Non-growing season soil CO₂ efflux patterns in five land-use types in northern China

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Non-growing season soil CO₂ efflux patterns in five land-use types in northern China

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1. Introduction

Grasslands cover nearly 400 million hectares of the earth’s land area and are extensive in China. About 78% of the grasslands in China occur in the northern temperate zone, which are an integral component of the Eurasian steppe and play an important role in...
supporting animal and crop production and providing ecological services (Kang et al., 2007). Soils in China's grassland are an important sink for C, storing 41.03 Pg C or about 13-fold more C than aboveground grassland vegetation (Ni, 2002). About 90% of China's grasslands exhibit some degree of degradation from heavy grazing, and large grassland areas have been converted to cultivated land and perennial pastures due to increasing food demand (SEPA, 1998). For example, 20 million hectares of China's grasslands have been ploughed since 1949 (SEPA, 1998). Meta-analysis indicated that soil C stocks declined 59% when land was converted from grassland to cultivated land (Guo and Gifford, 2002). Grassland conversion in China has resulted in a 1.24 Pg C loss from temperate grasslands in northern China during 2011 (Wang et al., 2013). Interannual variation of soil CO2 efflux (FC) is mainly a function of soil temperature (Ts) and soil water content (SWC) (Frank et al., 2002; Gilmanov et al., 2004; Chen et al., 2010). Moderate and heavy degradation has resulted in a 1.24 Pg C total net C loss from temperate grasslands in northern China during 1960–1990 (Wang et al., 2011). Therefore, it is critical to understand how land use impacts the process and magnitude of the C cycle and sink activity in China's grasslands.

Net ecosystem exchange (NEE) is the difference between C fixation by plants and heterotrophic and autotrophic respiration. The growing season of temperate grasslands in northern China is typically about six months. During the remainder of the year, grassland vegetation is primarily dormant, and NEE is comprised mainly of soil CO2 efflux (Rs), primarily soil respiration (Rg). Previous studies indicated that significant levels of Rg can occur during the non-growing season on grasslands (Monson et al., 2006; Panikov et al., 2006; Chen et al., 2013), which can result in important losses of C captured during the growing season (Wang et al., 2007; Chen et al., 2013). The rate of CO2 loss during the dormant period is mainly a function of soil temperature (Ts) and soil water content (SWC) (Frank et al., 2002; Gilmanov et al., 2004; Chen et al., 2013). Interannual variation of soil CO2 efflux can be considerable depending on annual weather patterns (Polley et al., 2008; Zhang et al., 2010).

The reported effects of livestock grazing on FC are inconsistent. Some studies showed that grazing reduced soil CO2 efflux (Zou et al., 2007; Chen et al., 2013), while other studies found that grazing increased soil CO2 efflux (Frank et al., 2002; Klumpp et al., 2007; Paz-Ferreiro et al., 2012). Moreover, Liebig et al. (2013) found that soil CO2 efflux differed among grazing treatments during spring (March–May) and fall (September–November), but did not differ during winter (December–February) and summer (June–August) in the Northern Great Plains of the USA. In addition, soil CO2 effluxes were greater from cultivated pastures compared to grazed and ungrazed grasslands during the growing season in the Northern Great Plains (Frank et al., 2002). These studies mainly focused on the growing season rather than the non-growing season and did not compare soil CO2 efflux from grasslands subjected to different stocking rates, cultivated pasture and annual cropland.

Various land-use types are present in a mosaic pattern in the agro-pastoral region of northern China, and these types can change markedly with social-economic conditions (Zhao et al., 2002). Understanding the magnitude and being able to predict soil CO2 efflux from various land-use types during the non-growing season is critical to accurately estimate C budgets in northern China. In this study, we hypothesized that interannual variability effects are greater than land-use effects on FC during the non-growing season in dominant land-use types of northern China. The objectives of our study were to: 1) evaluate and quantify FC from various land-use types including grasslands grazed at different stocking rates, perennial pasture and cropland; and 2) clarify the coupling effects between land-use types and environmental factors for FC in the agro-pastoral region of northern China.

