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Responses of soil respiration to soil management changes in an agropastoral ecotone in Inner Mongolia, China

Haili Xue | Haiping Tang 🔟

State Key Laboratory of Earth Surface Processes and Resource Ecology, Faculty of Geographical Science, Beijing Normal University, Beijing, China

Correspondence
Haiping Tang, Faculty of Geographical Science, Beijing Normal University, Beijing, China.
E-mail: tanghp@bnu.edu.cn

Abstract

Studying the responses of soil respiration (R_s) to soil management changes is critical for enhancing our understanding of the global carbon cycle and has practical implications for grassland management. Therefore, the objectives of this study were (1) quantify daily and seasonal patterns of R_s, (2) evaluate the influence of abiotic factors on R_s, and (3) detect the effects of soil management changes on R_s. We hypothesized that (1) most of daily and seasonal variation in R_s could be explained by soil temperature (T_s) and soil water content (S_w), (2) soil management changes could significantly affect R_s, and (3) soil management changes affected R_s via the significant change in abiotic and biotic factors. In *situ* R_s values were monitored in an agropastoral ecotone in Inner Mongolia, China, during the growing seasons in 2009 (August to October) and 2010 (May to October). The soil management changes sequences included free grazing grassland (FG), cropland (CL), grazing enclosure grassland (GE), and abandoned cultivated grassland (AC). During the growing season in 2010, cumulative R_s for FG, CL, GE, and AC averaged 265.97, 344.74, 236.70, and 226.42 gC m^{-2} year^{-1}, respectively. The T_s and S_w significantly influenced R_s and explained 66%–86% of the variability in daily R_s. Monthly mean temperature and precipitation explained 78%–96% of the variability in monthly R_s. The results clearly showed that R_s was increased by 29% with the conversion of FG to CL and decreased by 35% and 11% with the conversion of CL to AC and FG to GE. The factors impacting the change in R_s under different soil management changes sequences varied. Our results confirm the tested hypotheses. The increase in Q_{10} and litter biomass induced by conversion of FG to GE could lead to increased R_s if the climate warming. We suggest that after proper natural restoration period, grasslands should be utilized properly to decrease R_s.

KEYWORDS
cropland, grazing grassland, restoration grassland, soil temperature, soil water content

1 | INTRODUCTION

Soil respiration (R_s) is a crucial process in the global carbon cycle (Bahn, Janssens, Reichstein, Smith, & Trumbore, 2010). Minor changes in R_s have the potential to significantly affect atmospheric CO_2 concentrations (IPCC, 2007). Large-scale soil management changes have been affecting R_s, with considerable impacts on the terrestrial ecosystem carbon cycle. It has been estimated that global net flux due to land use change during the period of 1,850–2,000 is 148.6 Pg C (Kaul, Dadhwal, & Mohren, 2009); however, the

mechanisms of this effect remain subject of debate (Nazaries et al., 2015). In recent years, considerable efforts have been made to understand the effects of soil management changes, that is, conversion of cropland to woodland or forest (Kellman, Beltrami, & Risk, 2007; Saurette, Chang, & Thomas, 2007; Zhang et al., 2015), forest to cropland, or grassland (Sheng et al., 2010). However, few studies have focused on the conversion of grazed grassland to cropland, and not many studies focus on conversion of cropland to grassland in degraded ecosystems (Shi, Yan, Zhang, Guan, & Du, 2014; Zhang et al., 2015).

Soil management changes can potentially alter soil temperature (T_s) and soil water content (S_w) (Chen et al., 2016; Rong, Ma, Johnson, & Yuan, 2015; Wang, Gong, et al., 2015), which are the main abiotic factors affecting R_s (Fang & Moncrieff, 2001; Gomez-Casanovas, Matamala, Cook, & Gonzalez-Meler, 2012), and these two factors affect the productivity and the decomposition rate of soil organic matter (Han et al., 2007). Temperature sensitivity (Q_{10}) describes the relationship between R_s and temperature and can therefore also be changed with soil management changes (Gong et al., 2014; Rong et al., 2015). Furthermore, soil management changes can impact biotic factors, such as net primary production, belowground biomass (BGB), soil organic carbon (SOC) (Deng, Liu, & Shangguan, 2014; Frank, Liebig, & Tanaka, 2006; Sheng et al., 2010; Zhang et al., 2015), all of which greatly affect R_s. However, the effects of soil management changes from cropland to grassland on R_s have not been consistent among studies, some studies indicate that it increases R_s (Frank et al., 2006; Wang, Liu, et al., 2015), while other studies show that it reduces R_s (Iqbal et al., 2008; Zhang et al., 2015). Moreover, the effects of grazing on R_s also have no consistent conclusion (Rong et al., 2015). Therefore, additional studies are needed to clarify the effects of the soil management changes on R_s.

The northern agropastoral ecotone of China, which is a transition zone between agricultural and pastoral regions and encompasses various ecosystems, occupies an area of 8×10^5 km^2. Soil management changes from grassland to cropland or from cropland to grassland are frequently occurring in this region, making it the most sensitive eco-environmental area in China (Zhou et al., 2007). In this area, the typical soil management changes sequences have occurred, including the conversion of free grazing grassland (FG) to cropland (CL), both of which are under human disturbance, and the conversion of FG and CL to restoration grassland—grazing enclosure grassland (GE) and abandoned cultivated grassland (AC). This variety of different soil management changes provides a unique opportunity to study the response of R_s to soil management changes. Previous studies of R_s in the temperate grassland in China primarily focused on the influence of grassland management practices on R_s (Li & Sun, 2011; Lu, Liao, & Liao, 2016; Su, Li, Cui, & Zhao, 2005), further studies are needed to study the impacts of conversions from FG to CL and GE, CL to AC on R_s, biotic (aboveground biomass (AGB), BGB, SOC, etc.), and abiotic factors (T_s, S_w).

In this study, we measured R_s, AGB, BGB, SOC, and soil microclimate in degraded areas of the agropastoral ecotone (soil management types: FG, CL, GE, and AC) in Inner Mongolia from 2009 to 2010. The objectives of our study were to (1) quantify daily and seasonal patterns of R_s in four soil management types, (2) evaluate the influence of abiotic (T_s, S_w) factors on R_s in these soil management types, and (3) detect the effects of soil management changes on R_s.

