Winter Soil CO_2 Flux from Different Mid-Latitude Sites from Middle Taihang Mountain in North China

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Abstract

Winter soil respiration is a very important component of the annual soil carbon flux in some ecosystems. We hypothesized that, with all other factors being equal, shorter winter SR result in reduced contribution to annual soil C flux. In this study, the contribution of winter soil respiration to annual soil respiration was measured for three sites (grassland: dominated by *Artemisia sacrorum*, *Bothriochloa ischaemum* and *Themeda japonica*; shrubland: dominated by *Vitex negundo var. heterophylla*; plantation: dominated by *Populus tomatosa*) in a mountainous area of north China. Diurnal and intra-annual soil CO_2 flux patterns were consistent among different sites, with the maximum soil respiration rates at 12:00 or 14:00, and in July or August. The lowest respiration rates were seen in February. Mean soil respiration rates ranged from 0.26 to 0.45 μmol m^{-2} s^{-1} in the winter (December to February), and between 2.38 to 3.16 μmol m^{-2} s^{-1} during the growing season (May-September). The winter soil carbon flux was 24.6 to 42.8 g C m^{-2}, which contributed 4.8 to 7.1% of the annual soil carbon flux. Based on exponential functions, soil temperature explained 73.8 to 91.8% of the within year variability in soil respiration rates. The Q_{10} values of SR against ST at 10 cm ranged from 3.60 to 4.90 among different sites. In addition, the equation between soil respiration and soil temperature for the growing season was used to calculate the "modeled" annual soil carbon flux based on the actual measured soil temperature. The "measured" annual value was significantly higher than the "modeled" annual value. Our results suggest that winter soil respiration plays a significant role in annual soil carbon balance, and should not be neglected when soil ecosystems are assessed as either sinks or sources of atmospheric CO_2.

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Introduction

Soil respiration (SR) provides the main C flux from terrestrial ecosystems to the atmosphere [1,2] and is therefore one of the major components to consider in understanding ecosystem-atmosphere C exchange [3]. Carbon flux from soils has received growing attention in recent years, due to elevating atmospheric CO_2 concentration causing increasing air temperature [4–6]. Most SR measurements are conducted during the plant-growing season [6,7] when instantaneous flux rates are much higher than during colder seasons. However, Monson et al. [8] suggested that winter soil respiration could offset a major portion of the carbon fixed during the growing season, and thus, significantly contribute to the annual carbon cycling. Significant winter CO_2 flux, with a long snow-cover period, has been reported in the more productive meadow and forest ecosystems [9–11]. Mid-latitude ecosystems, on the other hand, are dominated by a shorter winter season and a thinner snow depth. These mid-latitude ecosystems are considered to be major terrestrial carbon sinks in the northern hemisphere [12]. However, little is known about the winter SR and its contribution to annual soil C flux in different mid-latitude ecosystems, which may yield inaccurate regional and global C budget predictions [13,14].

SR is a composite process shown, through field investigations, to be influenced by a multitude of environmental factors [15–16]. To date, most studies have based on SR rate predictions on the relationship between soil CO_2 flux and soil temperature (ST) and moisture (SM) [17–19]. Regional scale microclimates induced by topography and vegetation cover can affect SR rate by constraining microsite factors, such as ST and SM [19]. Therefore, there is clearly much to be learned about the major factors that control SR at the regional scale level across different ecosystems [20].

The Taihang Mountainous region covers approximately 42% of north China [21]. The vegetation of this area is a mosaic of grass, shrubs and plantation. The grass vegetation is dominated by the mixed drought-resistant species of *Artemisia sacrorum*, *Bothriochloa ischaemum* and *Themeda japonica*; shrub vegetation is dominated by *Vitex negundo var. heterophylla*; and plantation vegetation is dominated by *Populus tomatosa* species [21,22]. The region is characterized by short, cold, and dry winters, lasting approximately three months long from December to February, with varied snow cover. We hypothesized that, with all other factors being equal, shorter winter SR result in reduced contribution to annual soil C flux.

This hypothesis was tested by through field measurements of SR in three mountainous sites: grassland, shrubland, and plantation. The magnitude of winter SR rate and its contribution to annual soil C flux was compared among the different sites. In addition, the present study also investigated the relationships among SR and ST and SM.