2. Material and methods

2.1. Study site

Experiments were conducted at Guyuan County (41°46′ N, 115°41′ E, elevation 1380 m), located in Hebei Province, China. Geographically this region is part of the southeastern edge of the Mongolian Plateau and is temperate steppe. Large areas of the steppe have been converted to grain production. The region has a semi-arid continental climate and receives approximately 320–400 mm mean annual precipitation, nearly 60–80% of which is received during the growing season (June to August). Annual mean temperature is 1 °C, with monthly mean temperature ranging from −18.6 °C in January to 17.6 °C in July. The mean frost-free growing period is 85–95 days (Rong et al., 2015a, 2015b).

Five land-use types were used in this study and were 1.5–5 ha in size (Rong et al., 2015a, 2015b). Land-use types included grazed grasslands (1.5 ha each) subjected to three different stocking rates (UG: ungrazed site, MG: moderately grazed site, HG: heavily grazed site) since 2010, perennial pasture (PP) since 2010 and permanent annual cropland (CL) since 1980. UC was ungrazed since 2010, MG was grazed at a stocking rate of 6.7 sheep ha−1 during the growing season with 50–55% biomass removal (1.4 sheep units ha−1 year−1), and HG was grazed at a stocking rate of 9.3 sheep ha−1 during the growing season with 75–85% biomass removal (2.3 sheep units ha−1 year−1) (Rong et al., 2015a, 2015b). Vegetation in the grazed land-use types was dominated by Leymus chinensis (Trin.) Tzvelev and Stipa krylovii Roshev., accompanied with Cleistogenes chinensis (Maxim.) Keng, Phragmites communis (Trin.), Carex duriuscula C.A. Mey, Taraxacum mongolicum Hand.-Mazz., Artemisia frigida Willd. and Polygonum sibiricum Laxm.

PP included an area of 5 ha that was converted from native grassland to L. chinensis pasture in 2009. PP was hayed during 15–20 Aug. each year, and the remaining stubble was grazed by cattle and sheep during the autumn and winter since 2010. The estimated stocking rate for PP during the non-growing season was 2.3 sheep units ha−1 year−1. CL included an area of 5 ha that has been plowed and cropped each year since 1980, with a crop rotation of two years of Avena nuda L. and one year of Linum usitatissimum L. No irrigation was applied to any of the land-use types; fertilizers were only applied to CL at a rate of 100 kg/ha manure each year before sowing and 40 kg/ha urea at sowing (Rong et al., 2015a, 2015b). Soil in this area is a sandy soil and classified as a Kastanozem soil (FAO, 2006) or a Calciorthic Aridisol by the USA classification system (Soil Survey Staff, 2014).

In early Aug. of 2012 and 2013, vegetation and soil properties in each land-use type were sampled and measured. Aboveground biomass was determined inside a 0.5 m × 0.5 m quadrat with five replications in each land-use type. Plants were clipped to a 1-cm height, and clipped herbage was dried to constant weight in an oven at 80 °C for 48 h. Belowground biomass was sampled for the five land-use types at the locations where the aboveground biomass was clipped using a soil auger (6.5-cm inside diameter) to a 12-cm depth. Belowground samples were placed separately into a 0.02-mm nylon mesh bag, washed with water, dried in an oven at 80 °C for 48 h and weighed. Soil bulk density was determined using the ring-knife method with five replicate samples (ISSCAS, 1978). For analysis of soil characteristics, five soil samples (a mixture of five sampling points bulked into one sample) were collected in each land-use type to a 12-cm soil depth and dried at room temperature prior to analysis. Subsamples were ground to pass a 0.25-mm sieve and analyzed for soil organic carbon (SOC) and total N. A Rapid C Analyzer (Elementer, Germany) was used to determine SOC, whereas total N was determined by the Kjeldahl Method. Soil characteristics at the study sites are listed in Table 1.
the chamber was sealed by the lid. Values of soil CO2 efflux inside the chamber was recorded every 1 s for 2 min after the gas analyzer, which was placed in the center of the five PVC chamber collars (20-cm diameter, 15-cm height, 1.5–2-mm thickness) were inserted into the soil and maintained at 3 cm above the soil surface. The gas analyzer was connected to a MCCI–1 multiple processor (Lica United Inc., Beijing, China), which was linked to five stainless steel chambers with lids through five Teflon tubes (10-m long). During the measurements, CO2 concentrations inside the chamber was recorded every 1 s for 2 min after the chamber was sealed by the lid. Values of soil CO2 efflux (Fc, \( \mu \text{mol m}^{-2} \text{s}^{-1} \)) were calculated by the processor using the following equation:

\[
F_c = \frac{10V^*P^*}{R^*S^*T_0 + 273.15} \frac{dC}{dt}
\]

where \( V \) is volume of the chamber (cm\(^3\)), \( P \) is atmospheric pressure (kPa), \( W \) is initial concentration of water vapor (mol/cm\(^3\)), \( S \) is chamber basal area (cm\(^2\)), \( T_0 \) is inside chamber temperature (°C), \( R \) is value of the gas constant (\( R = 8.314 \text{ J mol}^{-1} \text{ K}^{-1} \)) and \( dc/dt \) is the concentration gradient of CO2 through time. The units of soil CO2 efflux were converted to mg C m\(^{-2} \) h\(^{-1} \) (Rong et al., 2015b).

In this study, CO2 fluxes during the non-growing season were measured from 1 Oct. to 30 April in 2012–13 and 2013–14 following Chen et al. (2013) who also studied the non-growing season relationships between daily Fc and Ta, Ts and SWC for each land-use type. Stepwise regression analysis was used to examine the relationships of Fc with air temperature (Ta), Ts and SWC.

### 2.2. Soil CO2 efflux measurements

Measurements of Fc were obtained with closed chambers as described by Rong et al. (2015a, 2015b). Soil CO2 concentrations were measured with a mobile greenhouse gas analyzer (LGR-9080010, Los Gatos Research Inc, CA, USA). In each land-use type, five sampling points were located about 5–m apart from the gas analyzer, which was placed in the center of the five sampling points. Five PVC chamber collars (20-cm diameter, 15-cm height, 1.5–2-mm thickness) were inserted into the soil and maintained at 3 cm above the soil surface. The gas analyzer was connected to a MCC-1–8 multiple processor (Lica United Inc., Beijing, China), which was linked to five stainless steel chambers with lids through five Teflon tubes (10-m long). During the measurements, CO2 concentrations inside the chamber was recorded every 1 s for 2 min after the chamber was sealed by the lid. Values of soil CO2 efflux (Fc, \( \mu \text{mol m}^{-2} \text{s}^{-1} \)) were calculated by the processor using the following equation:

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### 2.3. Soil temperature, soil water content and meteorological data

Values of SWC and Ta at a 6-cm soil depth (ECH2O, Decagon Devices, Pullman, WA, USA) were continuously recorded in HG, MG, UG and PP land-use types, and field meteorological data were recorded by an automated meteorological station (Weatherhawk XP, Logan, UT, USA) every 30 min. In addition, SWC and Ta at a 6-cm soil depth in CL were measured five times near each chamber with a hand-held thermometer and soil moisture sensors (ML2x, Delta-T Devices, Cambridge, UK) during Fc measurements. SWC in CL was determined by oven drying at 80 °C for 48 h, when soil was frozen. Snow data were obtained from the local meteorological station, which is located 10 km from the experimental area.

### 2.4. Data analysis

This study was not a truly replicated experiment. The disadvantages of pseudo-replication are well documented by Hurlbert (1984). However, large-scale experiments in ecological studies may not be strictly necessary for true replication due to time and money constraints, which may not allow for replication (Oksanen, 2001). Numerous pseudo-replicated experiments related to CO2 fluxes on grasslands have been published (LeCain et al., 2002; Gao et al., 2004; Byrne et al., 2005; Prater et al., 2006; Rong et al., 2015a, 2015b). Cumulative soil CO2 effluxes were calculated by linear interpolation of daily Fc between measurement days in each period, and then effluxes during the non-growing season were summed across each period (Rong et al., 2015b). In 2012–13, a total of 27 measurements were made across 185 days for the grazed land-use types with 34 measurements across 178 days for the other land-use types. In 2013–14, the number of measurements and sampling periods were as follows: 32 measurements across 180 days (UG and CL), 34 measurements across 178 days (MG and HG) and 33 measurements across 179 days (PP).