We hypothesized that (1) most of daily and seasonal variation in R_s could be explained by T_s and S_w, (2) soil management changes could significantly affect R_s and (3) soil management changes affected R_s via the significant change in abiotic and biotic factors.

2 | MATERIALS AND METHODS

2.1 | Site descriptions

The study was conducted in Duolun County in Inner Mongolia (15.83°–116.92°N, 41.77°–42.65°E, 1,150–1,800 m asl), located on the south edge of the Inner Mongolia Plateau, which belongs to a typical agropastoral ecotone in Northern China with a semi-arid monsoon climate. The long-term (1952–2009) mean annual temperature is 2.3°C, and the average temperature for July and January are 19.0°C and −17.5°C, respectively. Annual evaporation is 1,748 mm, and annual precipitation is 382 mm and accounts for 70% of the year from June to August. The soil has been classified as chestnut soil in the Chinese Soil Classification Standard (State Soil Survey Service of China, 1998) or as haplic calcisols by the Food and Agricultural Organization (FAO) of the United Nations.

Four adjacent experimental sites were established in the study area: free grazing grassland (FG), cropland (CL), grazing enclosure grassland (GE), and abandoned cultivated grassland (AC). The sites were flat terrain and located 150–800 m apart. The 11-ha FG site (42.04°N, 116.29°E) has been consistently grazed at a stocking rate of 9 sheep/ha during the growing season, and the dominated species are *Stipa krylovli* Roshev and *Leymus chinensis* (Trin.) Tzvel. The 20-ha CL site (42.04°N, 116.28°E) converted from FG and ploughed in 2008 for the grown of *Triticum aestivum* L. or *Fagopyrum sagittatum* Gilib each year, which were harvested by the end of September; the soil was ploughed about 20 cm and manure was applied at 80 kg/ha about 3 weeks before sowing, and no irrigation was applied in the site. GE and AC were enclosed grassland for the natural restoration of FG and CL. The 10-ha GE site (42.04°N, 116.29°E) converted from FG, and it had not been grazed since 2000 and was preserved as a natural grassland dominated by *Stipa krylovii* Roshev, *Leymus chinensis* (Trin.) Tzvel. and *Artemisia frigida* Willd. The 13-ha AC site (42.04°N, 116.28°E) converted from cropland (which had been converted from FG) in 2000, and *Agropyron cristatum* (Linn.) Gaertn. was planted at the enclosed first year.

2.2 | Measurement of R_s, T_s, and S_w

In each site, five 2 × 2 m sample plots were randomly selected with the constraint that the plots were located at least 10 m from the edge of the site to avoid edge effects. One day before the measurements, PVC collars were inserted (20 cm in diameter by 5 cm in height) 2 cm into the soil at each plot. To exclude respiration from aboveground vegetation, all visible living plants were removed from the collars before measurements. The measurements were taken eight times per day at 3-hr intervals from

6:00 a.m. to 03:00 p.m., and instantaneous R_s in each plot was measured three times with an LI-8100 Automated Soil CO_2 Flux System (LI-COR Environmental, Lincoln, NE, USA) with a 90-s enclosure period and a 30-s delay between measurements. The final instantaneous R_s for a given plot consisted of the average of the three measurements, and if necessary, one or more additional measurements were taken until the coefficient of flux variation was below than 2%. The measurements were conducted from August to October in 2009 and May to October in 2010. When measuring R_s, T_s was determined at a depth of 5 cm adjacent to each PVC collar with a thermocouple. Simultaneously, S_w at a depth of 5 cm was measured using a Theta Probe Soil Moisture Sensor. Field meteorological data were obtained from the local meteorological station.

2.3 | Biomass and soil characteristics

AGB and BGB were collected and measured at the end of every month (May to September) in 2010, five representative 1 × 1 m quadrats were established at each site. For determination of AGB, all plants from five quadrats were clipped above the soil surface at each site, and litter was collected using rake. After removal of AGB and litter biomass, five belowground core samples at the depth of 0–30 cm were collected from each quadrant using a soil auger with a diameter of 8 cm. The root was separated from the soil by washing over a 0.2-mm mesh to determine BGB. All plant samples were dried at 65°C to constant weight for biomass determination.

On 15 August 2010, three soil samples were collected in each plot using a soil auger with a diameter of 4 cm at a depth of 0–30 cm at 10-cm intervals, the samples were mixed to obtain one composite sample per plot. Subsequently, the samples were sieved (<2 mm) and any roots were removed. Then, samples were ground in a ball-bearing mill and sieved (<0.9 mm) prior to analysis of SOC. We determined SOC using the $K_2Cr_2O_7$–H_2SO_4 digestion method (Nelson & Sommers, 1982). Soil bulk density was determined using soil cores (volume of 100 cm^3) obtained from depths of 0–10 cm.

2.4 | Data analysis

Soil respiration, T_s, and S_w were calculated by averaging the five replicates on each sampling day. We conducted all statistical analyses using SPSS 19.0 (SPSS Inc., Chicago, IL, USA). Spatial variation of R_s in all sites was analyzed using one-way ANOVA. There was no temporal autocorrelation of soil respiration with soil temperature and water content according to the autocorrelation function (ACF) test; consequently, regression analysis was conducted between R_s and T_s, S_w. Multiple regression analysis was used to examine the relationships between R_s and T_s, S_w. Least significant difference (LSD) was used to evaluate differences between sites, and analyses were performed at significance levels of $p < .05$, $p < .01$, and $p < .001$. Monthly cumulative R_s (gC/m^2) were calculated by linear interpolation of daily R_s from 5 August to 15 October in 2009 and from 5 May to 31 October in 2010.

To simulate the relationship between R_s and T_s, we applied the exponential regression model:

$$R_s = \alpha e^{\beta T_s}$$

where R_s is the soil respiration rate ($\mu mol\ CO_2\ m^{-2}\ s^{-1}$), T_s is the soil temperature (°C) at a depth of 5 cm, and β is constants fitted by the models.