Materials and Methods

Ethics Statement

All necessary permits were obtained for the described field studies. We carried out the study based on the Hilly Ecosystem Experimental Station of Taihang Mountain, which belongs to the Center for Agricultural Resources Research, Institute of Genetics and Developmental Biology, Chinese Academy of Science. We obtained permissions to use the sample plots from the station and institute. Our study inflicted no harm to the environment and did not involve endangered or protected species.

Site Description

The field-study was conducted in the Taihang Mountain Ecological Experimental Station of the Chinese Academy of Science, Hebei Province. The long-term annual mean air temperature of this region is 13°C, with January (–4°C mean temperature) and July (26°C mean temperature) as the coldest and warmest months, respectively [22,23]. Mean annual precipitation is 560 mm, of which 70% falls between June and September. Monthly cumulative precipitation and mean air temperature during the study period are shown in Figure 1. The top 40-cm soil layer is classified as Luvisol (FAO-UNESCO 1974). In July 2012, three 10 m×10 m plots were randomly established within each grassland, shrubland and plantation site. The three different sites were separated by a minimum of 1000 m. Stand and soil characteristics of the three sites are summarized in Table 1. No sites from which SR was measured were irrigated.

Experimental Design and Measurement

In each plot, three 100 cm^3 soil columns were randomly taken from 0 to 20 cm depth to determine the soil bulk density. Meanwhile, a soil subsample of approximately 200 g was collected at the same locations and brought back to the lab for organic C content analysis. Soil total organic C content was determined using the potassium dichromate method. All methods described above are conducted based on Forestry Standards 'Observation Methodology for Long-term Forest Ecosystem Research' of the People's Republic of China.

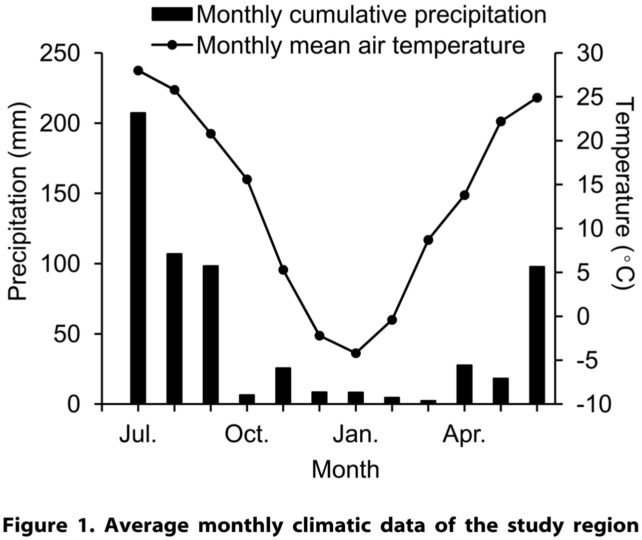

Figure 1. Average monthly climatic data of the study region during experimental periods from July 2012 to June 2013.
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Within each plot, three PVC collars (20 cm inner diameter and 10 cm height) were inserted into the soil with 3 cm exposed above the soil surface, and remained permanently installed throughout the experiment. Green plants and litter inside the collar were removed carefully before SR measurements. SR was measured using an automated soil CO_2 flux systems (Li-8100, Li-Cor Inc., Lincoln, Nebraska, USA) equipped with a 20 cm survey chamber (Model 8100-103). This system works as a dynamic closed chamber, which was manually controlled using a LifeDrive PDA (Palm Inc., Sunnyvale, CA, USA).

SR was measured on clear days once every month from July 2012 to June 2013. At the time of SR measurements, ST and SM at 10 cm depth were measured automatically using the soil temperature probe and moisture sensor equipped with the LI-8100 system. In order to minimize daily variation in SR measurements due to diurnal changes in SR, measurements were made between 8:00 and 11:00 h. Additionally, to assess seasonal effects on diurnal patterns, SR rates were measured every 2 h from 8:00 to 18:00 in July and October in 2012, and in January and April in 2013, representing spring, summer, autumn, and winter, respectively. The winter length in the present study was defined as the period during which mean diel ST at 5 cm was continuously $<$ 0.5°C [11], and occurred for 3 months from December to February. Respiration rates for each measurement for each site were calculated as means of the nine collars within each site.