The Kolmogorov–Smirnov Test was used to examine data normality of each land-use type before analysis. When necessary, data were adjusted using the cubic root transformation. ANOVA was used to test the effects of land-use type, period, year and their possible interactions on Fc. When significant interannual variability was observed (year effect \( P < 0.05 \)), Repeated Measures ANOVA (RM ANOVA) was used to test period and land-use type effects on \( T_a \), SWC and Fc during the non-growing season in 2012–13 and 2013–14. Between-subject effects were evaluated as land-use type treatment and within-subject effects were time-of-season. Linear and non-linear regression analyses were used to determine relationships between daily Fc and \( T_a \), Ts and SWC for each land-use type. Stepwise regression analysis was used to examine the relationships of Fc with air temperature (\( T_a \), Ts and SWC.

### 3. Results

#### 3.1. Variation in Fc during the non-growing season

Temporal dynamics of Fc during the non-growing season followed the seasonal patterns of \( T_a \) and Ts in the five land-use types during both measurement years (Fig. 1). However, the magnitudes of Fc values were markedly different between the two years, as indicated by ANOVA (Table 2). Mean daily values of Fc during the 2013–14 non-growing season (98 mg C m\(^{-2} \) h\(^{-1} \)) were significantly greater \((P < 0.05)\) than those in 2012–13 (32 mg C m\(^{-2} \) h\(^{-1} \)). Significant effects of period and its interaction with year were also

### Table 1

Mean and standard errors of various soil characteristics for the ungrazed (UG), moderately grazed (MG), heavily grazed (HG), perennial pasture (PP) and cropland (CL) land-use types.

<table>
<thead>
<tr>
<th>Land-use type</th>
<th>pH</th>
<th>SBD(^{-1}) g cm(^{-1})</th>
<th>SOC g kg(^{-1})</th>
<th>STC g kg(^{-1})</th>
<th>TN g kg(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>UG</td>
<td>9.15 ± 0.12a</td>
<td>1.34 ± 0.03c</td>
<td>12.28 ± 1.96c</td>
<td>21.86 ± 1.97c</td>
<td>1.55 ± 0.07b</td>
</tr>
<tr>
<td>MG</td>
<td>9.21 ± 0.20a</td>
<td>1.35 ± 0.04c</td>
<td>18.75 ± 2.28b</td>
<td>31.00 ± 0.41b</td>
<td>2.43 ± 0.13a</td>
</tr>
<tr>
<td>HG</td>
<td>9.03 ± 0.19a</td>
<td>1.43 ± 0.05a</td>
<td>13.46 ± 0.20c</td>
<td>27.94 ± 0.95b</td>
<td>2.22 ± 0.20a</td>
</tr>
<tr>
<td>PP</td>
<td>8.35 ± 0.13b</td>
<td>1.47 ± 0.02a</td>
<td>32.83 ± 5.96a</td>
<td>38.51 ± 6.37a</td>
<td>2.53 ± 0.28a</td>
</tr>
<tr>
<td>CL</td>
<td>8.26 ± 0.17b</td>
<td>1.39 ± 0.03bc</td>
<td>23.06 ± 4.21b</td>
<td>31.06 ± 1.76b</td>
<td>2.44 ± 0.08a</td>
</tr>
</tbody>
</table>

\( ^{a} \) Data within a column followed by a different letter indicates significance at \( P < 0.05 \).

\( ^{b} \) SBD = Soil bulk density, SOC = soil organic carbon, STC = soil total carbon, TN = soil total nitrogen.
detected ($P < 0.0001$, Table 2). When analyzed separately by year using RMANOVA, periods significantly affected $F_c$ in both years ($P < 0.01$). Mean $F_c$ during Period I (autumn freeze-thaw period) were 70 mg C m$^{-2}$ h$^{-1}$ in 2012 and 126 mg C m$^{-2}$ h$^{-1}$ in 2013, and for Period III (spring freeze-thaw period) were 27 mg C m$^{-2}$ h$^{-1}$ and 163 mg C m$^{-2}$ h$^{-1}$ for 2013 and 2014, respectively. Values of $F_c$ for these two freeze-thaw periods were significantly greater ($P < 0.05$) than for Period II (permanently frozen period), which was $1.5-2.0$ mg C m$^{-2}$ h$^{-1}$ for both 2012-13 and 2013-14.