The Q_{10} values were calculated with the Van't Hoff model:

$$Q_{10} = e^{\beta \times 10}$$

3 | RESULTS

3.1 | Abiotic and biotic factors among four soil management types

Changes in T_s coincided with air temperature, and the maximum and minimum T_s values were observed in July and October (Figures 1 and 2a); levels of S_w at the depth of 0–5 cm coincided with that of irregular rainfall, with the highest values in September due to high precipitation (Figures 1 and 2b). Levels of T_s significantly decreased from 21.9 ± 0.3 to 20.7 ± 0.2°C and 21.3 ± 0.1 to 20.4 ± 0.3°C with the conversion of CL to AC and FG to GE, respectively ($p < .05$). S_w significantly decreased from 13.6 ± 0.5% to 10.2 ± 0.7% and 11.5 ± 0.4% with the conversions of FG to CL and GE ($p < .05$).

The biotic parameters also varied significantly with soil management changes ($p < .05$). In particular, SOC decreased from 33.07 ± 0.05 g/kg to 11.78 ± 0.28 and 17.98 ± 0.87 g/kg with conversions of FG to

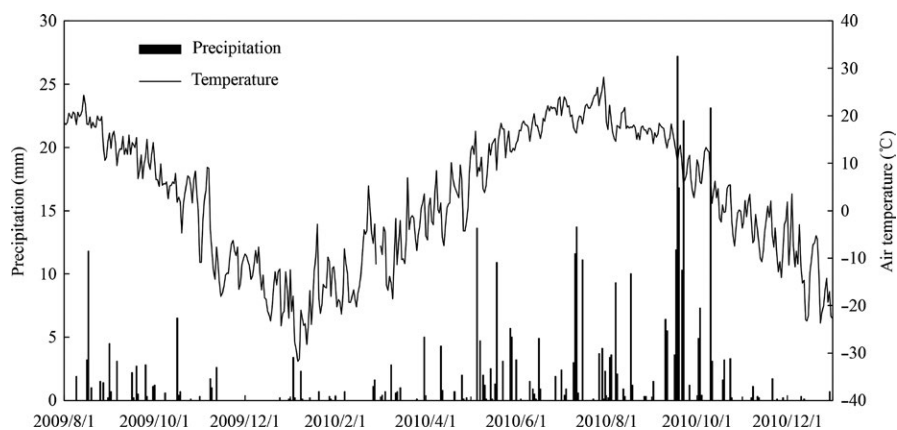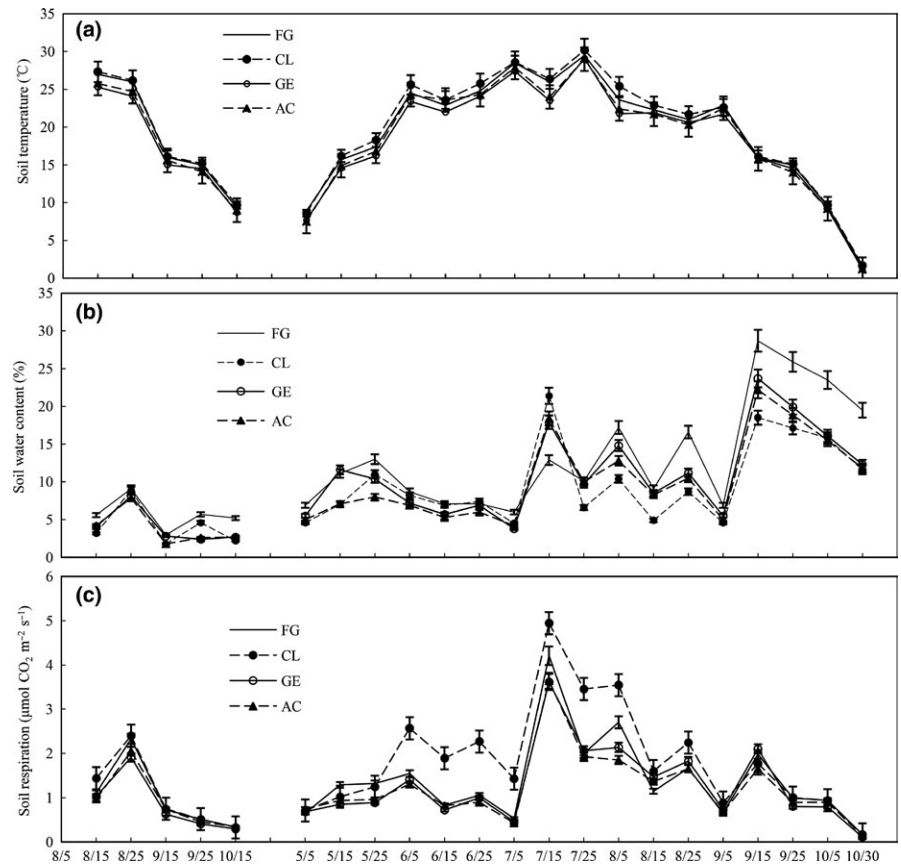**FIGURE 1** Dynamic of precipitation and air temperature from 1 August 2009 to 31 December 2010

FIGURE 2 Soil temperature (°C, 0–5 cm), soil water content (%, 0–5 cm), and soil respiration (μmol CO_2 m^{-2} s^{-1}) for free grazing grassland (FG), cropland (CL), grazing enclosure grassland (GE), and abandoned cultivated grassland (AC) in 2009 (August to October) and 2010 (May to October). (a) soil temperature, (b) soil water content, and (c) soil respiration. Bars indicate mean ± standard error

CL and GE. Similarly, mean BGB during growing season decreased from 1570.7 ± 198.6 g/m^2 to 532.6 ± 100.0 and 1141.1 ± 122.2 g/m^2 with the conversions of FG to CL and GE. Furthermore, mean AGB during the growing season significantly increased from 57.70 ± 10.0 to 246.62 ± 20.3 g/m^2 with the conversion of FG to CL (Table 1).

3.2 | Dynamic change in soil respiration

The R_s showed similar daily variations in the four soil management types. The extremely low R_s values coincided with a drought on July 5, and after the onset of rain on July 11, R_s sharply increased to its highest values of the growing season on July 15 (Figure 2c). The dynamics of monthly cumulative R_s coincided with T_s and air temperature, with maximum values in July and minimum values in October (Figure 3). The cumulative R_s followed the order of CL (344.74 gC m^{-2} year^{-1}) > FG (265.97 gC m^{-2} year^{-1}) > GE (236.70 gC m^{-2} year^{-1}) > AC (226.42 gC m^{-2} year^{-1}) during the growing season in 2010 (Table 2). Furthermore, R_s in 2010 was about 1.3 to 1.5 times higher than the corresponding values in 2009, possibly due to higher precipitation in 2010 than 2009 (363 vs. 248 mm) (Table 2).