Dependence of SR on ST and SM

Exponential and polynomial functions, based on the measurements collected, were established to describe the relationships between SR and ST and between SR and SM:

$$SR = a \cdot e^{b \cdot ST} \text{ and } Q_{10} = e^{10 \cdot b} \tag{1}$$

$$SR = a \cdot SM^2 + b \cdot SM + c \tag{2}$$

where a, b and c are fitted constants; Q_{10} is the temperature sensitivity of SR; ST and SM are the soil temperature (°C) and soil moisture (%) at 10 cm depth, respectively.

Non-linear regression analysis was used to express SR against ST and SM:

$$SR = a \cdot e^{b \cdot ST} \cdot SM^c \tag{3}$$

where a, b and c are fitted constants.

Scaling for Annual and Winter Soil C Flux

A further estimate of winter and annual soil CO_2 flux for each site was obtained by interpolating measured SR between respective sampling dates for each seasonal measurement period of the year, and then computing the sum to obtain the "measured" winter or annual values [20,24] as follows:

Table 1. Summary of characteristics of the different sites.

Characteristics	Grassland	Shrubland	Plantation
Latitude	N37°54′17.08″	N37°54′12.00″	N37°54′14.12″
Longitude	E114°14′55.37″	E114°14′50.82″	E114°15′18.16″
Altitude (m)	374	387	381
Plot size (m^2)	100	100	100
ST (°C)	−2.6–29.1	−3.8–30.0	−5.3–27.0
SM (%)	0.6–30.2	0.4–15.3	0.3–24.0
SOC ($g\ kg^{-1}$)	15.0±1.9	23.1±1.4	22.4±2.5
SBD ($g\ cm^{-3}$)	1.47±0.07	1.38±0.08	1.32±0.05
Vegetation type	*A. sacrorum* *B. ischcemum* *T. japonica*	*V. negundo var. heterophylla*	*P. tomatosa*

ST and SM are range of mean soil temperature and soil moisture, respectively at 10 cm depth, during the experimental period; SOC represents soil organic carbon in the top 20 cm depth; SBD means soil bulk density.

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$$\mathrm{TSR} = \sum_{k=1}^{n-1} \mathrm{SR}_{m,k} \Delta t_k \tag{4}$$

where $\Delta t_k = t_{k+1} - t_k$, which is the numbecr of days between each field measurement within the season; TSR is total SR during the prediction period (annual/winter); $\mathrm{SR}_{m,k}$ is the average SR rate over the interval $t_{k+1} - t_k$ recorded by the LI-8100 soil CO_2 flux system; and n is the number of soil CO_2 flux measurements made within each season.

In order to confirm whether measuring winter SR is important, the equation describing the relationship between SR and ST (Equation (1)) during the growing season was also used to estimate the "modeled" annual SR rates based on actual ST measurements. Equation (4) was also used to calculate the "modeled" annual values.

Statistical Analysis

A one-way ANOVA was used to compare differences in mean values of SR, ST and SM among the three sites. Pairwise *t* tests were carried out to compare the "measured" and "modeled" annual values. All statistical linear and nonlinear regression analyses, multiple comparisons including the one-way ANOVA were performed with a significance level of 0.05 using the SPSS 15.0 software (SPSS Inc., Chicago, IL, USA).

Results

Temporal Dynamics of SR

The diurnal pattern of SR for all three sites was described by asymmetric single-peak curves (Figure 2). On each day, the soil CO_2 flux increased gradually from 8:00, achieving a maximum rate at 12:00 or 14:00, and then decreasing. The morning SR followed the increasing trend of ST at 10 cm depth, but decreased more quickly than the temperature in the afternoon. In autumn, the diurnal range of SR in the grassland was larger than in shrubland and plantation. There were no obvious daily fluctuations among the three sites in winter or spring.

