Physiol* 24:1347–1357
- Compton JE, Watrud LS, Porteous LA et al (2004) Response of soil microbial biomass and community composition to chronic nitrogen additions at Harvard Forest. *For Ecol Manage* 196:143–158
- Conant RT, Steinweg JM, Haddix ML et al (2008) Experimental warming shows that decomposition temperature sensitivity increases with soil organic matter recalcitrance. *Ecology* 89:2384–2391
- Craine JM, Morrow C, Fierer N (2007) Microbial nitrogen limitation increases decomposition. *Ecology* 88:2105–2113
- Davidson EA, Janssens IA, Luo Y (2006) On the variability of respiration in terrestrial ecosystems: moving beyond Q_{10} . *Glob Change Biol* 12:154–164
- de Jong E (1974) Carbon dioxide evolution from virgin and cultivated soil as affected by management practices and climate. *Can J Soil Sci* 54:299–307
- Ding W, Cai Y, Cai Z et al (2007) Soil respiration under maize crops: Effects of water, temperature, and nitrogen fertilization. *Soil Sci Soc Am J* 71:944–951
- Dong Y, Zhang S, Qi Y et al (2000) Fluxes of CO_2 , N_2O and CH_4 from a typical temperate grassland in Inner Mongolia and its daily variation. *Chin Sci Bull* 45:1590–1594
- Dong Y, Qi Y, Liu J et al (2005) Variation characteristics of soil respiration fluxes in four types of grassland communities under different precipitation intensity. *Chin Sci Bull* 50:583–591
- Eliasson PE, McMurtrie RE, Pepper DA et al (2005) The response of heterotrophic CO_2 flux to soil warming. *Glob Change Biol* 11:167–181
- Fang C, Moncrieff JB (2001) The dependence of soil CO_2 efflux on temperature. *Soil Biol Biochem* 33:155–165
- Fang J, Liu S, Zhao K (1998) Factors affecting soil respiration in reference with temperature's role in the globe scale. *Chin Geogr Sci* 8(3):246–255
- Frey SD, Knorr M, Parrent J et al (2004) Chronic nitrogen enrichment affects the structure and function of the soil microbial community in a forest ecosystem. *For Ecol Manage* 196:159–171
- Gallardo A, Schlesinger WH (1994) Factors limiting microbial biomass in the mineral soil and forest floor of a warm-temperate forest. *Soil Biol Biochem* 26:1409–1415
- Galloway JN, Levy H II, Kasibhatla PS (1994) Year 2020: consequences of population growth and development on the deposition of oxidized nitrogen. *Ambio* 23:120–123
- Hart SC, Stark JM (1997) Nitrogen limitation of the microbial biomass in an old-growth forest soil. *Ecoscience* 4:91–98
- Hooper DU, Johnson L (1999) Nitrogen limitation in dryland ecosystems: responses to geographical and temporal variation in precipitation. *Biogeochemistry* 46:247–293
- Houghton RA (2002) Terrestrial carbon sinks—uncertain explanations. *Biologist* 49:155–160
- Jia B, Zhou G, Wang Y et al (2006) Effects of temperature and soil water-content on soil respiration of grazed and ungrazed *Leymus chinensis* steppes, Inner Mongolia. *J Arid Environ* 67:60–76
- Joffre R, Ourcival JM, Rambal S et al (2003) The key-role of topsoil moisture on CO_2 efflux from a Mediterranean *Quercus ilex* forest. *Ann For Sci* 60:519–526
- Jones SK, Rees RM, Kosmas D et al (2006) Carbon sequestration in a temperate grassland: management and climatic controls. *Soil Use Manage* 22:132–142
- Kang L, Han X, Zhang Z et al (2007) Grassland ecosystems in China: review of current knowledge and research advancement. *Philos Trans R Soc Lond B Biol Sci* 362:997–1008
- Liljeroth E, Van Veen JA, Miliier HJ (1990) Assimilate translocation to the rhizosphere of two wheat lines and subsequent utilization by rhizosphere microorganisms at two soil nitrogen concentrations. *Soil Biol Biochem* 22:1015–1021
- Lovell RD, Hatch DJ (1998) Stimulation of microbial activity following spring applications of nitrogen. *Biol Fertil Soils* 26:28–30