3.3 | Correlation between R_s and T_s, S_w

For the four soil management types, daily mean R_s significantly increased exponentially with T_s ($p < .001$). T_s explained 26%–70% of the variation in R_s (Figure 4, Table 3). Although the relationship between R_s and T_s was similar among the four soil management types,

the coefficient of determination (R^2) was greater in CL than FG and AC (R^2: 70% vs. 26% and 49%), and lower in FG than that in GE (R^2: 26% vs. 50%) (Table 3). Values of Q_{10} were 1.55, 2.66, 2.10, and 2.01 in FG, CL, GE, and AC, respectively (Table 3).

Daily mean R_s was significantly correlated with S_w ($p < .001$) and followed parabolic pattern for four soil management types. The S_w explained 26%–40% of the variation in R_s (Figure 4, Table 3). When S_w values were above about 2%, R_s increased with the increasing of S_w in CL, whereas R_s will decrease when S_w reached the threshold for the other sites. Multiple polynomial regression analysis showed that T_s and S_w explained 66%–84% of the variation in daily mean R_s (Figure 5, Table 4), while total monthly precipitation (MTP) and monthly mean temperature (MMT) explained 78%–96% of the variation in monthly cumulative R_s (Figure 6, Table 4).

3.4 | Soil respiration among soil management changes

Values of the daily mean R_s during growing season varied with soil management changes, and it significantly increased by 29% with the conversion of FG to CL and decreased by 35% and 11% with the conversion of CL to AC and FG to GE during the growing season in 2010 (Table 2). From June to August, R_s in CL was significantly higher than that in the other site types ($p < .001$), while at the end of the growing seasons, we observed no significant difference of R_s between the four soil management types (Figure 4).

TABLE 1 Vegetation and soil characteristics for free grazing grassland (FG), cropland (CL), grazing enclosure grassland (GE), and abandoned cultivated grassland (AC) (values represent mean ± standard error, $n = 5$). Different letters in each column indicate significant differences at $p < .05$

Soil management	Bulk density (g/cm^3, 0–10 cm)	SOC (g/kg, 0–30 cm)	AGB (g/m^2)	BGB (g/m^2, 0–30 cm)	Litter biomass (g/m^2)
FG	1.30 ± 0.0b	33.07 ± 0.05a	57.70 ± 10.0c	1570.7 ± 198.6a	10.11 ± 5.84c
CL	1.21 ± 0.04c	11.78 ± 0.28c	246.62 ± 20.3a	532.6 ± 100.0d	–
GE	1.37 ± 0.03ab	17.98 ± 0.87b	177.78 ± 15.2b	1141.1 ± 122.2b	75.39 ± 9.31a
AC	1.42 ± 0.02a	14.69 ± 1.45b	142.72 ± 13.9b	873.3 ± 116.2c	37.75 ± 4.21b

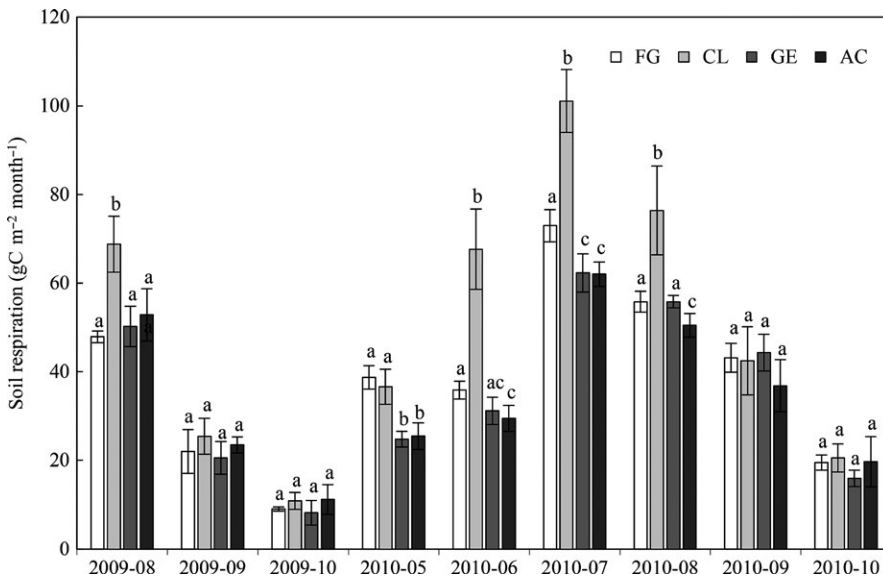SOC, soil organic carbon; AGB and BGB, average aboveground and belowground biomass from May to September in 2010.

FIGURE 3 Seasonal dynamic of monthly cumulative respiration (gC m^{-2} month^{-1}) for free grazing grassland (FG), cropland (CL), grazing enclosure grassland (GE), and abandoned cultivated grassland (AC) in 2009 (August to October) and 2010 (May to October). Bars indicate mean ± standard error. Different letters indicate significant differences at $p < .05$

TABLE 2 Daily mean soil respiration (R, µmol CO$_2$ m^{-2} s^{-1}) and cumulative soil respiration (CR, gC/m^2) during the growing seasons from 2009 to 2010 for free grazing grassland (FG), cropland (CL), grazing enclosure grassland (GE) and abandoned cultivated grassland (AC) (values represent mean ± standard error, $n = 5$). Different letters in each column indicate significant differences at $p < .05$

Soil management	R	CR		
	2010	2009	2010	
	(May to October)	(August to October)	(May to October)	(August to October)
FG	1.43 ± 0.04b	80.93 ± 1.10b	265.97 ± 7.49b	118.45 ± 9.23b
CL	1.85 ± 0.15a	105.02 ± 9.80a	344.74 ± 28.42a	139.42 ± 16.02a
GE	1.27 ± 0.04c	78.96 ± 8.91ba	236.70 ± 8.33c	116.06 ± 4.64b
AC	1.21 ± 0.06c	84.18 ± 7.60ba	226.42 ± 12.63c	107.02 ± 10.38b