3.2. Effects of land-use type on soil CO$_2$ effluxes

Land-use types had significant effects on soil CO$_2$ efflux ($P < 0.0001$, Table 2). The largest soil CO$_2$ effluxes were observed for
Stepwise regression equations relating $T_s$, $T_a$ and SWC to soil CO$_2$ effluxes showed that $T_s$ was most closely associated with soil CO$_2$ effluxes during the non-growing season (Table 4). $T_s$ was the only variable identified for inclusion in equations developed for each of the two years, PP, CL and across all land-use types. Partial $R^2$ values for the equations were 0.23 for 2012-13, 0.49 for 2013-14, 0.41 for both PP and CL, and 0.32 for all land-use types. $T_s$ and SWC were the variables identified for inclusion in equations for predicting soil CO$_2$ efflux for the three grazed sites (UG, MG and HG), whereas $T_a$ also was identified for inclusion in equations for UG and MG.

### 4. Discussion

#### 4.1. General patterns of soil CO$_2$ efflux

The magnitude of cumulative soil CO$_2$ efflux during the non-growing season was significantly higher in 2013–14 than 2012–13 across all the sites (Table 3). Aboveground and belowground biomass (measured in August each year) was greater in 2013 compared to 2012 ($P < 0.05$) (Rong et al., 2015b), which likely contributed to the greater soil CO$_2$ effluxes in 2013–14. Mean cumulative CO$_2$ efflux was 0.21–0.37 kg C m$^{-2}$ during the non-growing season, which is similar to results for alpine steppe in the Tibetan Plateau (0.35 kg C m$^{-2}$) (Cao et al., 2004) and considerably greater than that of steppe in Inner Mongolia (0.02–0.05 kg C m$^{-2}$) (Chen et al., 2013) and tall grass prairie in North America (0.09 kg C m$^{-2}$) (Frank et al., 2002). Our study area is located on the southeastern edge of the Mongolian Plateau, which has a higher mean $T_s$ during the non-growing season than these other grassland regions. The higher $T_s$ greater growing season precipitation (discussed later) and limited snow cover during the non-growing season probably led to higher soil CO$_2$ efflux compared to the other sites.

#### 4.2. Relationships between soil CO$_2$ effluxes and land-use types

Soil CO$_2$ effluxes during the non-growing season differed among land-use types and were in the order PP > CL > UG > MG > HG. Soil respiration is one of the most important losses of total soil C and accounts for about 30–50% of C loss when native grassland is converted to cropland (Schlesinger, 1995). Greater soil organic C (SOC) in PP than the grazed land-use types (Table 1) probably contributed to this increased soil CO$_2$ efflux (Chen et al., 2013). Moreover, greater root biomass in the PP land-use type also suggests increased soil CO$_2$ efflux, which was reported previously in other studies (Subke et al., 2006; Wan et al., 2007). The CL land-use type exhibited greater soil CO$_2$ effluxes during the non-growing season, which is likely related to annual cultivation and fertilization of CL, which increases aeration of top soil and provides additional substrate for soil microbial activity. Soil CO$_2$ efflux was lowest in HG compared to UG, MG, PP and CL land-use types during the

### Table 2

ANOVA table showing degrees of freedom, F value, and P value for the main and interactive effects for soil CO$_2$ efflux (Fc) in five land-use types.

<table>
<thead>
<tr>
<th>Effect</th>
<th>Degrees of freedom</th>
<th>F Value</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land-use type (L)</td>
<td>4</td>
<td>4.6</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Period (P)</td>
<td>2</td>
<td>234.9</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Year (Y)</td>
<td>1</td>
<td>181.3</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>L × P</td>
<td>8</td>
<td>9.4</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>L × Y</td>
<td>4</td>
<td>0.8</td>
<td>0.5446</td>
</tr>
<tr>
<td>P × Y</td>
<td>2</td>
<td>36.9</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>L × P × Y</td>
<td>8</td>
<td>2.6</td>
<td>0.0265</td>
</tr>
</tbody>
</table>

### Table 3

Cumulative soil CO$_2$ efflux (Fc) (mean ± standard error) (g C m$^{-2}$) for the ungrazed (UG), moderately grazed (MG), heavily grazed (HG), perennial pasture (PP) and cropland (CL) land-use types for three periods during the non-growing season.