The within year temporal dynamics of soil CO_2 flux were largely the same for the three sites (Figure 3A). From October, SR declined steadily until the next March, and then began to increase in April (the beginning of the growing season). The lowest monthly SR rate was 0.22 $\mu mol\ m^{-2}\ s^{-1}$, and occurred in the grassland in February. SR rate peaked in July or August in all of the sites, with the maximum rate of 4.56 $\mu mol\ m^{-2}\ s^{-1}$ in the plantation in August.

Dependence of SR on ST and SM

ST varied distinctly with season paralling the seasonality observed in SR (Figure 3B). Over the whole year, a significant ($p<0.001$) exponential relationship was found between SR and ST for different sites. ST alone explained 73.8 to 91.8% of the within year temporal variability in SR rates (Table 2). The Q_{10} values of SR against ST at 10 cm ranged from 3.60 to 4.90 among different sites. The polynomial function provided the best fit for the relationship between SR and SM. However, the SM-based models could only explain 13.0 to 26.4% of the variation in SR (Table 2). The combined use of ST and SM functions explained 70.6 to 81.9% of the variation in SR, indicating that the inclusion of SM did not improve the explanation of SR compared with the regressions based on ST only.

Winter SR Rates and their Contributions to Annual soil C Flux

Mean monthly soil CO_2 flux rates were 1.58, 1.22 and 1.70 $\mu mol\ m^{-2}\ s^{-1}$, and the "measured" annual soil C fluxes were 602.7, 464.1 and 648.5 $g\ C\ m^{-2}$ for the grassland, shrubland and plantation sites, respectively (Figure 4). Mean winter soil CO_2 flux rate ranged from 0.26 to 0.45 $\mu mol\ m^{-2}\ s^{-1}$ depending on site, which made up 10.6 to 15.6% of the mean growing season soil CO_2 flux. Winter soil C flux, from December 2012 to February 2013, ranged from 24.6 to 42.8 $g\ C\ m^{-2}$ (Figure 5). In the Spring and Fall seasons, mean soil CO_2 flux rate ranged from 0.48 to 0.91 $\mu mol\ m^{-2}\ s^{-1}$ depending on site, and made up 20.2 to 28.7% of the mean growing season soil CO_2 flux. Total non-growing season (Winter and Spring and Fall) soil C flux ranged from 85.1 to 146.1 $g\ C\ m^{-2}$ (Figure 5). The contributions of winter (December to February) and total non-growing season (November to April) soil C flux to annual soil C flux were 4.8 to 7.1% and 18.3 to 23.6%, respectively, depending on site. In addition, the pairwise *t* test showed that the "measured" annual value was significantly higher than the "modeled" annual value for each site ($p<0.01$) (Figure 4).