4 | DISCUSSION

4.1 | Soil respiration under four different soil management types

In this study, daily mean R_s values of grassland during the growing seasons ranged from 1.21 to 1.43 µmol CO$_2$ m^{-2} s^{-1}, which were lower than that in the northern grassland in China (1.87 µmol CO$_2$ m^{-2} s^{-1}) (Zhang et al., 2015). Again, daily mean R_s during the growing seasons in CL (1.85 µmol CO$_2$ m^{-2} s^{-1}), was also lower than that in the agricultural ecosystem in the northern China plain (3.95 µmol CO$_2$ m^{-2} s^{-1})

(Zhang et al., 2013). The lower R_s observed in our study is possibly due to lower precipitation (382 vs. 532 mm and 560 mm for cropland and grassland, respectively). Cumulative R_s ranged from 226.42 to 344.74 gC/m^2 during the growing seasons, and it fell right into the range reported for temperate grassland (range: 132–830 gC/m^2) (Raich & Schlesinger, 1992), and close to the study in the same region (262–309 gC/m^2) (Gong et al., 2014).

Different ecosystem types, in regard to different plant community patterns within an ecosystem, exhibit different Q_{10} values. In our study, Q_{10} values ranged between 1.55 and 2.66 for the four soil management types, which fell right into the range of the Q_{10} in China
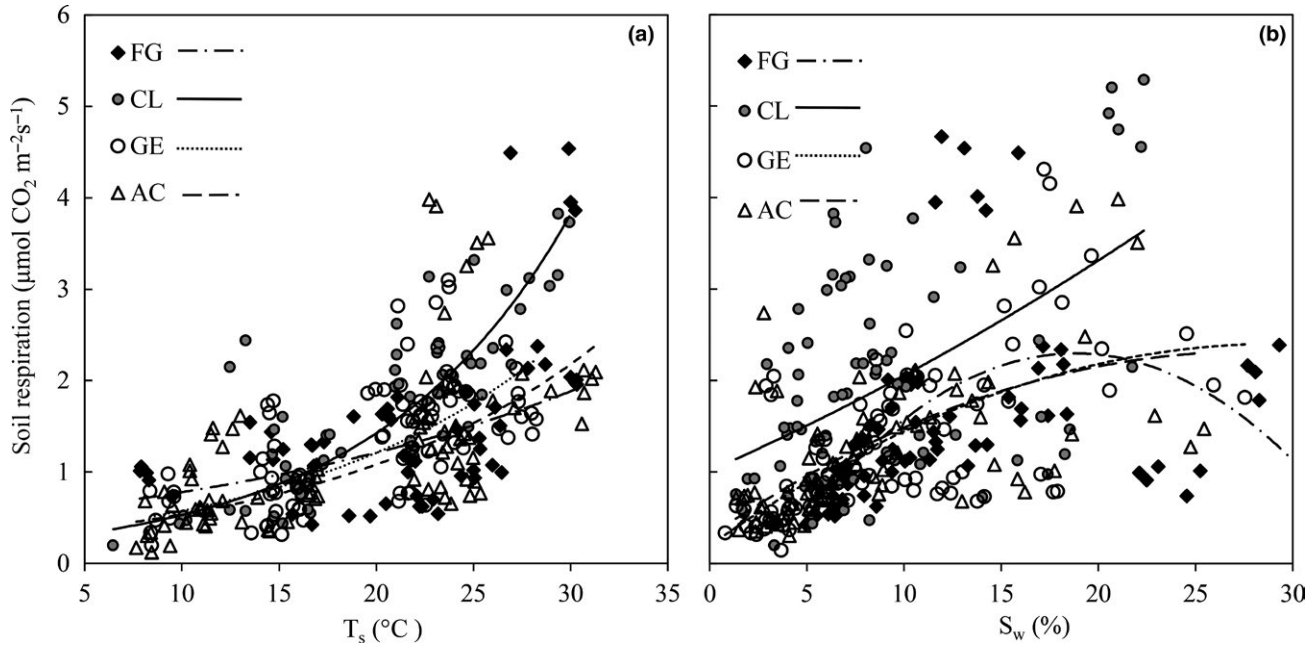
FIGURE 4 The relationship between daily mean R_s (μmol CO_2 m^{-2} s^{-1}) and soil temperature (T_s, °C, 0–5 cm), soil water content (S_w, %, 0–5 cm) for free grazing grassland (FG), cropland (CL), grazing enclosure grassland (GE), and abandoned cultivated grassland (AC). (a) relationship between R_s and T_s; (b) relationship between R_s and S_w

(range: 1.28–4.75) (Zheng et al., 2009). Values of Q_{10} values far greater in CL than that in the other sites, which confirmed previous conclusion that cropland may be more sensitive to climate warming, whereas grassland may have adapted to climatic warming (Tungate, Israel, Watson, & Rufty, 2007). In FG, Q_{10} was 1.55, which was close to the lowest value of the range, study has indicated that small quantities of fungi and bacteria may result in lower Q_{10} values in grazed grasslands in China (Cao et al., 2004).

4.2 | Effects of abiotic factors on R_s in different soil management types

Generally, T_s and S_w are considered two of the most important abiotic factors controlling temporal variations of R_s (Raich & Potter, 1995; Rong et al., 2015). In fact, all biogeochemical processes associated with R_s inevitably relate to T_s and S_w (Risch, Haynes, Busse, Filli, & Schuetz, 2013), and the dependence of R_s on T_s and S_w could be explained by the influence of T_s and S_w on availability of carbon substrate (Campbell & Law, 2005). Although the relationship between R_s and T_s and S_w is similar, the coefficient of determination (R^2) was different (Table 3), suggesting that soil management changes changed the R_s through influencing the relationship between R_s and abiotic factors.

The effect of S_w on R_s is complex, as soil water affects not only enzymatic activities and physiological processes, but also gas diffusion (Balogh et al., 2011; Unger, Maguas, Pereira, David, & Werner, 2010). Low values of S_w slow down solute diffusion and limit the supply of organic substrate for microorganisms (Moyano, Manzoni, & Chenu, 2013). In our study, S_w had the threshold in grassland ecosystem, above or below the threshold, R_s would decrease, but values of R_s for CL were almost positively related to S_w, and the result agreed with finding of Rong et al. (2015).