<table>
<thead>
<tr>
<th>Period†</th>
<th>2012–13</th>
<th>2013–14</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UG</td>
<td>MG</td>
</tr>
<tr>
<td>I</td>
<td>48 ± 2</td>
<td>46 ± 2</td>
</tr>
<tr>
<td>II</td>
<td>11 ± 1</td>
<td>7 ± 1</td>
</tr>
<tr>
<td>III</td>
<td>31 ± 1</td>
<td>35 ± 2</td>
</tr>
<tr>
<td>Total</td>
<td>90 ± 4c</td>
<td>85 ± c</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>243 ± 7</td>
<td>211 ± 6</td>
<td>205 ± 6</td>
</tr>
<tr>
<td>II</td>
<td>16 ± 1</td>
<td>15 ± 1</td>
<td>12 ± 1</td>
</tr>
<tr>
<td>III</td>
<td>265 ± 8</td>
<td>169 ± 7</td>
<td>126 ± 7</td>
</tr>
<tr>
<td>Total</td>
<td>524 ± 14</td>
<td>394 ± 12</td>
<td>343 ± 10</td>
</tr>
</tbody>
</table>

* I = Autumn freeze-thaw period (30 Sept.–30 Nov.), II = Winter permanently frozen period (1 Dec.–28 Feb.), III = Spring freeze–thaw period (1 Mar.–30 Apr.),

† Total = I + II + III (non-growing season).

‡ Data followed by a different letter indicates significance at $P < 0.05$ during 2012–13 and 2013–14, respectively.
non-growing season. Considering the entire year, CO₂ efflux from the HG site was still less due to a larger reduction in gross primary productivity (GPP) compared to ecosystem respiration. Heavy grazing resulted in decreased GPP more than ecosystem respiration for our study sites (Zhu et al., 2015). Grazing has been shown in other studies to increase soil bulk density and decrease soil aeration, which leads to decreased soil CO₂ efflux due to the inhibition of soil CO₂ diffusion from the soil and reduced soil microbial activity (Cao et al., 2004; Jia et al., 2006; Yan et al., 2011). This was confirmed in our study where HG had the highest soil bulk density (Table 1) and also exhibited the lowest soil CO₂ efflux (Table 3). Similar results were reported by Chen et al. (2013) for the Mongolian steppe.

4.3. Impacts of the non-growing season climate and period on soil CO₂ efflux

Temperature is a critical factor in controlling soil CO₂ efflux during the non-growing season, and both T_a and T_s fluctuated dramatically during this period. Even though soil microbial activity and plant root growth are typically quite low during the non-growing season, changes in T_a and T_s markedly influenced soil
CO₂ efflux (Fig. 2). Mean long-term (1952–2012) Tₘ during the non-growing season was −8.2 °C in our study area, but was considerably lower during 2012–13 (−13.5 °C) and somewhat higher during 2013–14 (−5.4 °C). As expected, Tₑ followed a similar trend as Tₘ, being lower in 2012–13 (0.8 °C) than 2013–14 (1.5 °C). Lower Tₑ and Tₘ in 2012–13 resulted in a lower daily soil CO₂ efflux during 2012–13 (132 mg C m⁻² h⁻¹) compared to 2013–14 (182 mg C m⁻² h⁻¹) for the non-growing season. Growing season precipitation in our study area was 249 mm in 2012 compared to 336 mm in 2013. Although precipitation during the growing season was 81 mm in 2012–13 compared to 49 mm in 2013–14, this greater precipitation during the non-growing season in 2012–13 did not lead to a greater soil CO₂ efflux during the non-growing season in 2012–13. Apparently the higher Tₑ and Tₘ in 2013–14 and the greater precipitation received during the growing season of 2013 more than compensated for the greater precipitation received during the non-growing season of 2012–13. Similar responses of soil CO₂ efflux to precipitation also have been found in other studies (Sponseller, 2007; Ma et al., 2012; Cable et al., 2013; Shen et al., 2016).