- Luo Y, Wan S, Hui D et al (2001) Acclimatization of soil respiration to warming in a tall grass prairie. *Nature* 413:622–625
- Magill AH, Aber JD (1998) Long-term effects of experimental nitrogen additions on foliar litter decay and humus formation. *Plant Soil* 203:301–311

- Magill AH, Aber JD, Hendricks JJ et al (1997) Biogeochemical response of forest ecosystems to simulated chronic nitrogen deposition. *Ecol Appl* 7:402–415
- Malhi SS, Harapiak JT, Nyborg M et al (2003) Total and light fraction organic C in a thin Black Chernozemic grassland soil as affected by 27 annual applications of six rates of fertilizer N. *Fertil Res* 66:33–41
- Marland G, Boden TA, Andres RJ (2000) Global, regional and national fossil fuel CO₂ emissions. In: Trends: a compendium of data on global change. Oak Ridge National Laboratory, Oak Ridge, Tennessee
- Micks P, Aber JD, Boone RD et al (2004) Short-term soil respiration and nitrogen immobilization response to nitrogen applications in control and nitrogen-enriched temperate forests. *For Ecol Manage* 196:57–70
- Mo J, Zhang W, Zhu W et al (2008) Nitrogen addition reduces soil respiration in a mature tropical forest in southern China. *Glob Change Biol* 14:403–412
- Mosier AR, Morgan JA, King JY et al (2002) Soil-atmosphere exchange of CH₄, CO₂, NO_x, and N₂O in the Colorado Shortgrass Steppe under Elevated CO₂. *Plant Soil* 240:201–211
- Nadelhoffer KJ, Downs MR, Fry B (1999) Sinks for N additions to an oak forest and a red pine plantation. *Ecol Appl* 9:72–86
- Olsson P, Linder S, Giesler R et al (2005) Fertilization of boreal forest reduces both autotrophic and heterotrophic soil respiration. *Glob Change Biol* 11:1745–1763
- Phillips RP, Fahey TJ (2007) Fertilization effects on fine root biomass, rhizosphere microbes and respiratory fluxes in hardwood forest soils. *New Phytol* 176:655–664
- Qi Y, Dong Y, Liu J et al (2007) Effect of the conversion of grassland to spring wheat field on the CO₂ emission characteristics in Inner Mongolia, China. *Soil Till Res* 94:310–320
- Raich JW, Potter CS (1995) Global patterns of carbon dioxide emissions from soils. *Glob Biogeochem Cycles* 9:23–36
- Raich JW, Schlesinger WH (1992) The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate. *Tellus* 44B:81–99
- Söderström B, Bääth E, Lundgren B (1983) Decreases in soil microbial activity and biomass owing to nitrogen amendments. *Can J Microbiol* 29:1500–1506
- Sun HL (2005) Ecosystems of China. Science Press, Beijing
- Vose JM, Ryan MG (2002) Seasonal respiration of foliage, fine roots, and woody tissues in relation to growth, tissue N, and photosynthesis. *Glob Change Biol* 8:182–193
- Wang WJ, Baldock JA, Dalal RC et al (2004) Decomposition dynamics of plant materials in relation to nitrogen availability and biochemistry determined by NMR and wet-chemical analysis. *Soil Biol Biochem* 36:2045–2058
- Xu W, Wan S (2008) Water- and plant-mediated responses of soil respiration to topography, fire, and nitrogen fertilization in a semiarid grassland in northern China. *Soil Biol Biochem* 40:679–687
- Zhang J, Han X (2008) N₂O emission from the semi-arid ecosystem under mineral fertilizer (urea and superphosphate) and increased precipitation in northern China. *Atmos Environ* 42:291–302
- Zhang Q, Zak JC (1998) Effects of water and nitrogen amendment on soil microbial biomass and fine root production in a semi-arid environment in West Texas. *Soil Biol Biochem* 30:39–45
- Zou J, Huang Y, Zheng X et al (2004) Static opaque chamber-based technique for determination of net exchange of CO₂ between terrestrial ecosystem and atmosphere. *Chin Sci Bull* 49:381–388