Although the result suggested that T_s was more important than S_w in determining soil respiration during growing seasons (Table 3), the dramatic change in S_w has a significant influence on R_s. Conant, Dalla-Betta, Klopatek, and Klopatek (2004) indicated that S_w had an overriding influence on R_s, particularly during the dry season in semi-arid environments. In a similar study, Rey et al. (2011) found that S_w was the main driver of R_s for most of the year when soil temperatures were above 20°C in semi-arid steppe ecosystems of Spain. In our study, dramatic increase or decrease in R_s were observed after rainfall or dry events for all soil management types (Figure 2), and the result was in agreement with findings from the other studies (Rey et al.,2011; Rong et al., 2015), suggesting that the dramatic change in S_w have a pronounced influence on R_s.

Abiotic factors explained less daily variation of R_s in FG than that in the other sites (R^2: 66% vs. 79%–86%, Figure 5), and it indicated that other factors also play an important role in R_s in FG. Grazing significantly changes soil physical and chemical characteristics, including SOC, soil bulk density, and soil texture (Bremer, Ham, Owensby, & Knapp, 1998; Gong et al., 2014; Wilsey, Parent, Roulet, Moore, & Potvin, 2002), so the terms above should be considered to improve the explanation of daily mean R_s in FG.

4.3 | Effects of soil management changes on soil respiration

Soil management changes result in changes in the soil microclimate and the biotic factors such as vegetation structure, primary productivity, and soil organic matter, thus indirectly affecting R_s (Chen et al., 2006; Gong et al., 2014; Rong et al., 2015). Values of R_s increased by 29% due to the conversion of FG to CL, and the result is similar to previous studies that conversion of natural grassland to cropland can

Soil management	$R_s = a*e^{b*Ts}$	$R_s = a*S_w^2 + b*S_w + c$	Q_{10}
FG	$R_s = 0.501e^{0.044\ Ts}$, $R^2 = .26$, $p < .001$	$R_s = -0.009\ S_w^2 + 0.350\ S_w - 1.000$, $R^2 = .26$, $p < .001$	1.55
CL	$R_s = 0.197e^{0.098\ Ts}$, $R^2 = .70$, $p < .001$	$R_s = 0.001\ S_w^2 + 0.093\ S_w + 1.015$, $R^2 = .26$, $p < .001$	2.66
GE	$R_s = 0.272e^{0.074\ Ts}$, $R^2 = .50$, $p < .001$	$R_s = -0.002\ S_w^2 + 0.150\ S_w + 0.195$, $R^2 = .37$, $p < .001$	2.10
AC	$R_s = 0.266e^{0.070\ Ts}$, $R^2 = .49$, $p < .001$	$R_s = -0.002\ S_w^2 + 0.144\ S_w + 0.300$, $R^2 = .40$, $p < .001$	2.01

FIGURE 5 Correlation of daily mean R_s (μmol CO_2 m^{-2} s^{-1}) with soil temperature (T_s, °C, 0–5 cm), soil water content (S_w, %, 0–5 cm) for free grazing grassland (FG), cropland (CL), grazing enclosure grassland (GE), and abandoned cultivated grassland (AC). The regression equations for each curve are listed in Table 4
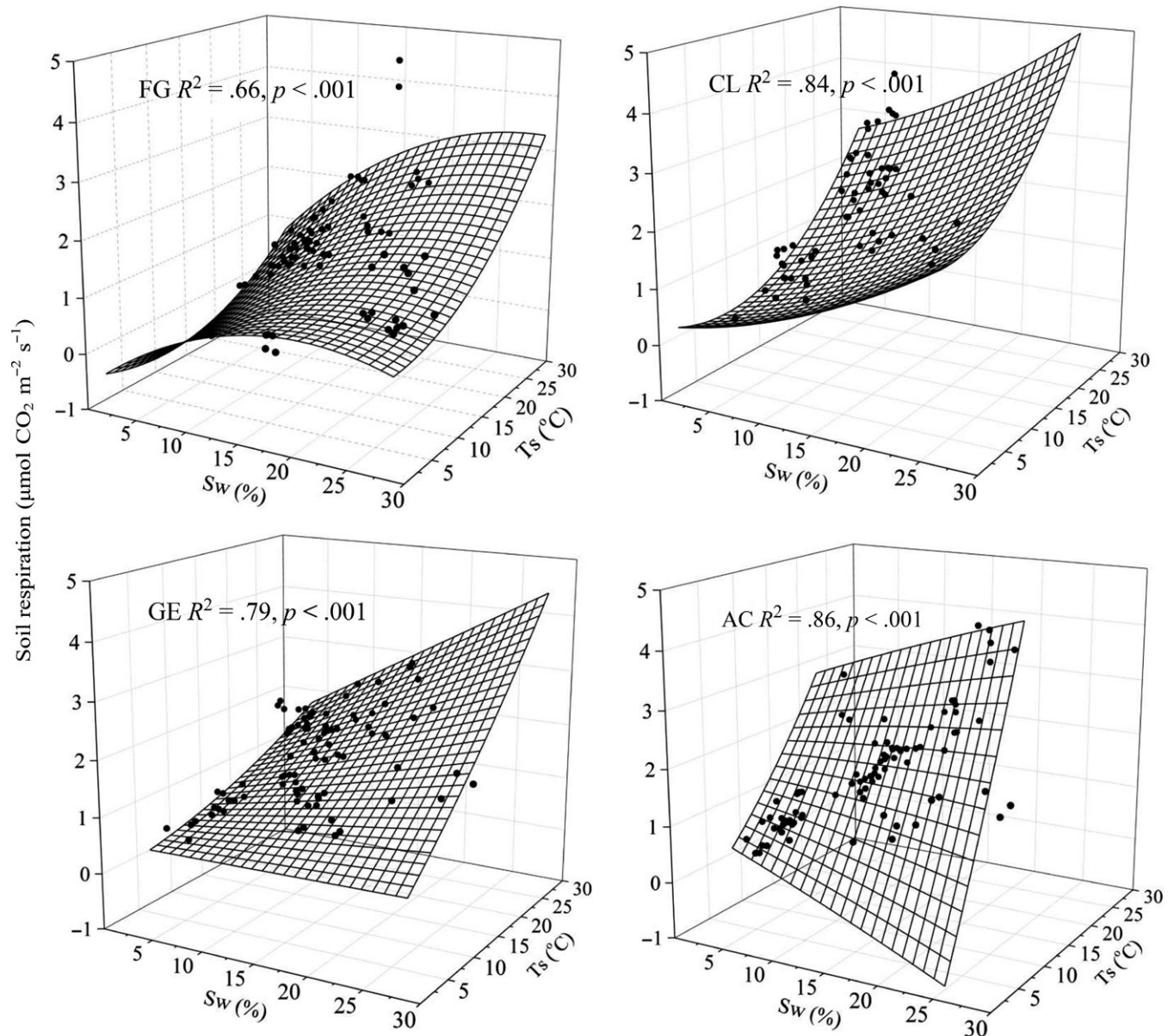
increase R_s (Frank et al., 2006; Wang, Liu, et al., 2015). Changes in soil microclimate due to soil management changes could not explain the increased R_s. S_w decreased, while there was no significant change in T_s, whereas R_s increased with the conversion of FG to CL. This significant change may be explained as follows: First, Q_{10} was higher for CL compared to FG, which suggests that soil management change from