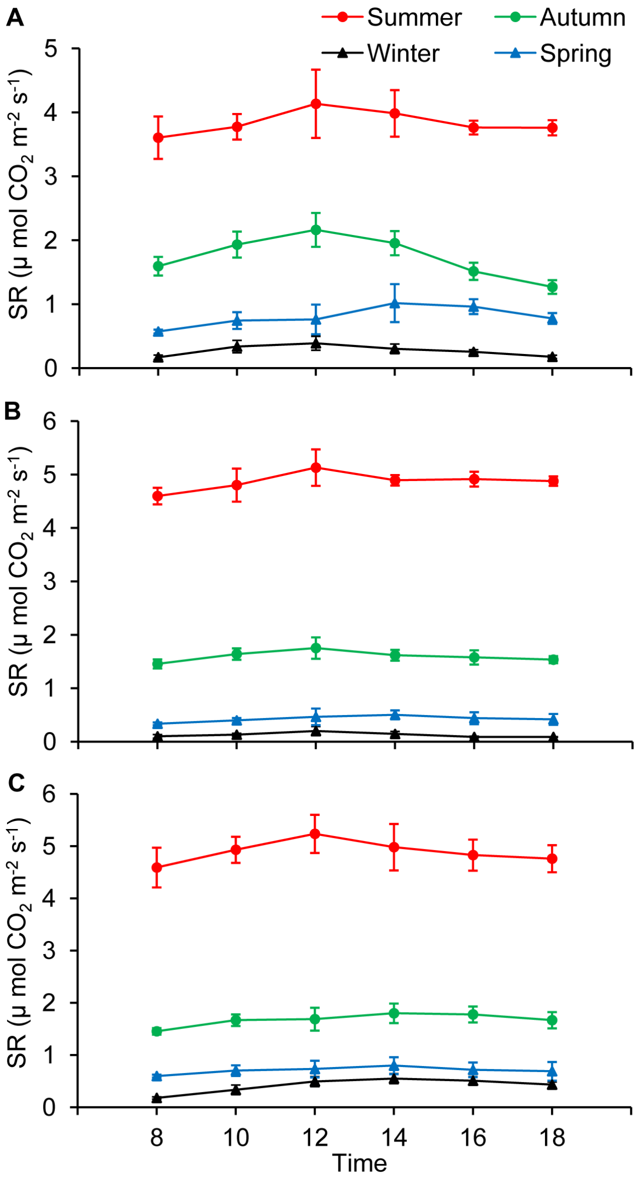

Figure 2. Daily and seasonal variations in soil respiration (SR) in the grassland (A), shrubland (B) and plantation (C) sites, respectively. Note: Time of *x*-axis is Chinese Standard Time (UTC+8). Error bars are standard error of means (n = 9).
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Discussion

Winter SR

Due to the assumption that winter SR was very small compared to growing season respiration, previous to this study, most SR measurements had been conducted during the growing season [3,7,25], and the annual soil CO_2 flux has generally been calculated by extrapolation of growing-season empirical functions [26,27]. However, winter SR can lead to significant carbon losses. For instance, winter soil CO_2 flux accounted for 3.5 to 17% of annual SR estimates in mid-latitude sites [20,24,28,29]. Therefore, winter SR should not be ignored when attempting to quantify and understand the annual carbon balance of terrestrial ecosystems [20,24,25].