Precipitation directly affects SWC, which in turn influences soil CO₂ efflux. A somewhat greater SWC (19%) during the autumn freeze-thaw period in 2012–13 should have increased soil CO₂ effluxes compared to a SWC of 15% in 2013–14. However, soil CO₂ efflux was considerably greater for 2013–14 than 2012–13. Previous studies have shown that relationships between soil CO₂ efflux and SWC can be either positive or negative (Rochette et al., 1991; Lee et al., 2002). A positive linear relationship between soil CO₂ efflux and SWC was observed during summer in a Zoysia japonica Steud. grassland in central Japan, while no relationship was observed during spring and autumn (Inoue and Koizumi, 2012). Our study showed that effects of SWC on soil CO₂ efflux critically depend on Tₑ and Tₘ during the non-growing season, which was lower in 2012–13 than 2013–14.

Stepwise regression showed that Tₑ was the only variable identified to predict soil CO₂ effluxes during the non-growing season in 2012–13, 2013–14, PP and CL (Table 4). Although Tₑ was not identified for the prediction of soil CO₂ efflux for HG, Tₑ was again the only variable identified when data were included for both years across all five land-use types (R² = 0.32, P < 0.001, n = 310). SWC was identified as important for predicting soil CO₂ efflux in UG, MG and HG.

Table 4

<table>
<thead>
<tr>
<th>Year/type</th>
<th>n</th>
<th>Equation for daily Fc</th>
<th>Partial R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012–13</td>
<td>145</td>
<td>48.27 + 2.57Tₑ</td>
<td>0.23**</td>
</tr>
<tr>
<td>2013–14</td>
<td>165</td>
<td>135.29 - 9.75Tₑ</td>
<td>0.49**</td>
</tr>
<tr>
<td>UG</td>
<td>59</td>
<td>479.76 - 2.39Tₑ + 18.92Tₛ - 2308.07 SWC</td>
<td>0.67**</td>
</tr>
<tr>
<td>MG</td>
<td>61</td>
<td>201.26 + 2.51Tₑ + 8.40Tₛ - 708.09 SWC</td>
<td>0.66**</td>
</tr>
<tr>
<td>HG</td>
<td>61</td>
<td>204.14 + 11.76Tₑ - 958.15 SWC</td>
<td>0.56**</td>
</tr>
<tr>
<td>PP</td>
<td>65</td>
<td>138.87 + 10.99Tₑ</td>
<td>0.41**</td>
</tr>
<tr>
<td>CL</td>
<td>64</td>
<td>105.97 - 6.58Tₑ</td>
<td>0.41**</td>
</tr>
<tr>
<td>All types</td>
<td>310</td>
<td>100.14 + 6.19Tₑ</td>
<td>0.32**</td>
</tr>
</tbody>
</table>

a UG = ungrazed, MG = moderately grazed, HG = heavily grazed, PP = Perennial pasture, CL = cropland land-use types.

** Significant at P < 0.001.

5. Conclusions

Measurements of soil CO₂ efflux during the non-growing season for different land-use types on the southeastern edge of the Mongolian Plateau showed that soil CO₂ efflux averaged 307 mg C m⁻² for UG, 241 mg C m⁻² for MG, 210 g C m⁻² for HG, 308 mg C m⁻² for CL and 374 mg C m⁻² for PP. These values are higher than estimates of soil CO₂ effluxes from other northern latitude ecosystems. Greater soil CO₂ effluxes in 2013–14 compared to 2012–13 were associated with higher annual precipitation and resulted in three- to six-fold higher soil CO₂ effluxes in 2013–14 compared to 2012–13. Stepwise regression showed that Tₑ was the most important variable for predicting soil CO₂ efflux during the non-growing season; however, prediction equations were very site-specific and year-specific. Soil CO₂ effluxes for the grazed sites (UG, MG and HG) were influenced by Tₑ, Tₛ and SWC, whereas Tₑ was the only variable identified in the prediction of soil CO₂ efflux for PP and CL. Large differences in soil CO₂ efflux between years were associated with differences in precipitation, Tₑ and Tₛ and showed that CO₂ effluxes can be considerable in major land-use types of northern China during the non-growing season.

Acknowledgements

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2016.08.085.

References


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