TABLE 4 Regression equations for monthly cumulative R_s (gC m^{-2} month^{-1}) and monthly total precipitation (MTP), monthly mean temperature (MMT) for free grazing grassland (FG), cropland (CL), grazing enclosure grassland (GE), and abandoned cultivated grassland (AC)

| Soil management	$R_s = a \cdot T_s^2 + b \cdot S_w^2 + c \cdot T_s \cdot S_w + d \cdot T_s + e \cdot S_w + f$	$R_s = a \cdot MMT^2 + b \cdot MTP^2 + c \cdot MMT \cdot MTP + d \cdot MMT + e \cdot MTP + f$
FG	$R_s = 0.004 \cdot T_s^2 + 0.003 \cdot S_w^2 + 0.002 \cdot T_s S_w + 0.164 \cdot T_s - 0.063 \cdot S_w - 0.674$	$R_s = 0.073 \cdot MMT^2 0.004 \cdot MTP^2 + 0.017 \cdot MMT \cdot MTP + 0.489 \cdot MMT + 0.043 \cdot MTP + 1.806$
CL	$R_s = 0.002 \cdot T_s^2 + 0.005 \cdot S_w^2 + 0.001 \cdot T_s \cdot S_w + 0.017 \cdot T_s - 0.073 \cdot S_w + 0.396$	$R_s = 0.003 \cdot MMT^2 + 0.277 \cdot MTP^2 + 0.001 \cdot MMT \cdot MTP + 0.440 \cdot MMT - 2.549 \cdot MTP + 10.938$
GE	$R_s = 0.001 \cdot S_w^2 + 0.004 \cdot T_s \cdot S_w - 0.017 \cdot T_s + 0.002 \cdot S_w + 0.202$	$R_s = 0.240 \cdot MMT + 2.532 \cdot MTP - 9.184$
AC	$R_s = 0.002 \cdot T_s^2 + 0.003 \cdot S_w^2 + 0.008 \cdot T_s^2 S_w + 0.115 \cdot T_s - 0.099 \cdot S_w - 0.354$	$R_s = 2.243 \cdot MMT + 0.139 \cdot MTP - 1.791$
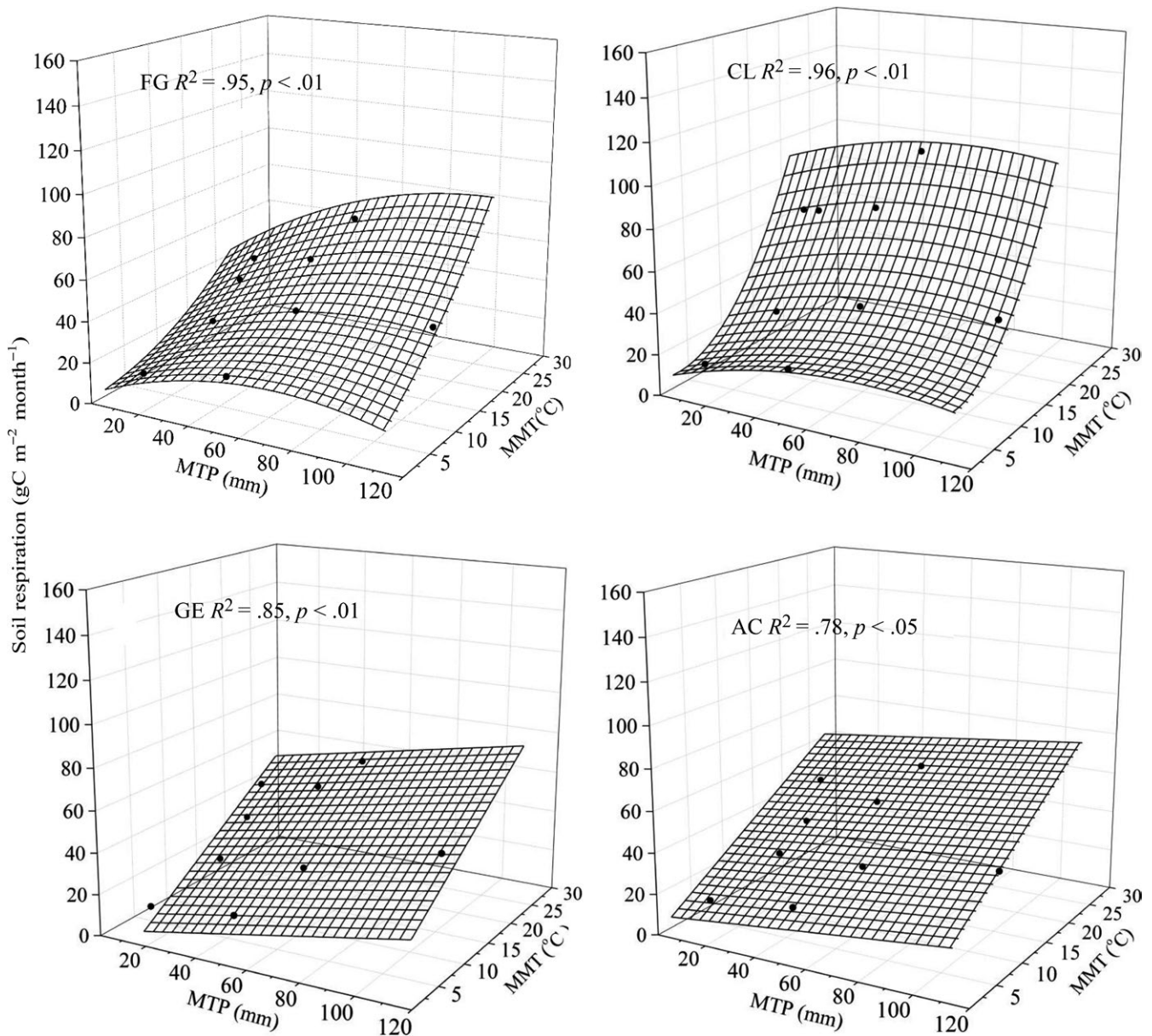
FIGURE 6 The relationship between monthly cumulative R_s (gC m^{-2} month^{-1}) and monthly total precipitation (MTP), monthly mean temperature (MMT) for free grazing grassland (FG), cropland (CL), grazing enclosure grassland (GE), and abandoned cultivated grassland (AC). The regression equations for each curve are listed in Table 4