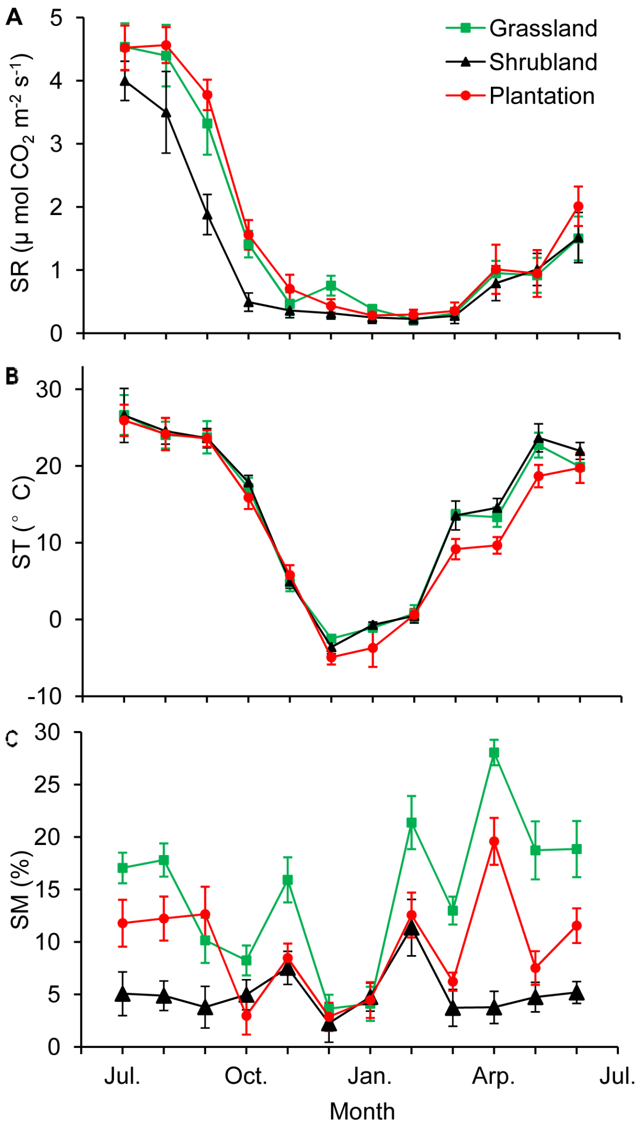

Figure 3. Temporal variations in SR (A), ST at 10 cm depth (B) and SM at 10 cm depth (C) for the three different sites. SR, ST and SM represents soil respiration, soil temperature and soil moisture, respectively. Error bars are standard error of means (n = 9).
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Our measured mean winter SR rates (0.26–0.45 μmol m^{-2} s^{-1}) were consistent with the results from a study conducted in a forest-steppe ecotone in north China (0.15–0.26 μmol m^{-2} s^{-1}) [20] and another study on three vegetation types in the Yellow River Delta of China (0.17–0.60 μmol m^{-2} s^{-1}) [30]. Our results were generally lower than other studies conducted in coniferous forests, including those by McDowell et al. [28] (2000) from the mid-elevation forests in northern Idaho (0.8 μmol m^{-2} s^{-1}), and Schindlbacher et al. [29] in a mountain forest in Austria (0.64 μmol m^{-2} s^{-1}). Higher surface soil organic matter and biological activity in forests may contribute to the higher winter SR rates than those of the present study. In addition, the thickness and duration of snow cover influence the subsurface ST, which may further affect winter SR rates [30]. The snow cover was generally between 0 and 10 cm and the duration of snow cover was very short in the present study region, both of which could also contribute to low winter ST and correspondingly low soil CO_2 flux in this study region.

Table 2. Effects of soil temperature and soil moisture on the variation in soil respiration rate of different sites during the experimental period.

Ecosystem	Regression equation											
	$SR = a{\cdot}e^{b{\cdot}ST}$				$SR = a{\cdot}SM^2 + b{\cdot}SM + c$				$SR = a{\cdot}e^{b{\cdot}ST}{\cdot}SW^c$			
	a	*b*	R^2	Q_{10}	*a*	*b*	*c*	R^2	*a*	*b*	*c*	R^2
Grassland	0.120	0.135	0.738***	3.86	−0.010	0.298	−0.244	0.134*	1.110	0.093	−0.541	0.706***
Shrubland	0.052	0.167	0.775***	4.90	−0.038	0.501	−0.017	0.130*	0.154	0.084	0.282	0.758***
Plantation	0.176	0.128	0.913***	3.60	−0.021	0.557	−1.213	0.264**	0.361	0.088	0.0048	0.819***

SR is monthly mean soil respiration (μmol m^{-2} s^{-1}); ST and SM denote soil temperature (°C) and soil moisture (%) at 10 cm depth, respectively; *a*, *b* and *c* are fitted constants; Q_{10} is the temperature sensitivity of SR.
*means $p<0.1$;
**means $p<0.05$;
***means $p<0.001$.
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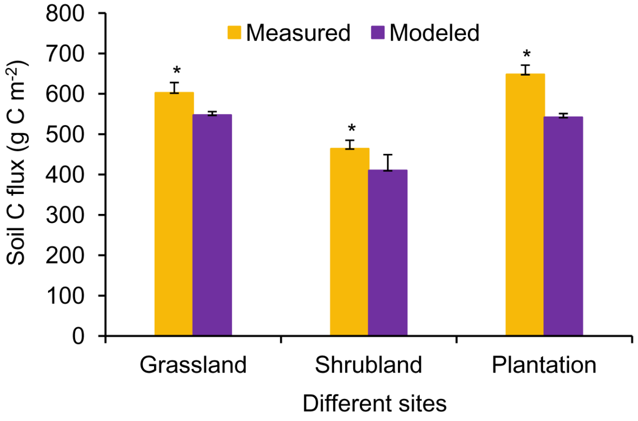