FG to CL could increase the temperature sensitivity of soil respiration and lead to a concomitant loss of soil carbon storage. Second, soil management change from FG to CL increased R_s through decreasing soil carbon levels (Xie et al., 2007) and soil bulk density. In this study, SOC and soil bulk density in cropland were both significantly lower than that in the FG (Table 1), suggesting that annual tillage enhanced substrate availability and soil aeration, which in turn may have led to increased soil microbial activity and decomposition of soil organic carbon, resulting in a rapid increase in R_s. Third, the higher R_s in CL may relate to higher AGB, plant photosynthesis has a driving effect on R_s (Tang, Baldocchi, & Xu, 2005), and R_s increase with increase in AGB (Gong et al., 2014). In this study, AGB was significantly higher in CL than in FG and AC (Table 1), indicating that the higher AGB promote the release of CO_2 in CL. Furthermore, manure application also affects the R_s process in CL. A study in a Mediterranean maize (_Zea mays_ L.)-based cropping system assessed the effect of different fertilization regimes on R_s, with the result that manure fertilization increased R_s (Lai et al., 2017). In our study, manure fertilization of cattle slurry was used in CL site, which may promote the emission of soil CO_2.

Soil management change from CL to AC remarkably decreased R_s by 35%, and it may relate to lower T_s, Q_{10} and higher soil bulk density in AC. When the cropland converted to abandoned cultivated grassland, SOC increased and AGB decreased (Table 1), which was conducive to the accumulation of soil organic matter and decrease the release of CO_2. The result differed from the finding of Wang, Liu, et al. (2015), which showed that R_s was increased with the conversion of CL to AC. This may be due to shorter restoration year (10 vs. 15 years), which result in lower accumulation of litter biomass (38 vs. 103 g/m²). Litter is the main source of soil organic carbon and provides substrate for soil microbial activity, resulting in heterotrophic respiration (Ngao, Epron, Brechet, & Granier, 2005), and it is one of the main factors affecting R_s along the restoration chronosequence (Wang, Liu, et al., 2015). Our results suggest that after a proper natural restoration period, restoration grasslands should be utilized properly to decrease R_s.

The values of R_s significantly decreased by 11% with the conversion of FG to GE. On the one hand, T_s and S_w both were significantly decreased with soil management change from FG to GE (Figure 2a, b), which lead to the decrease in R_s. On the other hand, grazing animals deposit large amounts of manure that could increase SOC and BGB in FG (Table 1) and, consequently, increased R_s. The active carbon pool in the soil directly provides respiration substrate for decomposition and R_s increase with the increase of SOC (Smith 2003; Chen, Huang, & Zou, 2010), while root respiration accounts for 13%–55% of total R_s in temperate grasslands (Gong et al., 2014). The conversion of FG- to GE-induced changes in soil microclimate also contributed to the relatively high Q_{10} values (Table 3); the same result also has been reported for the Yellowstone National Park and Tibetan Plateau (Chen et al., 2016; Chuckran & Frank, 2013), and it implies that the carbon stored in the soils of the GE may be particularly vulnerable to the climate warming. Moreover, litter biomass was significantly higher in GE than that in FG (Table 1), and it will continuously increase with restoration

years. Given these results, we predict that the rate of CO_2 release is faster in GE than that in FG if the climate warming.

5 | CONCLUSIONS

Our findings support the hypotheses that most of the daily and seasonal variation in soil respiration could be explained by soil temperature and soil water content, and soil respiration is significantly affected by soil management changes. This study monitored the effects of soil management changes from free grazing grassland to cropland and grazing enclosure grassland, cropland to abandoned cultivated grassland on soil respiration in Inner Mongolia, China, and it is critical for enhancing our understanding of the global carbon cycle and has practical implications for grassland management. Soil temperature and soil water content significantly influenced soil respiration for all soil management types and explained 66%–86% of the variability in daily soil respiration. Monthly mean temperature and precipitation explained 78%–96% of the variability in monthly cumulative soil respiration. The results showed that soil respiration increased by 29% with the conversion of free grazing grassland to cropland and decreased by 35% and 11% with the conversion of cropland to abandoned cultivated grassland and free grazing grassland to grazing enclosure grassland. The increase in Q_{10} and litter biomass induced by the conversion of free grazing grassland to grazing enclosure grassland could lead to increased CO_2 emissions if the climate warming.

Given the limitations of biotic factors data of this study, soil organic carbon and bulk density were only determined once a year, and biomass was only measured once a month from May to September in 2010, further studies are worthwhile to evaluate the influence of biotic factors (soil organic carbon, aboveground biomass, root biomass, and litter biomass) on soil respiration, and to detect relative contribution of different factors to soil respiration in different soil management types. Furthermore, the studies about the contribution ratio of root and heterotrophic respiration to soil respiration under soil management changes are also needed to fully explain the effect of soil management changes on soil respiration.

CONFLICT OF INTEREST

None declared.

AUTHOR CONTRIBUTIONS

Haili Xue analyzed the data and wrote the paper. Haiping Tang designed the research and revised the manuscript. All authors have read and approved the final manuscript.

ORCID

Haiping Tang http://orcid.org/0000-0002-3802-7466

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