Figure 4. Comparison of "measured" and "modeled" annul soil C flux from the different sites. *denotes statistical significance using a pairwise *t* test comparing "measured" with "modeled" annual values at each site.
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Changes in winter SR in response to climate change have the potential to substantially reduce the net carbon sink in terrestrial ecosystems [9,31]. The contribution of winter SR to annual soil C flux varies with sites and may be affected by many factors, e.g. relative length of winter and growing season, temperature, snow cover, vegetation and soil properties [8,11,25]. Brooks et al. [9] reviewed published studies showing that, on average, 50% of the growing season carbon uptake is respired during the winter. In this study, the contribution of winter SR to annual soil C flux (4.8–7.1%) among different sites was consistent with reported results in a forest-steppe ecotone in northeast China (3.5–7.3%) [20] and in crop rotation fields of northeast China (5.1–7.2%) [24]. Moreover, we also computed an SR-ST relationship for the growing season, and then used this equation to calculate the "modeled" annual soil C flux based on the actual measured ST. The "measured" annual value was significantly higher than the "modeled" annual value, which seems to contradict the hypothesis that shorter winter result in reduced winter contribution to annual C flux. Though our results highlighted the importance of winter SR to annual soil C flux in mid-latitude sites of mountainous region, where winter are short, they can't be generalized to broad scales without further sampling.

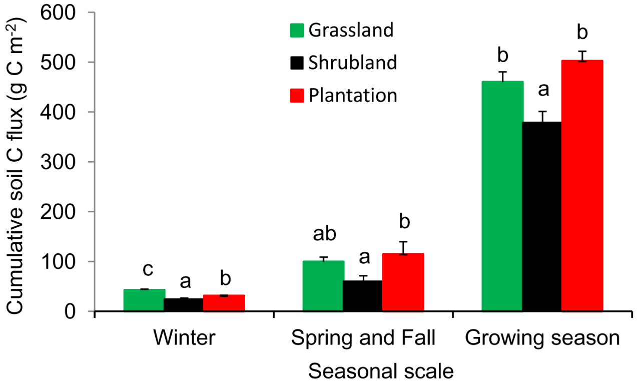

Figure 5. Cumulative soil C flux (g C m^{-2}) for Winter (December-February), Spring and Fall (March-April and October-November), and Growing season (May-September) in the three different sites. Error bars are standard error of means (n = 3). Different letters denote significant differences as determined by Tukey's HSD test.
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Dependence of SR on ST and SM

In this study, the exponential relationship between SR and ST for the three different sites was consistent with other field SR studies [33–35]. The ST-based model explained temporal variation in SR of all three sites very well during the experimental period (Table 2). Previous studies suggested that SR rates increased with an increase in ST [36,37], and this effect was clearly evident in this study as well. In addition to ST, SM has also been recognized as an important factor controlling the variations in SR [17,38,39]. In this study, polynomial equations best fitted the SR with SM relationship. However, the fits of the SM-based models were very low (13.0–26.4%) (Table 2). The combined use of ST and SM functions did not improve model fitting compared with the functions based on ST alone, thus suggesting that ST was a good surrogate for estimating annual SR in the three studied sites of Middle Taihang Mountain. However, previous studies have indentified other factors, such as litter and fine roots, which impact SR [6,40,41].

The Q_{10} is commonly used to express the relationship between SR and ST. The annual Q_{10} values ranged from 3.60 to 4.60 in this study, which is consistent with the range (1.12–5.53) reported for other temperate ecosystems [6,19,20]. The differences in Q_{10} values among sites point to site effects on the response of SR to ST. In addition, the seasonal variations in Q_{10} may reflect confounding effects of seasonal changes in physiological activities induced by root phenology, microbial biomass and other factors [1,42]. Understanding the sensitivity of SR to temperature change and other soil factors makes it possible to improve accuracy of evaluation of the response of terrestrial carbon balance to climatic change [43].

Summary

We measured SR rates during the growing season and non-growing season throughout the year in north China. This study showed that the winter (December to February) and non-growing season (October to April) SR accounted for 4.8 to 7.1% and 18.3 to 23.6%, respectively, of annual soil C flux in the study area. ST was a good proxy for estimating within year temporal variation in SR. This study found that ignoring the winter SR would lead to underestimates of C loss potential in temperate sites. Our results presented here are consistent with other studies indicating that winter soil C flux plays an important role in the global carbon budget.

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Author Contributions

Conceived and designed the experiments: HTS JSC WJZ. Performed the experiments: HTS JSC XHZ. Analyzed the data: HTS JSC HRW. Contributed reagents/materials/analysis tools: HTS JSC XHZ. Wrote the paper: HTS JSC.

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